Energy Technology Perspectives

2024

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Foreword

In July 2021, the International Energy Agency (IEA) declared that a new global energy economy was emerging – one based on clean and modern technologies such as solar, wind, electric cars and others. This was a trend that had become clear in our data and analysis, which covers all fuels and all technologies across the global energy system.

Our work has continued to chart the rise of this new energy economy and its implications for the world. Much of this has focused on what the changes mean for energy security, economic development and international efforts to bring down greenhouse gas emissions. But as the adoption of clean energy technologies has surged in many countries across the globe, other factors have increasingly come into play.

As a new energy economy takes shape, access to a range of components and inputs for clean technologies – many of which are produced in vast factories – is rising in importance. More and more countries are enacting bold new industrial strategies to bolster the security of clean energy supply chains and to gain an economic edge as demand grows. The result is that manufacturing and trade are emerging as crucial variables that will determine how our energy system develops and how quickly emissions from it will decline.

The deepening connections between energy, trade, manufacturing and climate are the focus of this latest edition of *Energy Technology Perspectives (ETP)*, the IEA's flagship technology publication. Building on the comprehensive assessment of clean energy technology supply chains set out in *ETP-2023*, this year's edition offers cutting-edge analysis based on rich and detailed new data, granular surveys of industry, and a bottom-up approach to fresh modelling. Its significance is amplified by what has been, until now, a dearth of information in this space, and it will provide policymakers with an in-depth, quantified basis to inform their deliberations for years to come.

One point to emphasise: the IEA does not aim to prescribe trade policy, which is not our Agency's role. Instead, this report is intended to provide detailed insights that are relevant to the conversations and considerations facing governments around the world today, in line with our longstanding practice.

As major economies have introduced new industrial strategies to stake out their places in the growing clean energy economy, the manufacturing of clean technologies has boomed. This report homes in on the six major ones: solar PV, wind, electric vehicles, batteries, electrolysers and heat pumps, whose market size and trade value is set to soar over the next decade. It also looks at key components of these technologies, as well as industries that provide important building blocks for them, such as steel, aluminium and ammonia.

The remarkable growth in clean energy technologies can offer many benefits and opportunities, including new manufacturing industries, job creation, lower energy bills, improved energy security, cleaner air and emissions reductions. In the case of trade, as clean energy technologies reshape a landscape that has historically been dominated by fossil fuels, resilience could improve. Fossil fuels tend to be quickly consumed, which can lead to a reliance on certain exporters for recurring supplies. Clean energy technologies operate over longer time frames. That could result in less exposure to short-term supply disruptions and market volatility, shielding countries from the destabilising boom-and-bust cycles seen in some energy markets in recent decades.

However, there can also be tensions and trade-offs. We already see the intense competition among major economies to gain advantage in the new energy economy. As countries race to reap the maximum economic benefits, what are the broader implications? Does it risk making clean energy transitions less cost-effective if too many trade barriers go up? Will it result in inefficient government subsidies? Could smaller and less developed economies be sidelined? This report aims to explore these vital questions and highlight the most promising pathways forward.

ETP-2024 lays out the state of play and the outlook for the key economies that are the major manufacturers of clean energy technologies today. But it also finds, on the basis of 60 indicators, that the door remains open for emerging and developing economies to play to their strengths and move up the value chain in manufacturing as the clean energy transition gathers speed. While the top fossil fuel producers are countries with ample natural resources, many more countries could build up strong clean energy manufacturing bases if they can ensure the right enabling conditions.

Yet even as countries have a chance to tap the benefits of clean energy transitions for their citizens, *ETP-2024* finds a need for global perspective and cooperation in pursuit of industrial and trade strategies that can ensure widespread prosperity and help keep international energy and climate goals within reach. Here, the IEA stands ready to provide support. Amid a complex environment, collaboration remains essential.

I would like to thank the hardworking members on the *ETP* team who wrote this groundbreaking report under the excellent leadership of the IEA's Chief Energy Technology Officer Timur Gül. The efforts to assemble the data and develop the analysis presented here have been a major undertaking, and they represent a vital contribution to the global energy dialogue. I hope this *ETP* supports the work of decision-makers as they strive to build a more secure and sustainable energy system for all.

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Executive Director
International Energy Agency

Acknowledgements

This study was prepared by the Energy Technology Policy (ETP) Division of the Directorate of Sustainability, Technology and Outlooks (STO), with input from other divisions of the International Energy Agency (IEA). The study was designed and directed by **Timur Gül**, IEA Chief Energy Technology Officer.

The modelling and analytical teams of Energy Technology Perspectives 2024 (*ETP-2024*) were co-ordinated and supervised by **Araceli Fernandez** (Head of the Technology Innovation Unit) and **Uwe Remme** (Head of the Hydrogen and Alternative Fuels Unit). **Peter Levi** (materials and competitiveness) and **Leonardo Paoli** (clean energy technology manufacturing and trade routes) were responsible for the analysis of cross-cutting topics throughout the report. **Simon Bennett** led on strategic considerations and policy.

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Other key contributors from across the IEA were Caleigh Andrews, Heymi Bahar, Blandine Barreau, Piotr Bojek, Jianlan Dou**,** Mathilde Fajardy, Carl Greenfield, Jack Jaensch, Megumi Kotani, Martin Kueppers, Maija Lehtonen, Shane McDonagh, Quentin Minier, Luis Munuera (external), Soyoung Oh, Diana Marcela Perez Sanchez, Hiroyasu Sakagushi, Mirko Uliano, Agrata Verma, Fabian Voswinkel, Brent Wanner, Daniel Wetzel and Biqing Yang.

Special thanks to Frank van Tongeren (former Head of OECD's SMART Data and Modelling unit within the Directorate on Trade and Agriculture), who provided strategic advice on trade modelling and policy throughout the project; and Jasper Verschuur (Assistant Professor at University of Technology Delft), who advised on trade routes and ports activity.

Valuable comments and feedback were provided by senior management and other colleagues within the IEA, in particular, Keisuke Sadamori, Laura Cozzi, Alessandro Blasi, Dan Dorner, Tim Gould, Brian Motherway, Paolo Frankl, Dennis Hesseling and Yang Jun.

Trevor Morgan provided writing support and holds editorial responsibility; Lizzie Sayer supported the editing of the manuscript. Charlotte Bracke, Anna Kalista, Mao Takeuchi and Per-Anders Widell provided essential support throughout the process.

Thanks also to the IEA Communications and Digital Office for their help in producing the report, particularly to Jethro Mullen, Poeli Bojorquez, Curtis Brainard, Gaelle Bruneau, Jon Custer, Grace Gordon, Julia Horowitz, Oliver Joy, Isabelle Nonain-Semelin, Robert Stone, Sam Tarling Clara Vallois, Lucile Wall, and Wonjik Yang.

The work could not have been achieved without the financial support provided by the Governments of Canada, Germany and Japan.

Several senior government officials and experts provided essential input and feedback to improve the quality of the report. They include:

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Prasoon Agarwal	Clean Energy Ministerial Secretariat
Bentley Allan	Johns Hopkins University, United States
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Thomas Becker	BMW
Hassiba Benamara	UN Trade and Development
Marlen Bertram	International Aluminium Institute
Vincent Berrutto	Directorate-General for Energy, European Commission
Reed Blakemore	Atlantic Council
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Camille Bourgeon	International Maritime Organization
Anne Sophie Castelnau	ING
Jon Creyts	Rocky Mountain Institute
Ilka von Dalwigk	Recharge
Laurent Daniel	Organisation for Economic Co-operation and Development
Faustine Delasalle	Mission Possible Partnership

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Caroline Haglund Stignor	Heat Pump Centre
David Hart	George Mason University, United States
Jan Hoffmann	UN Trade and Development
Noé van Hulst	Gasunie
Tsutomu Ishihara	Panasonic Corporation
Rishabh Jain	Council on Energy Environment and Water, India
Andreas Klein	Northvolt
Leif Christian Kröger	thyssenkrupp nucera
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Gustavo Naciff de Andrade	Energy Research Office, Brazil
Kei Nomura	Kawasaki Heavy Industries
Takashi Nomura	Toyota Motor
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Agustín Rodríguez Riccio	Topsoe
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Akiyuki Yonekaw	Honda Motor
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Executive Summary

Three strategic areas of public policy – energy, industry and trade – are increasingly interwoven. Tensions and trade-offs arise in each of these areas as governments seek to reconcile their commitment to well-functioning markets and cost-effective clean energy transitions, on the one hand, with the need to establish secure, resilient clean technology supply chains, on the other. This involves tough decisions around choosing which industries to support, collaboration with trading partners, and how to prioritise innovation efforts. This 2024 edition of *Energy Technology Perspectives (ETP)* – the "world's clean energy technology guidebook" – is designed to support decision-making in these areas. *ETP-2024* is the first analysis of its kind to explore the future of manufacturing and trade of clean energy technologies, with granular sectoral detail across supply chains, built on a unique bottom-up dataset and a quantitative assessment of countries' industrial strategies.

Manufacturing and trade are foundational for the new clean energy economy

The sizeable economic opportunities associated with manufacturing clean energy technologies are a top priority for government and industry. The global market size for six of the main clean energy technologies – solar PV, wind, electric vehicles (EVs), batteries, electrolysers and heat pumps – has grown nearly fourfold since 2015 to exceed USD 700 billion in 2023, which is around half the value of all the natural gas produced globally that year. Growth has been driven by surging clean technology deployment, particularly for EVs, solar PV and wind. Under today's policy settings, the market for key clean technologies is set to nearly triple by 2035, to more than USD 2 trillion. This is close to the average value of the global crude oil market in recent years.

International trade is essential to the proper functioning of the global economy – including the energy system. Global goods trade – comprising vital supplies of everything from food and clothing to smart phones and semiconductors – amounted to around USD 24 trillion in 2023 in value terms. Fossil fuels accounted for around 10% of this, while bulk materials and chemicals – including steel, aluminium and ammonia – accounted for around 20%. Clean energy technology trade today accounts for a comparatively small share relative to these established industries, at around 1%, but it is growing fast.

At around USD 200 billion, the value of trade in clean technologies is nearly 30% of their global market value. The biggest element is trade in electric cars, which has doubled since 2020, reaching around one-fifth of trade in all cars in 2023 in value terms. Solar PV is the second-most traded technology in value terms. Under today's policy settings, overall clean technology trade is on track to reach USD 575 billion by 2035, or around 50% more than the value of global trade in natural gas today.

Investments in manufacturing are surging in response to rapidly growing demand for clean technologies

A major wave of manufacturing investment in clean technologies is underway, with many new factories being built across the world. Global investment in clean technology manufacturing rose by 50% in 2023, reaching USD 235 billion. This is equal to nearly 10% of the growth in investment across the entire world economy, and around 3% of global GDP growth. Four-fifths of the clean technology manufacturing investment in 2023 went to solar PV and battery manufacturing, with EV plants accounting for a further 15%. The amount of manufacturing capacity being added has been comfortably outpacing current deployment levels. Despite some recent cancellations and postponements of solar PV and battery manufacturing projects, investment in clean technology manufacturing facilities is set to remain close to its recent record levels, at around USD 200 billion in 2024.

Cost competitiveness is an important driver of manufacturing investment – but not the only one. China is currently the cheapest location for manufacturing all the major clean energy technologies considered in this report, without taking into account explicit financial support from governments. Compared with China, it costs up to 40% more on average to produce solar PV modules, wind turbines and battery technologies in the United States, up to 45% more in the European Union, and up to 25% more in India. Cost competitiveness is a key factor explaining China's outsized role in clean technology manufacturing today: it accounts for between 40% and 98% of global manufacturing capacity for the key clean technologies and components we examine, depending on the case. Relative to other countries, China has greater economies of scale, a larger domestic market and highly integrated firms and facilities along the supply chain for these technologies. An IEA survey of more than 50 major manufacturers across clean technology and material supply chains reveals other factors, besides costs, that influence investment decisions. These include various forms of policy support, access to markets, skills and knowledge in the industrial base, and infrastructure.

Trade can help countries play to their economic strengths

Moving energy-related trade towards clean technologies is part of a broader shift in the energy sector that has long-term implications for trade volumes. Fossil fuels provide recurring flows of energy trade, whereas clean technology trade results in a long-lived stocks of energy generation and transformation equipment. For example, based on today's policy settings, the European Union's net imports of fossil fuels and clean energy technologies reach around USD 400 billion in 2035. But the bloc's total import bill tilts towards a higher share of clean energy technologies, from less than 10% in 2023 to 35% in 2035, at the expense of fossil fuels. This has positive impacts on energy resilience: a single journey by a large container ship filled with solar PV modules can provide the means to generate electricity equivalent to the amount generated from the natural gas onboard more than 50 large LNG tankers, or the coal onboard 100 large ships.

Industrial strategies in Europe and the United States are set to alter the outlook for manufacturing and trade

In the European Union, the future of clean technology manufacturing will be shaped by how successfully the targets of the Net Zero Industry Act (NZIA) can be achieved. While the NZIA targets are readily achievable for some technologies like the final steps of wind component and heat pump manufacturing, the task facing the automotive industry is much larger. More than 40% of the internal combustion engine (ICE) vehicles produced in the European Union today are destined for export and facing competition from EV manufacturers in China, as are domestically produced EVs for the EU market. For the EU car industry to compete in the growing EV market, manufacturing cost reductions for electric cars and full integration of supply chains, including batteries, will be essential. In 2023, imports from China accounted for around 20% of EV sales in the European Union. Under today's policy settings, this share roughly doubles to 40% by 2035 despite recently announced import duties that will be in effect for 5 years. If the goals of the NZIA are achieved, a fully integrated EV and battery supply chain would help bring the share down to 20%.

In the United States, the Inflation Reduction Act and Bipartisan Infrastructure Law are bearing fruit. They have already mobilised USD 230 billion of investment in clean technology manufacturing through to 2030. Based on current policy settings – and driven by the incentives provided under these pieces of legislation – US demand for solar PV modules and polysilicon could be met almost entirely by domestic production by 2035, while some demand for cells and wafers would still be met by imports. Existing trading relationships also provide a strong foundation: Mexico is well placed to become a hub for EV manufacturing for the North American market (as it is today for ICE cars), with Southeast Asia, Korea and Japan being other potential key suppliers.

China remains the world's manufacturing powerhouse and India makes major strides, becoming a net exporter

China's share of global manufacturing for all six key clean technologies in value terms is around 70% today. China's largest solar PV manufacturing facility currently under construction, located in Shanxi province, could alone produce enough modules to cover virtually all EU demand today. Despite the ongoing implementation of industrial strategies in other countries, the value of China's clean technology exports is on track to exceed USD 340 billion in 2035, based on today's policy settings. This is roughly equivalent to the projected oil export revenue of both Saudi Arabia and the United Arab Emirates combined in 2024. China's fossil fuel import bill is currently the highest of any country in the world. Under today's policy settings, the net import bill – accounting for fossil fuel imports and clean technology exports – is cut by around 70% between now and 2035. If markets for clean technologies grow more quickly than projected under today's policy settings, then China's exports of clean technologies would, in value terms, entirely offset its imports of fossil fuels, before 2035.

India pivots from being a net importer of clean technologies today to a net exporter in 2035, if the clean energy transition accelerates. Under today's policy settings, India remains a net importer of clean technologies in value terms in 2035, but with modestly growing production and exports of solar PV modules, EVs and batteries incentivised under the Production Linked Incentive Scheme. In contrast, if the clean energy transition proceeds more quickly in India and around the world, the country's net exports of clean energy technologies could grow rapidly to reach USD 30 billion in 2035, after supplying a large portion of its own rapidly increasing demand. This offsets around 20% of its remaining fossil fuel import bill of around USD 170 billion, reducing India's energy-related trade deficit to around USD 140 billion.

The door of the new clean energy economy is still open to emerging markets

Emerging and developing economies in Latin America, Africa and Southeast Asia account for less than 5% of the value generated from producing clean technologies today. A fair and just transition requires enabling more regions to reap the economic benefits from growing supply chains for clean and modern energy technologies. A faster clean energy transition and larger overall market for clean energy technologies will be foundational for this. Other factors that presently deter investment in emerging markets also need to be overcome, including political and currency risks, a lack of skilled workers and poor infrastructure. But the opportunities exist: beyond the mining and processing of critical minerals, countries in Africa, Latin America and Southeast Asia all have prospects to boost their competitive advantages and move up the value chain. We collected country-by-country data across over 60 indicators, assessing the business environment, infrastructure for energy and transport (such as electricity grids, gas pipelines and ports), resource availability and domestic market size, to identify opportunities for each country.

Southeast Asia is already an important player in clean technology supply chains, and several countries can take a step up the value chain. The region could be among the cheapest places to produce polysilicon and wafers for solar PV modules by 2035. Several countries there can build on existing manufacturing strengths for electronic and electrical equipment, competitive labour and energy prices, and government policies that are supportive for export-oriented industries. If the region can fully exploit these competitive advantages, and policy action worldwide is compatible with reaching net zero emissions globally by 2050, Southeast Asia could produce over 8 million EVs by 2035 (up from about 40 000 today), of which almost half would be exported.

Latin America, and Brazil in particular, has favourable starting conditions for wind turbine manufacturing, but significant investments in infrastructure and logistics are required to capitalise on this. Today, Brazil produces over 5% of wind turbine blades globally. If the country is able to take advantage of its favourable enabling conditions, in a scenario compatible with net zero emissions by 2050, exports of these components increase sixfold by 2035 compared with current levels, assuming long-lead-time investments in port infrastructure bear fruit. Brazil – among other Latin American countries – is also endowed with abundant renewable energy resources, which form a good basis for exports of near-zero emissions ammonia, iron and steel to markets where these commodities are more costly to produce, such as Europe and Japan.

North Africa could become an EV manufacturing hub. Investment is already underway, and if the region is able to achieve its potential in line with achieving net zero emissions by 2050 globally, North Africa in 2035 exports almost half of the 3.7 million EVs it produces by then, mostly to the European Union. This would build on the existing project pipeline in countries such as Morocco. Elsewhere in Africa, countries have the potential to leverage iron ore and renewable energy resources, for example, to move up the value chain and produce iron with electrolytic hydrogen. Such exports to Europe and Japan could be worth more than four times the value of the same tonnage of iron ore exports at today's prices, if the world pursues climate targets compatible with reaching net zero emissions by 2050, and the barriers to investment in African countries are overcome.

Supply chain concentration puts pressure on the busiest maritime shipping routes

Traffic through some of the busiest maritime chokepoints increases, despite growth in overall shipping activity slowing down. Based on today's policy settings, global maritime goods trade increases by 1% per year by weight over the coming decade – significantly more slowly than over the past two decades, due to slower growth in fossil fuel and steel demand. However, traffic through certain chokepoints intensifies. Around 50% of all maritime trade in clean technologies trade passes through the Strait of Malacca today. Based on today's policy settings, clean technology shipments through Malacca are set to rise substantially, though their share in total maritime trade remains very small. This dependency on maritime chokepoints poses risks to supply chain resilience, especially as the average clean technology cargo is more than ten times the value of the average fossil fuel cargo per tonne.

Well-designed industrial strategies will be crucial for clean energy transitions to continue gathering pace

The tensions and trade-offs between the goals of energy and industrial policies mean that getting trade policy measures right is essential for clean energy transitions. In some cases, the clean energy dividends of trade would be higher if barriers to trade were lower. Today, tariffs on renewable energy systems and components, for example, are more than twice those applied to fossil fuels, on average. Trade measures – including both tariffs and non-tariff measures – already increase the cost of clean technologies. For example, a 100% tariff on solar PV modules today would cancel out the decline in technology costs seen over the past 5 years. The knock-on impact on electricity generation costs would be more limited, as the solar PV modules themselves make up 20-30% of the total installation cost. But for consumer goods, such as electric cars, the impact is likely to be more direct and risks slowing down adoption.

Well-designed industrial strategies can help companies address competitiveness gaps or reach the innovation frontier sooner, but their interplay with trade policy measures needs careful consideration. Industrial policy deployed with a specific, measurable and time-bound goal can support the achievement of energy policy and climate goals. For example, battery production in the European Union is around 50% more expensive than in China today. Innovative battery technologies currently under development could help reduce the cost gap by up to 40% – at which point, the advantages of manufacturing being located in the European Union may outweigh the remaining cost difference. To cultivate and maintain competitiveness and innovation, industrial policies must be closely monitored and amenable to course correction. Trade policy must be designed carefully if it is to support such goals – broad-based protectionism or blanket financial support are very unlikely to make for a winning industrial strategy.

Industrial strategies must take into account the new parameters and objectives of international trade in clean technology supply chains. To balance efforts to reach climate goals with energy and industrial policy objectives, trade policies will need to be designed with a view to their role in the new clean energy economy, and what it means for industrial competitiveness today. There is no single recipe to follow for these policies, but the analysis presented in *ETP-2024* is designed to help move the debate in this area forward.

Introduction

The International Energy Agency (IEA) *Energy Technology Perspectives (ETP)* flagship series of reports has been providing critical insights into key technological aspects of the energy sector since 2006. It was revamped in 2020 to serve as the IEA's guidebook for clean energy technologies, with a focus on themes that are particularly pertinent for policy makers in view of the vital importance of clean energy technologies and innovation in meeting the policy goals of energy security, economic development and environmental sustainability. Efforts to achieve these goals cut across different dimensions of industrial, energy and trade policies – seeking positive synergies between them and managing any trade-offs will be key to success. Based on granular sectoral data and innovative analysis, *Energy Technology Perspectives 2024 (ETP-2024)* is the first report of its kind to analyse the future of manufacturing and international trade of clean energy technologies and related materials. It aims to provide policy makers with a quantitative assessment of the opportunities and complexities associated with the manufacturing and trade of such technologies and materials across the world in order to support decision-making on these topics.

The analysis covers six key clean energy technologies – electric vehicles (EVs), batteries, solar photovoltaics (PV), wind turbines, heat pumps and electrolysers – which together account for around half of global clean energy investment spending and have a combined market size of more than USD 700 billion. The analysis also covers the manufacturing and trade of the main components of these technologies, alongside three categories of materials – steel, aluminium and ammonia (both for industrial and fuel-related applications) – with a focus on near-zero emissions manufacturing processes.

The analysis of *ETP-2024* takes into account the need to build secure and resilient supply chains for the clean energy transition. It assesses the economic opportunities that the clean, modern energy economy is generating and how investment in the manufacturing of clean energy technologies and materials is reshaping global trade flows. Clean energy technologies have come to the fore in new industrial strategies that are being devised by governments around the world to boost domestic manufacturing, create jobs and enhance resilience, while also supporting decarbonisation efforts. Policy has a vital role to play in these areas: each country needs to devise its own clean energy industrial strategy, reflecting its inherent strengths and weakness, including access to low-cost mineral and energy resources, a skilled workforce and synergies with existing industries. Policy makers need to balance the goals of supply security and resilience, affordability and equity in designing effective policies and strategies to get to net zero emissions of GHGs as quickly as possible. *ETP-2024* explores various ways of navigating trade-offs in meeting these goals.

This report greatly expands on the analysis contained in *ETP-2023*, which focused on clean energy technology supply chains and their importance in the energy transition, finding that manufacturing of key technologies was heavily concentrated in a few major markets. *ETP-2024* provides a deeper look into the factors shaping the current status and outlook for manufacturing and trade of these key clean energy technologies and materials, informed by a unique, richly detailed dataset.

Chapter 1 reviews the current status of manufacturing supply chains and assesses the drivers of investment decisions in the manufacturing industry, notably cost competitiveness. Chapter 2 analyses the outlook for clean energy manufacturing capacity and production, as well as inter-regional trade, using projections based on policy scenarios, while Chapter 3 looks in detail at prospects in four main markets: the United States, the European Union, China and India. Chapter 4 provides a detailed assessment of opportunities for emerging markets and developing economies to move up the value chain and reap the benefits of investment in manufacturing and material production. Chapter 5 identifies the main shipping routes and chokepoints associated with the trade of clean energy technologies, as well as the role of ports and ships for decarbonising international trade. Finally, Chapter 6 discusses strategic considerations for policy makers.

Chapter 1: The state of manufacturing and trade

Highlights

- Global manufacturing capacity for clean energy technologies is expanding quickly. Between 2021 and 2023 alone, production capacity increased from just over 450 GW to 1.2 TW for solar PV modules, 125 GW to 180 GW for wind, 10.5 to 22.2 million units for EVs, 1.1 TWh to 2.5 TWh for batteries, and tripled to 25 GW for electrolysers. Announced expansions could lead to a manufacturing capacity of 1.6 TW for solar in 2030, 260 GW for wind, 9.3 TWh for batteries and 165 GW for electrolysers.
- China is by far the largest producer of clean energy technologies and related materials, including steel, aluminium and ammonia. Based on announced projects, geographic concentration in manufacturing is expected to persist to 2030, with China, the European Union and the United States accounting for over 80% of production capacity for the six clean technology supply chains – solar PV, wind, electric vehicles, batteries, electrolysers and heat pumps – considered in this report.
- Investment in manufacturing capacity for the six clean energy technology supply chains reached USD 235 billion in 2023, up from USD 160 billion in 2022. Based on announced projects, investments in these facilities are expected to remain around USD 200 billion in 2024, with an average of USD 180 billion per year due to be invested through to 2030, around 35% of which is committed.
- Trade in clean technologies is increasing rapidly. Global exports of solar PV modules have increased more than tenfold since 2015; those of electric cars have increased nearly twentyfold. The trade routes for bulk carriers are more congested than those for oil tankers and container ships, and more concentrated in Asia. The clean energy transition is changing the landscape of trade – economies rely less on fossil fuels, which are consumed, and more on manufactured technologies, which are added to installed capacity and operated for years at a time. This is changing the nature of supply chain risks.
- Cost is the main determinant of the level and location of investments in manufacturing. Variable operating costs, including materials, components and energy, make up more than three-quarters of the levelised cost of producing the technologies considered, when factories are utilised intensively. For materials production, the share of energy is generally much higher. Producing these commodities with near-zero emissions technologies is currently much more expensive than with conventional technologies, but the premium could fall significantly once they reach commercial scale.
- An IEA industry survey of more than 50 companies highlights the importance of other factors besides cost, notably the size of the domestic market. In China, where manufacturing capacity has expanded most rapidly in recent years, the size of the market for clean technologies has grown from USD 25 billion in 2010 to more than USD 400 billion in 2023 in real terms. A large existing industrial base and co-location with suppliers and customers are also strong pull factors.

This chapter starts with an overview of the current state of play with respect to manufacturing of and international trade in clean energy technologies and related materials, including investment trends in the sector. This includes analysis of trends in demand for the six key technologies considered in this report – solar PV, wind, electric vehicles (including batteries), electrolysers and heat pumps[1] – together with the latest developments in three strategic upstream industries – steel, aluminium and ammonia. We then assess the drivers of competitiveness in manufacturing these technologies and materials, including regional differences in capital and operating costs, and then conclude with an overview of the various policies and instruments comprised by government industrial strategies.

1.1 Manufacturing

The importance of manufacturing

Manufacturing – a vital economic activity, accounting for nearly one-fifth of global gross domestic product (GDP) – is central to the clean energy transition. The United States, the European Union, Japan and the People's Republic of China (hereafter, "China") collectively accounted for around 65% of manufacturing value added in 2023, a share that has remained almost constant over the past two decades. China has emerged as the world's manufacturing powerhouse, nearly tripling its share of global manufacturing value added between 2005 and 2023 to one-third and increasing its output fivefold in absolute terms to over USD 6 trillion in 2023 prices (Figure 1.1). This was driven by highly supportive government policies and a massive increase in investment. Manufacturing in other major economies has grown less rapidly.

Despite services accounting for around 60% of value added in the global economy in 2023, the manufacturing sector remains significant. Manufacturing contributes just under 20% of global value added, which is roughly equivalent to several core service sub-sectors combined, including retail (10%), finance (7%) and information and communications (5%). Other sub-sectors such as health and construction (5% each), transport (4%), and fossil fuel extraction, metals mining, and agriculture and fishing (1-2% each), account for much less value added in the global economy than manufacturing. For this reason, this report takes a closer look at manufacturing while excluding critical minerals and installation of clean energy technologies from the immediate scope. Manufacturing also generates important productivity gains and spillovers across other sectors. Within

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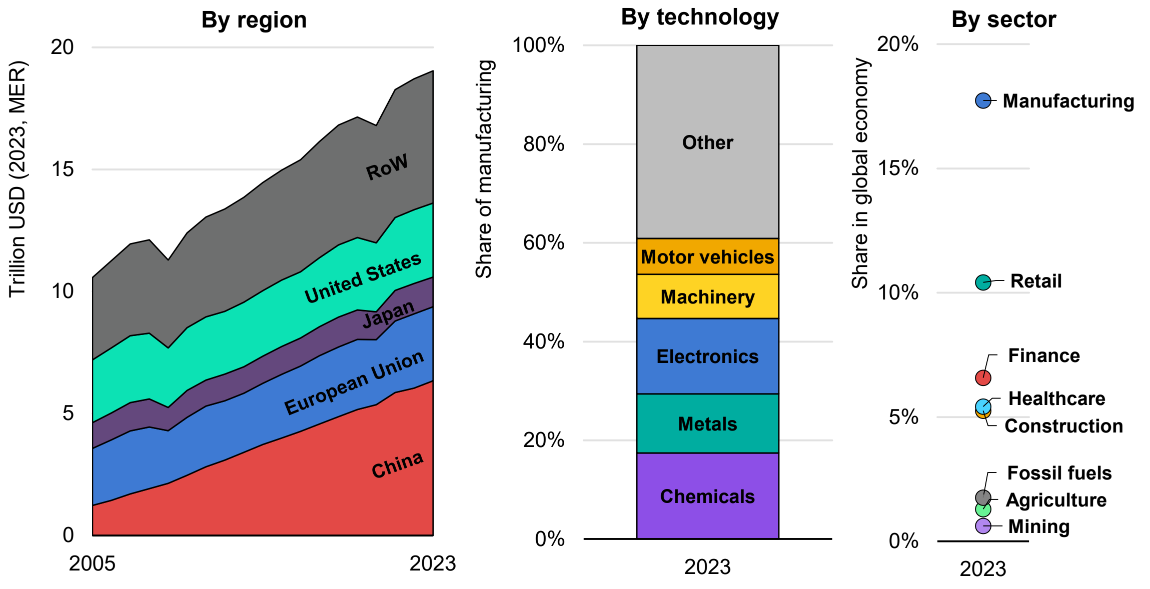
[1] Heat pumps in this report refer to those that deliver heat directly to households and residential or commercial buildings for space heating and/or domestic hot water provision. They include natural source heat pumps, including reversible air conditioners used as primary heating equipment. They exclude reversible air conditioners used only for cooling, or used as a complement to other heating equipment, such as a boiler.

manufacturing, chemicals, electronics, metals, machinery and motor vehicles combined account for 60% of global economic value added.

Figure 1.1 Global economic value added in manufacturing industry



Notes: RoW = Rest of World. The middle chart refers to the share of each technology area within the value added of manufacturing. The right-hand side chart refers to the share of each sector's value added in the value added of the whole economy. Data for retail, finance and agriculture are the result of a weighted average over 2019-2021 in major advanced economies. Fossil fuels refer to fossil fuel extraction.

Source: IEA analysis based on IEA (2024a); OECD (2024a); and Oxford Economics Limited (2024a).

Manufacturing accounts for nearly one-fifth of global GDP, with China the leading producer, followed by the United States and the European Union.

The energy transition calls for a massive deployment of clean technologies and the transformation of the processes to manufacture them. In many cases, clean energy technologies are still emerging, in the sense that their deployment rate is still low relative to that of incumbent technologies, or that it is concentrated in a few countries or regions. Manufacturing of all types of clean energy technology needs to ramp up rapidly, sometimes from scratch, in order to meet climate goals (see Chapter 2). Recent success stories, such as for solar PV, wind power and electric vehicles (EVs) – demonstrate the critical role of policy in developing manufacturing capacity and fostering demand for emerging clean energy technologies. There is also a need to transform existing manufacturing activities to make them compatible with net zero emissions, including near-zero emissions materials required as inputs for making clean technologies and other products (Box 1.1); materials production is highly energy-intensive and responsible today for a large share of carbon dioxide (CO_2) emissions worldwide. For example, in 2023, CO_2 emissions from global production of iron and steel and aluminium accounted for over 3 gigatonnes (Gt) of CO_2, or 8% of global emissions.

Box 1.1 Near-zero emissions technologies for materials production

Among materials, this report focuses on three key commodities – steel, aluminium and ammonia – that are particularly relevant to clean technology manufacturing and trade. Steel and aluminium are direct inputs to the manufacturing processes for several clean energy technologies, while ammonia could play an important role in decarbonising global maritime trade. The production of all three materials is currently both very energy- and emissions-intensive, together accounting for nearly 10% of global energy sector emissions in 2023.

Increased energy and materials efficiency, together with other modifications to the operation of existing manufacturing facilities, are expected to make substantial contributions to reducing emissions in these industries. However, getting to net zero emissions globally also requires a fundamental shift to new manufacturing processes for these commodities. Many of the technologies required for these processes are at an earlier stage in their development than the other clean technologies addressed in this report (such as solar PV and wind turbines), and most are not commercially available on the market today (IEA, 2023a).

In this report, we refer to technologies that can produce steel from iron ore, aluminium from bauxite, and ammonia with emissions intensities that are compatible with the IEA's Net Zero Emissions by 2050 Scenario (see Chapter 2) as "near-zero emissions technologies", and their outputs as "near-zero emissions materials". This terminology echoes that used in the IEA's report, *Achieving Net Zero Heavy Industries*, produced for the Group of Seven (G7) (IEA, 2022a). IEA work on near-zero emissions definitions and measurement protocols has only addressed steel and cement production as yet, but forthcoming analyses, including those produced by the IEA Working Party on Industrial Decarbonisation (WPID) and the Climate Club may well consider similar definitions for aluminium, ammonia and other outputs of heavy industry (IEA, 2024b).

The use of the term near-zero emissions in this *ETP* differs from that used in the work on definitions for the G7 in two important respects:

- The original definition is based on a set of emissions-intensity thresholds, including various categories of indirect emissions and taking into consideration process arrangements at the facility level. These specificities cannot be considered precisely at the regional level in our modelling work for this report, so a narrower emissions boundary is used based on direct emissions only.
- The definition used in this report excludes production of steel and aluminium based fully on scrap, thereby focusing on production technologies that are barely deployed today and that require the most innovation and policy support (for example, hydrogen-based direct iron reduction (H2-DRI) production, aluminium smelters with inert anodes and carbon capture, utilisation and storage (CCUS)-equipped steam methane reforming for ammonia production).

These modifications to the usage of "near-zero emissions" apply only to this report and do not affect ongoing WPID and Climate Club work on definitions.

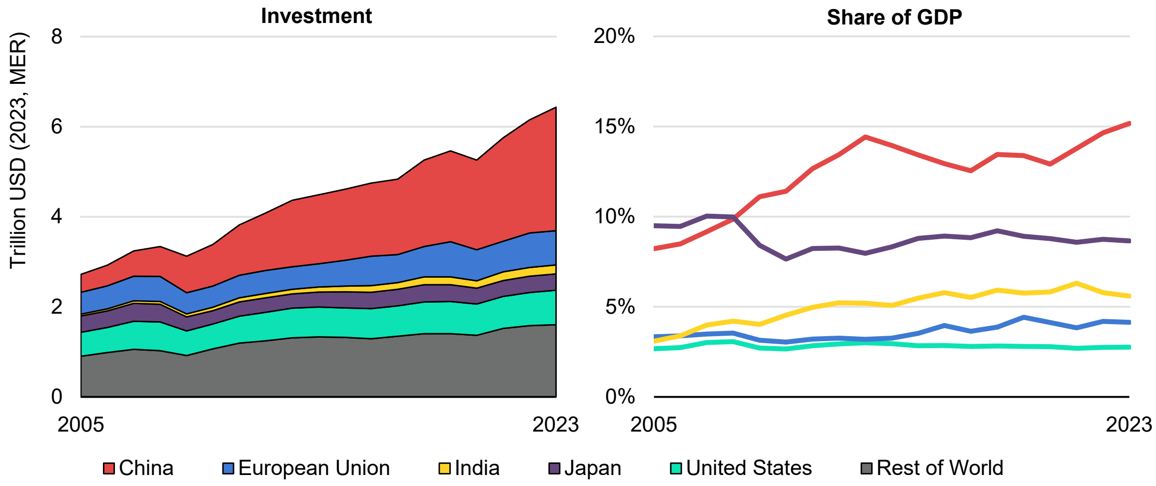
Investment in manufacturing

Investment in the overall manufacturing sector has more than doubled in real terms over the past two decades, reaching over USD 6 trillion in 2023. Growth has been most spectacular in China, which has seen a sevenfold increase in manufacturing investment since 2005, with capital spending rising on average by 11% per year, accounting for nearly two-thirds of global growth in manufacturing investment. The share of the leading Western economies in global manufacturing investment has dwindled over the same period, despite rising investment in absolute terms in most cases (Japan is the only major advanced economy where manufacturing investment has contracted in absolute terms). In the United States and the European Union, it grew by more than 40% (around 2% per year on average). India's manufacturing investment grew fivefold (averaging 10% per year), but from a much lower base, such that its share of global investment rose from around 1.5% to 3%.

The share of investment in manufacturing in the overall economy has evolved differently across countries. In the United States and the European Union, manufacturing investment has been fairly constant at around 3-4% of GDP over the past two decades, whereas in Japan it remains around 9%, even after a sharp contraction during the global financial crisis of 2008. By contrast, China's manufacturing investment as a share of GDP rocketed from around 8% in 2005 to nearly 15% in 2023, despite a dip in 2017 (alongside investment more broadly) that resulted from government policies to reorientate the economy towards consumer spending. Manufacturing investment resumed its upward path in 2018, falling back temporarily in 2020 due to the effects of the Covid-19 pandemic.

The productivity of manufacturing investment also varies considerably across the world. In 2023, the ratio of manufacturing value added to investment ranged from 2.3 in China, 3.0 in India, and 4.0 in the European Union and the United States, averaging 3.0 worldwide. These differences are explained largely by the structure of the manufacturing sectors in each economy – investment in higher value-added sectors (those that generate higher levels of value added per unit of capital invested) tends to be more concentrated in more developed economies.

Figure 1.2 Manufacturing sector investment by country/region, 2005-2023



IEA. CC BY 4.0.

Sources: IEA analysis based on Oxford Economics Limited (2024a).

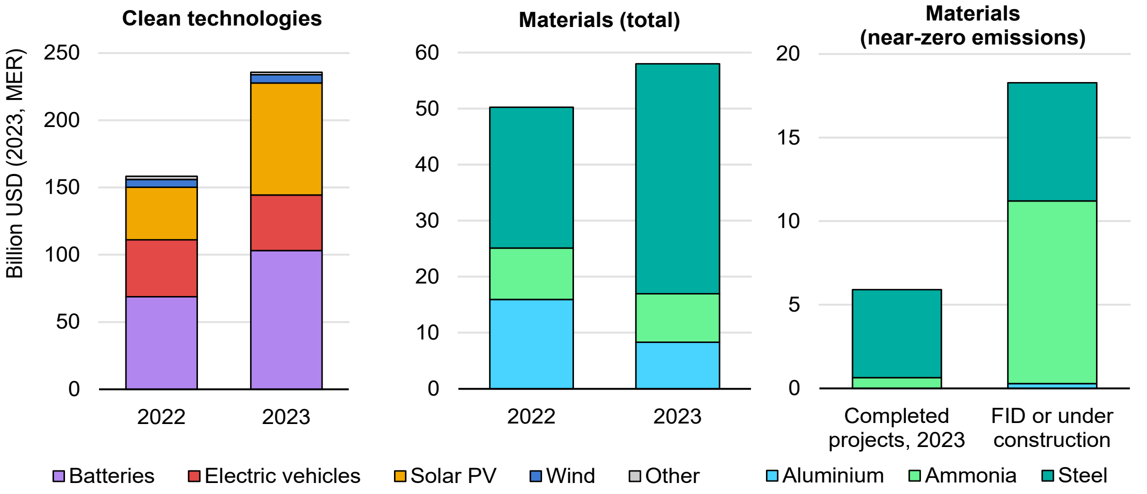
Manufacturing investment has risen most rapidly in China over the past two decades, while the share of investment in GDP has stagnated in major advanced economies.

Investment in clean energy technology supply chains

Global investment in manufacturing in the five key clean technology supply chains this report focuses on – solar PV, wind, EVs (including batteries), electrolysers and heat pumps – jumped 50% to USD 235 billion in 2023, up from USD 160 billion in 2022 (Figure 1.3). Investments were led by solar PV and batteries, which together accounted for 80% of the total in 2023. China accounted for nearly three-quarters of total investment in 2023, with the United States and the European Union together accounting for around one-fifth. India, Japan, Korea and Southeast Asia accounted for most of the rest, with virtually no investment taking place in either Africa or Central and South America.

Overall investments in the steel, aluminium and ammonia industries increased more slowly than in clean energy technologies in 2023, rising from around USD 50 billion to just under USD 60 billion globally. Investment in aluminium capacity halved, while that in ammonia facilities decreased slightly, whereas investment in steel jumped by nearly 65%. Annual investment figures for these industries depend on the spending associated with the scheduling of a handful of projects and so tends to be cyclical. The majority of investment in these three industries took place in emerging markets and developing economies (EMDEs).

Figure 1.3 Global investment in clean energy technology and materials manufacturing, 2022-2023



Notes: FID = final investment decision. Materials includes investment associated with global capacity additions for crude steel and iron for steel, and alumina and primary production for aluminium. Only investments in new capacity are included. Completed projects include all projects in operation at end-2023. FID or under construction is as of end-June 2024.

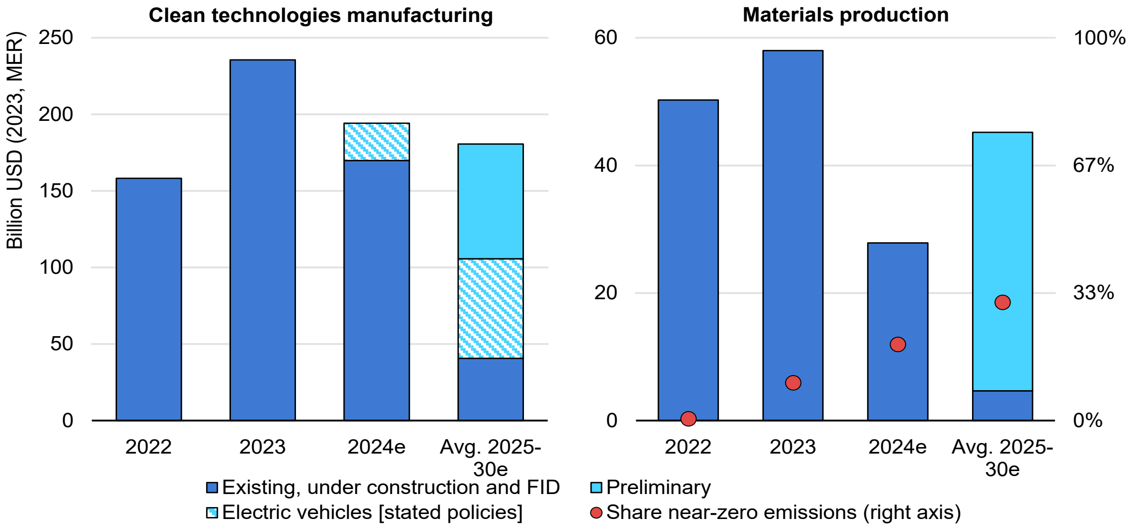
Sources: IEA analysis based on S&P Global (2024); WindEurope (2023); BNEF (2024a); GWEC (2023); (Wood Mackenzie (2024); InfoLink (2024); SPV Market Research (2024); BMI (2024); EV Volumes (2024); BNEF (2024b); BNEF (2024c); IEA (2024a); Atlas EV hub (2024); IFA (2024); OECD (2024b); CRU (2024); Oxford Economics Limited (2024b); CEPII (2024) as well as announcements by manufacturers and personal communications, gathered by the IEA.

Investments in clean technology manufacturing grew by 50% year-on-year in 2023; much faster than investments in materials manufacturing.

Cumulative investment in near-zero emissions technologies for materials production reached just under USD 6 billion in 2023, with iron and steel accounting for around 90% and ammonia for the rest. A further USD 15 billion of investment is expected to take place in projects that have either reached final investment decision or are already under construction. The majority of this is for ammonia facilities using low-emissions hydrogen for new energy applications like shipping and power generation. Only around USD 300 million of capital investment has been committed to near-zero emission aluminium production, and this is limited to demonstration projects with capacity typically around 1% of that of commercial-scale facilities. Commercial investment targeting emissions reductions in the aluminium industry is mostly limited to the utilisation of greater shares of low-emissions electricity (which reduces indirect emissions), energy efficiency and fuel switching in alumina production.

Projecting forward investments for the project pipeline for clean technologies is highly uncertain, as projects may well be cancelled, postponed or brought forward according to changes in policy incentives and market conditions. Assuming the whole project pipeline is completed and there is no change in the inflation-adjusted cost of building manufacturing facilities, total investment in clean technology manufacturing projects is expected to stand at roughly USD 200 billion (in 2023 dollars) in 2024 (Figure 1.4). Current projects alone point to nearly USD 180 billion per year of investment over the period 2025-30, around 35% of which is committed. This includes an estimated USD 65 billion per year for EV manufacturing facilities.[2] More projects will undoubtedly be announced for the second half of the 2020s, but the already high levels of capacity for solar PV and batteries (the main contributors to investment spending on manufacturing plants today) relative to global demand suggest that some decline in the rate of investment is likely to occur.

Figure 1.4 Global investment in clean energy manufacturing associated with announced projects, 2022-2030



IEA. CC BY 4.0.

Notes: FID = final investment decision; e = estimated. Clean technologies include solar PV, wind, electric vehicles (EVs), batteries, electrolysers and heat pumps. Materials include investment spending associated with global capacity additions for crude steel, iron, aluminium, alumina and ammonia production. Avg. 2025-30e = average annual investments associated with announced projects over the period 2025-30, excluding electric vehicle (EV) factories, for which there are no project announcements. Investment in EV manufacturing in this analysis corresponds to projected capacity additions under stated policies (see Chapter 2 for full projections), as no project pipeline information is available for these facilities. Investment is allocated to the year in which it takes place, rather than when new capacity is due to come online up to 2024. From 2025 onwards, investment spending is calculated on an overnight basis.

Sources: IEA analysis based on S&P Global (2024); WindEurope (2023); BNEF (2024e); BNEF (2024a); GWEC (2023); Wood Mackenzie (2024); InfoLink (2024); BMI (2024); EV Volumes (2024); BNEF (2024b); IFA (2024); OECD (2024b); CRU (2024); Oxford Economics Limited (2024b); CEPII (2024); as well as announcements by manufacturers and personal communications, gathered by the IEA.

Clean technology manufacturing investment associated with announced projects is set to stand at roughly USD 200 billion in 2024 and USD 180 billion per year to 2030.

Investment in material production facilities for steel, aluminium and ammonia is projected to slump to under USD 30 billion in 2024, but then rebound to an average level of USD 45 billion per year over the rest of the decade, based on the pipeline of announced projects. The near-term slump is in large part due to a levelling-off of conventional capacity additions in China, which has contributed much of the growth over the past two decades. The projected rebound is primarily driven by the huge pipeline of announced projects for ammonia for energy

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[2] No public information is available on the project pipeline for EV manufacturing facilities. An estimate based on the capacity required to meet demand under stated policies is used here; see Chapter 2 for an overview of the scenarios used in this report.

applications. This raises the share of near-zero emissions technology in total ammonia investment to around 85%, up from under 15% in 2023. Of the total investment associated with the project pipelines for materials, less than 25% can be considered committed.

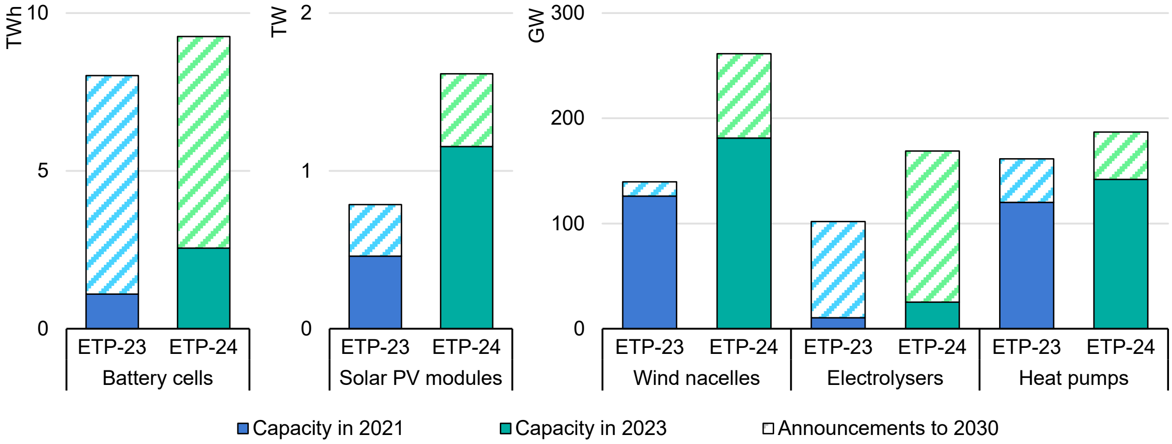
Manufacturing capacity

Clean technology manufacturing

Clean technology manufacturing has been growing fast since *ETP-2023*, as have announcements for further capacity additions (IEA, 2023b). Even solar PV manufacturing, a comparatively mature industry, has expanded rapidly over the past 4 years. For example, at the end of 2021 – the base year for *ETP-2023* – capacity for making solar PV modules stood at just over 450 GW; it is more than doubled to 1.2 TW by the end of 2023 – the base year for *ETP-2024* (Figure 1.5). At the end of November 2022, announcements of manufacturing capacity expansions for solar PV modules implied an increase in capacity to just 790 GW by 2030. In other words, global manufacturing capacity exceeded 2030 expectations by 50% in the space of only about 12 months.

In 2020, around 75 GW of PV module manufacturing capacity was added (Figure 1.6). In 2023, this number jumped to 500 GW, well above the record levels of solar PV installations for electricity generation that year, which stood around 425 GW. Manufacturing capacity additions of 430 GW in China alone in 2023 were larger than the levels of global installations for electricity generation, and larger than the global manufacturing capacity additions between 2020 and 2022.

Figure 1.5 Manufacturing capacity and additions associated with announced projects for selected clean technologies



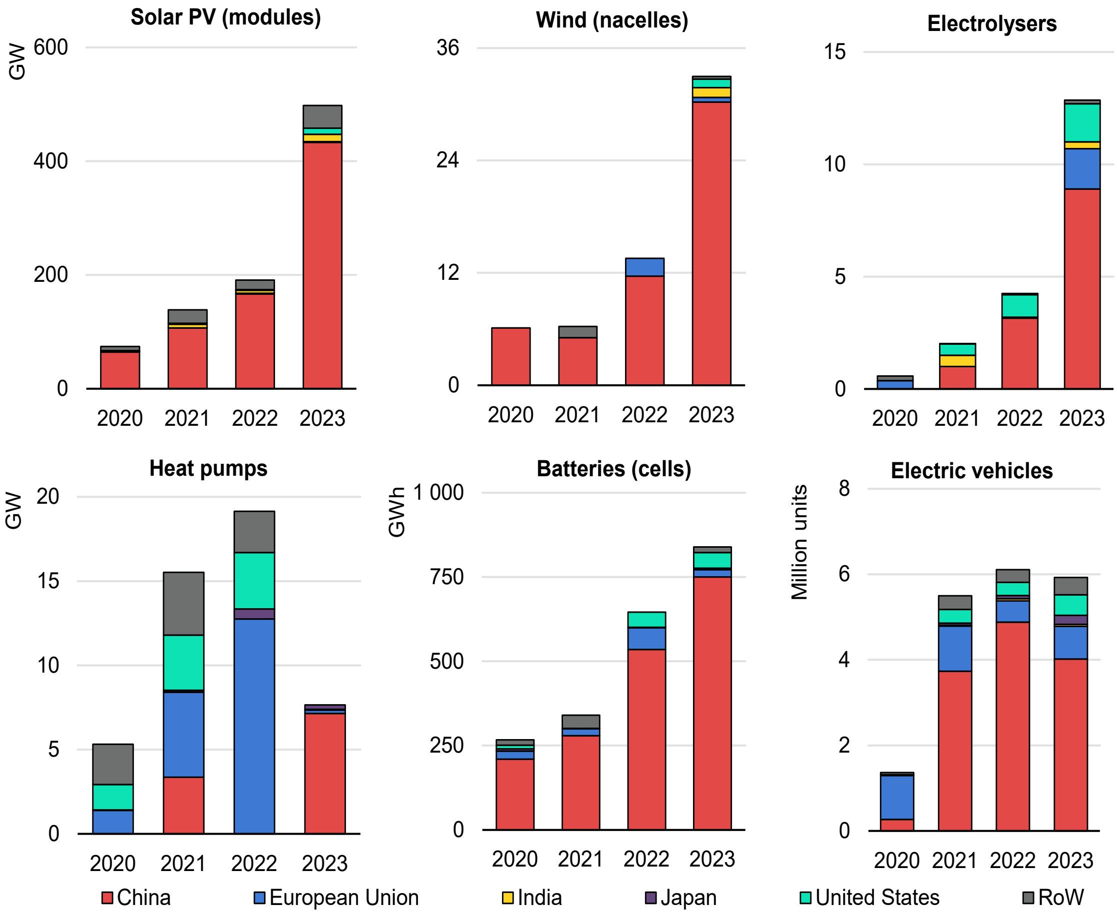
IEA. CC BY 4.0.

Notes: *ETP-23* assessed the capacity additions related to announced projects as of the end of November 2022. The cutoff point for *ETP-24* is the end of June 2024. For batteries, values for 2021 and announcements for *ETP-24* may differ slightly from *ETP-23* due to the inclusion of Tier 3 (See the Annex) battery makers for comparability with *ETP-24*.

Source: IEA analysis based on IEA (2023b); and IEA (2024a).

Since the last edition of *ETP*, manufacturing capacity and announced capacity additions for most technologies have expanded substantially.

Figure 1.6 Net manufacturing capacity additions for selected clean energy technologies by country/region, 2020-2023



IEA. CC BY 4.0.

Note: RoW = Rest of World.

Sources: IEA analysis based on S&P Global (2024); WindEurope (2023); BNEF (2024a); GWEC (2023); Wood Mackenzie (2024); InfoLink (2024); SPV Market Research (2024); BMI (2024); EV Volumes (2024), BNEF (2024b); BNEF (2024c); Oxford Economics Limited (2024b); CEPII (2024); as well as announcements by manufacturers and personal communications, gathered by the IEA.

Clean technology manufacturing capacity surged in 2023, with only heat pumps and electric vehicles seeing smaller capacity additions than in 2022.

In the case of solar PV, manufacturing capacity additions for assembling modules have generally exceeded those of the key components – polysilicon, wafers and cells – with the notable exception of China over the last 2 years (Figure 1.7). However, the utilisation rates of component manufacturing facilities generally remain low, averting bottlenecks. Average utilisation rates across PV module manufacturing facilities worldwide remained steady in 2023, at around 55%. In parallel, facilities for newer technologies like tunnel oxide passivated contact (TOPCon), heterojunction (HJT) and back contact (BC) cells are gaining market share over the older ones like passivated emitter rear cells (PERC). This has driven down prices and led to some downscaling of expansion plans, especially in China (Box 1.2).

The capacity additions associated with new projects have increased less rapidly for other clean technologies. In the case of EVs, manufacturing capacity additions reached more than 6 million units in 2022, but fell slightly to 5.7 million in 2023.[3] However, year-on-year growth in EV sales slowed from 60% in 2022 to just 30% in 2023, which could have an impact on further manufacturing capacity additions, as automakers adjust near-term plans based on sales expectations. An estimated 70% of the manufacturing capacity additions in 2023 were in China, 13% in the European Union and 8% in the United States.

In the case of batteries, most of which are for electric cars, manufacturing capacity in 2021 stood at around 1.1 TWh, increasing to more than 2.5 TWh in 2023; announced capacity additions have similarly grown, from 8 TWh at end-November 2022 to more than 9 TWh as of end-June 2024. Total manufacturing capacity for anodes and cathodes in 2023 stood well above that of battery cells. Cell manufacturing capacity nonetheless remains well above global demand: in 2023, the utilisation rate of cell production facilities was less than 25% in China, which accounts for around 85% of global production capacity, and 35% worldwide.

For wind turbines, manufacturing capacity expanded rapidly over 2020-23, with capacity additions more than doubling in 2023 to around 30 GW. For wind nacelles, global manufacturing capacity stood at 125 GW at the end of 2021, increasing to 180 GW at the end of 2023. Wind power installations during this period also grew rapidly – 75 GW in 2022 and 115 GW in 2023 – despite rising costs (see below). Nearly all of the manufacturing capacity additions for wind in 2020-23 were in China, though the country accounted for only around 45% of global wind deployment for electricity generation.

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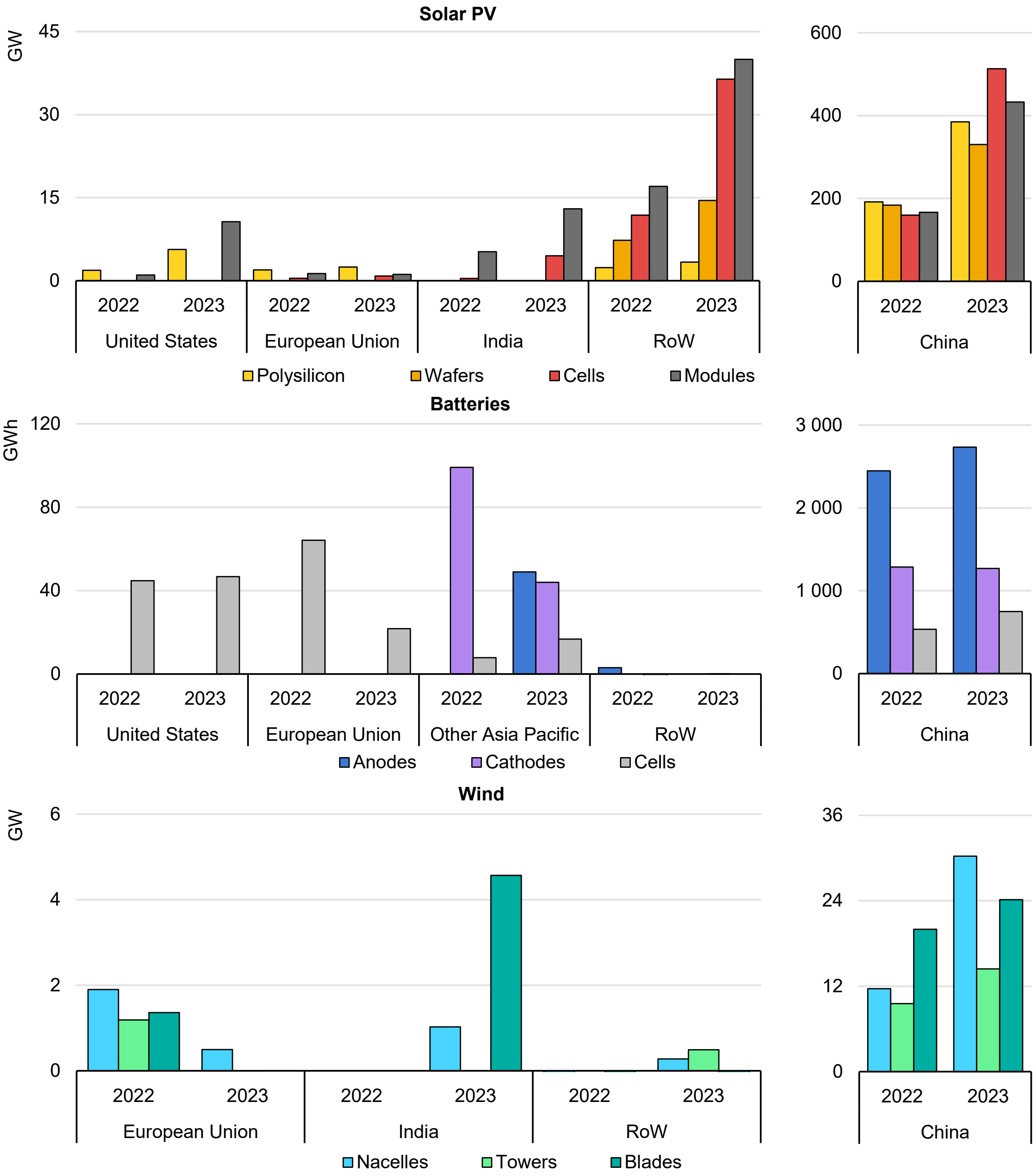
[3] Quantifying manufacturing capacity is hard for EVs, as most assembly plants also produce conventional vehicles. We estimate capacity additions here based on actual production and the utilisation rates of existing car plants, regardless of whether they manufacture electric models exclusively or not.

Figure 1.7 Net manufacturing capacity additions for solar PV, wind and battery components by country/region, 2022-2023



IEA. CC BY 4.0.

Notes: RoW = Rest of World. Other Asia Pacific excludes China.

Sources: Sources: IEA analysis based on S&P Global (2024); WindEurope (2023); BNEF (2024a); GWEC (2023); Wood Mackenzie (2024); InfoLink (2024); SPV Market Research (2024); BMI (2024); BNEF (2024b); and BNEF (2024c).

China's lead in battery and solar PV manufacturing has increased further as a result of enormous recent capacity additions for anodes, cathodes, polysilicon and wafers.

Looking forward, there are many clean technology manufacturing projects underway at present around the world to add new capacity at existing or new facilities, including some that are already under construction or for which a final investment decision has been made (i.e. committed), and others at preliminary stages of development.

The project pipeline for solar PV as of end-June 2024 amounts to around 460 GW for modules, 280 GW for cells, 490 GW for polysilicon and about 150 GW for wafers. Wafer manufacturing capacity is expected to reach 1 100 GW by end-2024, but then gradually decrease as capacity to produce older technologies is decommissioned and expansion plans are curtailed. While total manufacturing capacity for polysilicon is set to continue increasing, the pace of expansion is likely to slow down (see Box 1.2).

Were all the planned solar PV capacity additions to take place, full chain capacity would jump from 850 GW at end-2023 (with polysilicon being the limiting component), to around 1 TW by end-2030 (with wafers being the limiting component). Module capacity would reach more than 1 600 GW, compared with just around 1 150 GW at end-2023 (Figure 1.8). Nearly 85% of the capacity in the pipeline for modules and components appears today to be committed, but that could change. The majority of these planned capacity additions are in China, where the existing manufacturing facilities, together with those under construction or committed, would be capable of producing more than 7 TW of solar PV modules between 2024 and 2030, which is almost five times more than has been installed globally by end-2023.

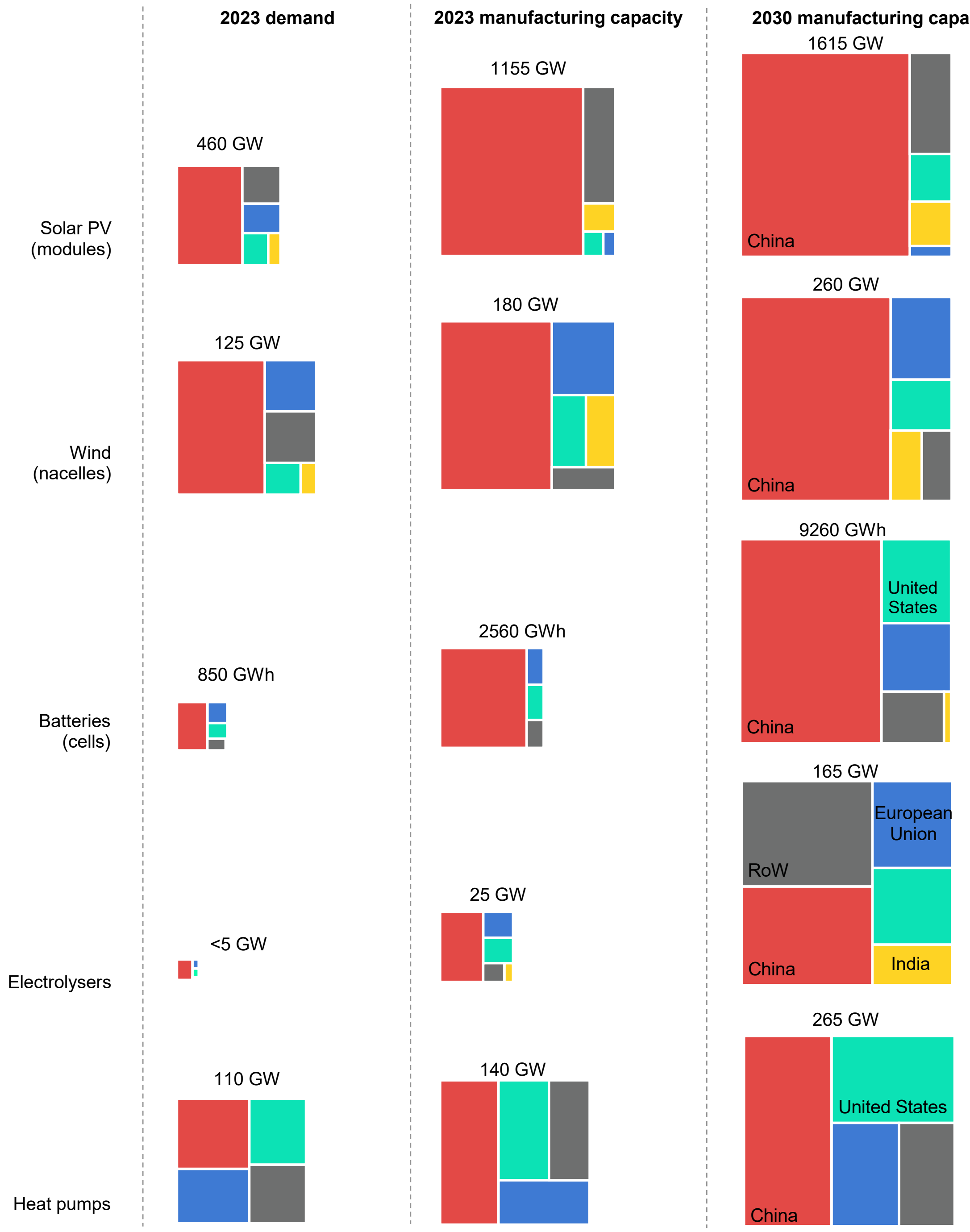
For battery cell manufacturing, the current project pipeline to 2030 of 6 700 GWh amounts to about 260% of total installed capacity at end-2023, and more than half of it is committed. Some projects, however, have recently been postponed or cancelled due to higher costs or lower demand than previously expected. China accounts for 55% of the announced committed capacity, and the United States and the European Union for most of the rest. By contrast, virtually all of the announced committed capacity additions for anodes is in China.

Compared to solar PV and batteries, announced manufacturing capacity for the other clean energy technologies considered in this report is much smaller relative to existing installed capacity. The capacity additions to 2030 associated with current announced wind nacelle manufacturing projects amount to 80 GW by 2030, but that is still about six times more than was the case at end-November 2022, and around 35-45 GW of capacity is planned to 2030 for blades and towers. Of these announcements, about 80-90% is considered committed. The majority of planned capacity is in China and most of the rest in the European Union and the United States.

In the case of electrolysers, even if manufacturing capacity development is still in its early stages, it far exceeds demand. In the past, demand primarily came from brine electrolysers for the chlor-alkali industry, but demand for water electrolysers is now growing. Global manufacturing capacity amounted to 25 GW at end-2023. Capacity in the project pipeline is much bigger, at 140 GW by 2030, almost 90% of it being for alkaline, proton exchange membrane and solid oxide water electrolyser units. However, less than 20% of these capacity announcements are committed. China accounts for the largest share of the project announcements, followed by the European Union, the United States, and India.

For heat pumps, announced manufacturing projects would boost global capacity by about one-third, from 140 GW at end-2023 to 185 GW in 2030, though how much of this new capacity can be considered committed is unknown. There are doubts about many of these projects given the recent decline in sales, policy uncertainties and cost inflation seen across major heat pump markets. The project pipeline is concentrated in Europe, where manufacturers announced new plans after the surge in sales following the energy crisis triggered by the Russian Federation (hereafter “Russia”)’s full-scale invasion of Ukraine, though this reflects the fact that new manufacturing projects are commonly not announced publicly by heat pump manufacturers in other regions.

Figure 1.8 Global demand and manufacturing capacity by country/region for selected clean energy technologies based on announced projects, 2023-2030



Notes: RoW = Rest of World. Capacity at year-end. 2030 manufacturing capacity includes existing and planned capacity based on project announcements. The size of each square is proportional to demand/capacity, with each row scaled relative to 2030 manufacturing capacity.

Sources: IEA analysis based on S&P Global (2024); WindEurope (2023); BNEF (2024a); GWEC (2023); Wood Mackenzie (2024); InfoLink (2024); SPV Market Research (2024); BMI (2024); EV Volumes (2024); BNEF (2024b); BNEF (2024c); Oxford Economics Limited (2024b); CEPII (2024); as well as announcements by manufacturers and personal communications, gathered by the IEA.

Most planned capacity additions in clean energy technology manufacturing are in the countries that already dominate the sector today.

Box 1.2 Recent dynamics in solar PV and battery manufacturing

The supply chains of solar PV and batteries have grown remarkably in recent years, yet the combination of a tightening economic outlook and shrinking profit margins, along with uncertainties about the real-world pace of deployment, have recently led several companies to recalibrate their ambitious expansion plans. Committed battery manufacturing capacity to 2030 decreased by almost 10% for battery cells between the end of 2023 (IEA, 2024a) and Q2 2024, and announced polysilicon and wafer capacity projections declined by one-fifth at the end of Q2 2024 compared to Q1. However, consolidation is not unusual in new sectors, and the difficulties faced by some companies can create opportunities for others.

Several factors have contributed to this evolution. First, substantial growth in capacity across the solar PV supply chain has outpaced growth in deployment, helping to drive down module prices to nearly USD 0.10/W by the end of 2023, with suppliers often selling at a loss. A considerable inventory has been built up, suggesting that current oversupply may persist beyond 2025 (BNEF, 2024d), until eventually being absorbed by growing demand. New technologies are also capturing a larger share of the market, with the result that older modules are being sold at a relative discount and losing profit. In China, regulatory changes that aim to curb overinvestment and reduce corporate debt have led manufacturers to scale back their plans, primarily in China but also in Southeast Asia (pv-magazine, 2024a). While losses are being experienced across the supply chain, consolidation has been most evident in the upstream sectors. Companies that are vertically integrated are better positioned to weather the storm, as they have greater possibilities to balance the profit and loss-having parts of their business.

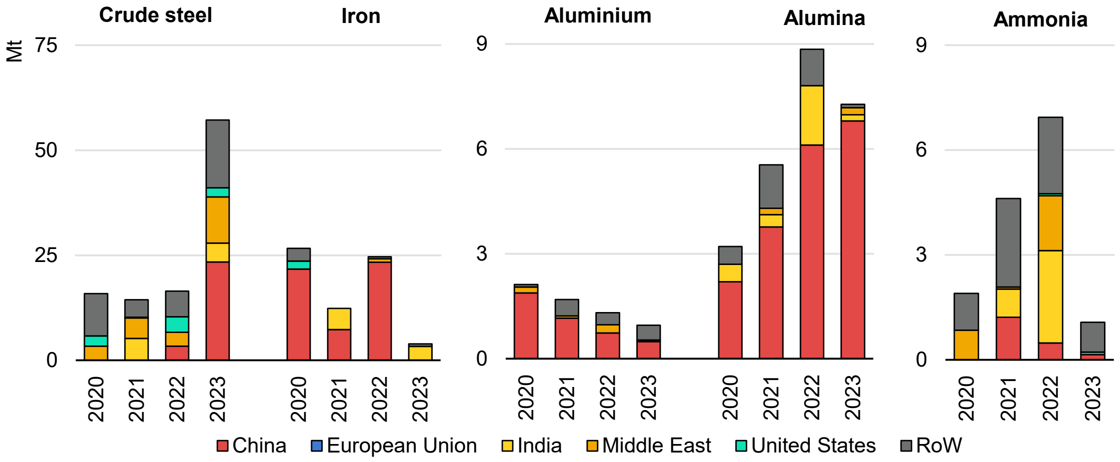
The effects of market consolidation in battery manufacturing are also entering into view. In the first half of 2024, 350 GWh of manufacturing capacity in China previously announced for 2025 was cancelled. This is more than the total manufacturing capacity in the European Union and the United States in 2023. At the same time, almost 70 GWh of new announcements have been made in China, and the announced capacity of some plants announced for 2025 has been expanded by over 250 GWh. Germany has the largest battery manufacturing project pipeline in Europe, but in the first half of 2024, 20% of its announced capacity was cancelled, and no significant additions were made during 2023 – a year in which global capacity grew 50%.

Battery production is a large volume, low profit-margin business (Intercalation Station, 2023), in which manufacturing optimisation, cost reduction and technological innovation are essential to compete in the global market. This offers a notable advantage to incumbent producers that can benefit from economies of scale and more efficient manufacturing, while at the same time investing heavily in R&D.

Materials production

The rate of expansion of global capacity for producing key materials is generally much slower than for clean technology manufacturing, as they also serve the needs of other manufacturing sectors and construction, where materials demand is growing less rapidly. In the case of crude steel, nearly 60 Mt per year of new capacity was added on a net basis worldwide in 2023, boosting total capacity by around 2.5% (Figure 1.9). Around 40% of the steelmaking capacity added in 2023, and 50% in 2022, was associated with iron production, whereas the remainder consisted of standalone steelmaking capacity, much of which is used to recycle scrap steel in electric furnaces. This is reflected in the greater absolute quantities of steelmaking capacity added over the past 4 years (105 Mt cumulatively) relative to ironmaking capacity (70 Mt cumulatively), despite the fact that it takes around 1.1 tonnes of iron to make a tonne of steel, when not using any scrap.

Figure 1.9 Global net manufacturing capacity additions for selected materials, 2020-2023



Notes: RoW = Rest of World. Capacity additions exclude regions where capacity has fallen. Aluminium refers to primary production capacity only.
Sources: IEA analysis based on IFA (2024); IEA (2024c); OECD (2024b); GEM (2024); and CRU (2024).

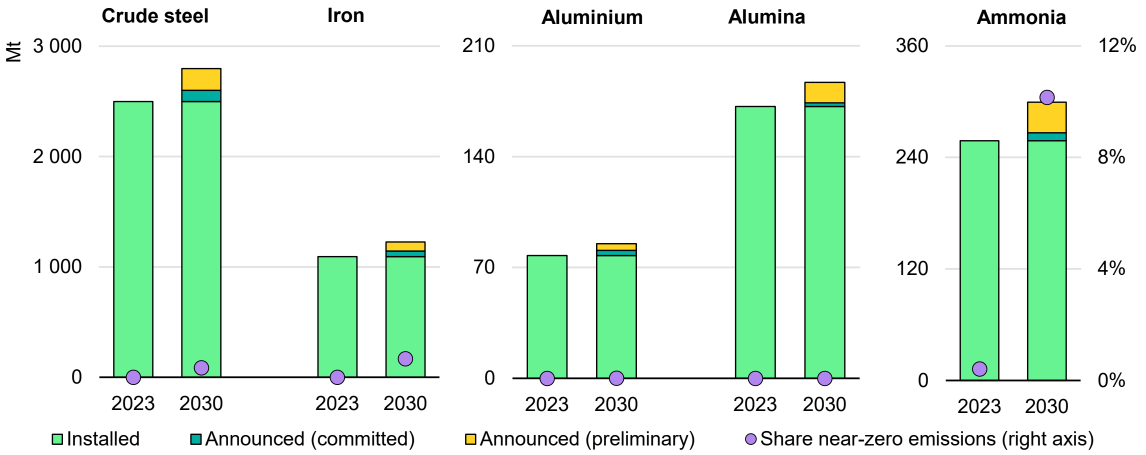
China, India and the Middle East have together accounted for more than half of global net capacity additions for key materials and their intermediates since 2020.

Installed primary aluminium production capacity grew by just 1% in 2023, reflecting a slowdown in China as production levels approached annual limits imposed by the government (S&P Global, 2022). Capacity for alumina production grew by around 5% in both 2022 and 2023.

Ammonia capacity expanded by 7 Mt, or 3%, in 2022 – equivalent to around eight modern plants being completed – but was virtually unchanged in 2023. While the pipeline of electrolysis projects for ammonia for energy applications is growing rapidly, the average size of these projects today is very small compared with plants serving existing agricultural and industrial demand (IEA, 2024c).

The project pipelines for the production of steel, aluminium and ammonia are also relatively limited compared with planned capacity additions for clean technology manufacturing, with capacity set to grow only modestly (Figure 1.10).[4] Only a small share of the announced materials manufacturing projects to 2030 involves near-zero emissions technologies for iron, steel and aluminium, though there is potential for their deployment to grow quickly once these technologies have been demonstrated at commercial scale and there is a clear demand signal. If all the projects using near-zero emissions technologies came to fruition, their share of global capacity would reach less than 1% for iron and steel, less than 0.1% for aluminium, and just 10% for ammonia – far below the levels required to get on track with global climate goals (see Chapter 2). Achieving net zero emissions by mid-century calls for the rapid and widespread deployment of these technologies, both for new capacity and retrofitting of existing plants.

Figure 1.10 Global installed manufacturing capacity and announced capacity additions for selected materials, 2023-2030



IEA. CC BY 4.0.

Notes: At year-end. Committed = existing projects, those under construction and other projects having achieved a final investment decision. Aluminium refers to primary production only. Near-zero emissions capable projects are not included in the share of near-zero emissions.

Sources: IEA analysis based on IFA (2024); OECD (2024b); GEM (2024); CRU (2024); and IEA (2024c).

The share of near-zero emissions technologies in planned capacity additions is highest in the ammonia industry.

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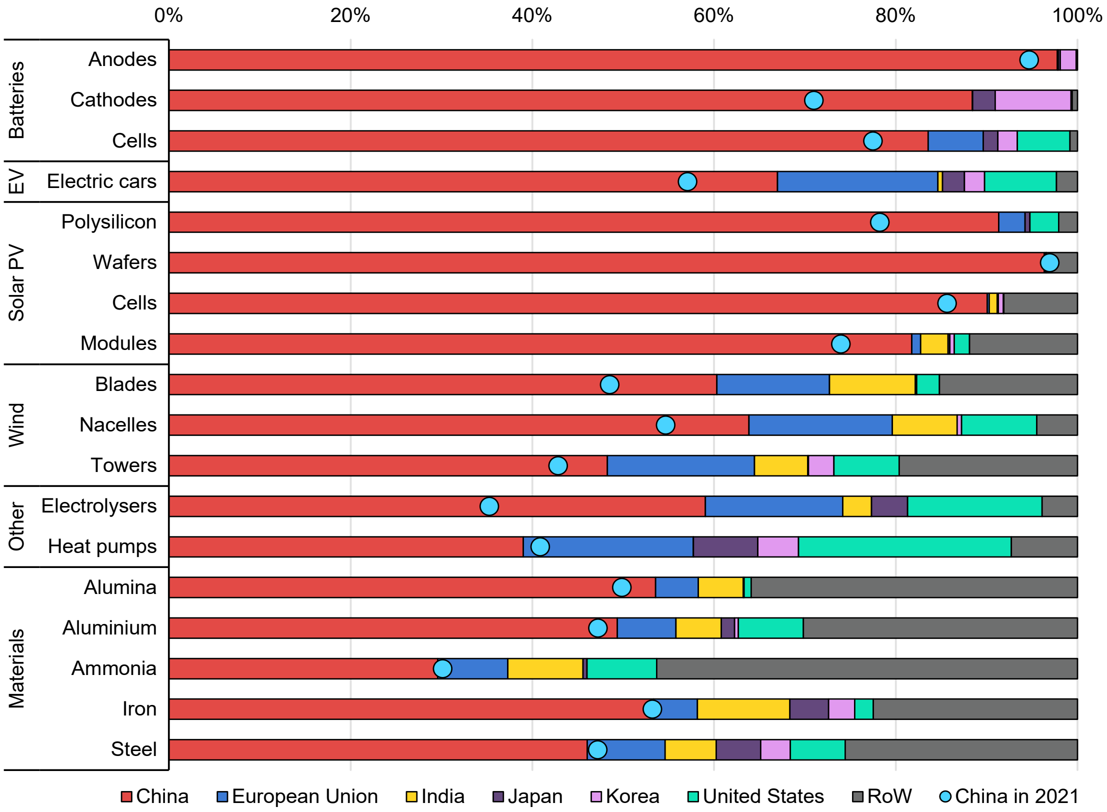
[4] This excludes the capacity at existing plants that needs to be refurbished or replaced at the end of its economic life, which is assumed to be around 25 years (i.e. roughly 4% of that capacity needs to be replaced or refurbished in any given year to maintain the same overall level of capacity).

Geographical concentration

Each of the different steps of most clean energy technology supply chains are highly geographically concentrated, from the extraction and refining of raw materials to the manufacturing of those technologies, their components and the materials required as inputs (IEA, 2023b). This concentration can create supply chain risks or vulnerabilities. The global landscape has not changed much between 2021 and 2023, with manufacturing remaining far more concentrated than fossil fuel supply, and China continuing to play a leading role in the world's clean energy technology supply chains (Figure 1.11).

Geographical concentration is expected to persist despite the growing number of new project announcements (IEA, 2024a). If all announced capacity additions come to fruition, the three major producing countries and regions are expected to continue to account for around 80% or more of global capacity in all cases, with only minor shifts in relative shares. In the case of battery manufacturing, China's share could fall as that of both the European Union and the United States increases. In contrast, China's share of wind manufacturing is set to grow. For heat pumps, Europe's share is set to increase its share the most.

Figure 1.11 Installed manufacturing capacity by country/region, 2023



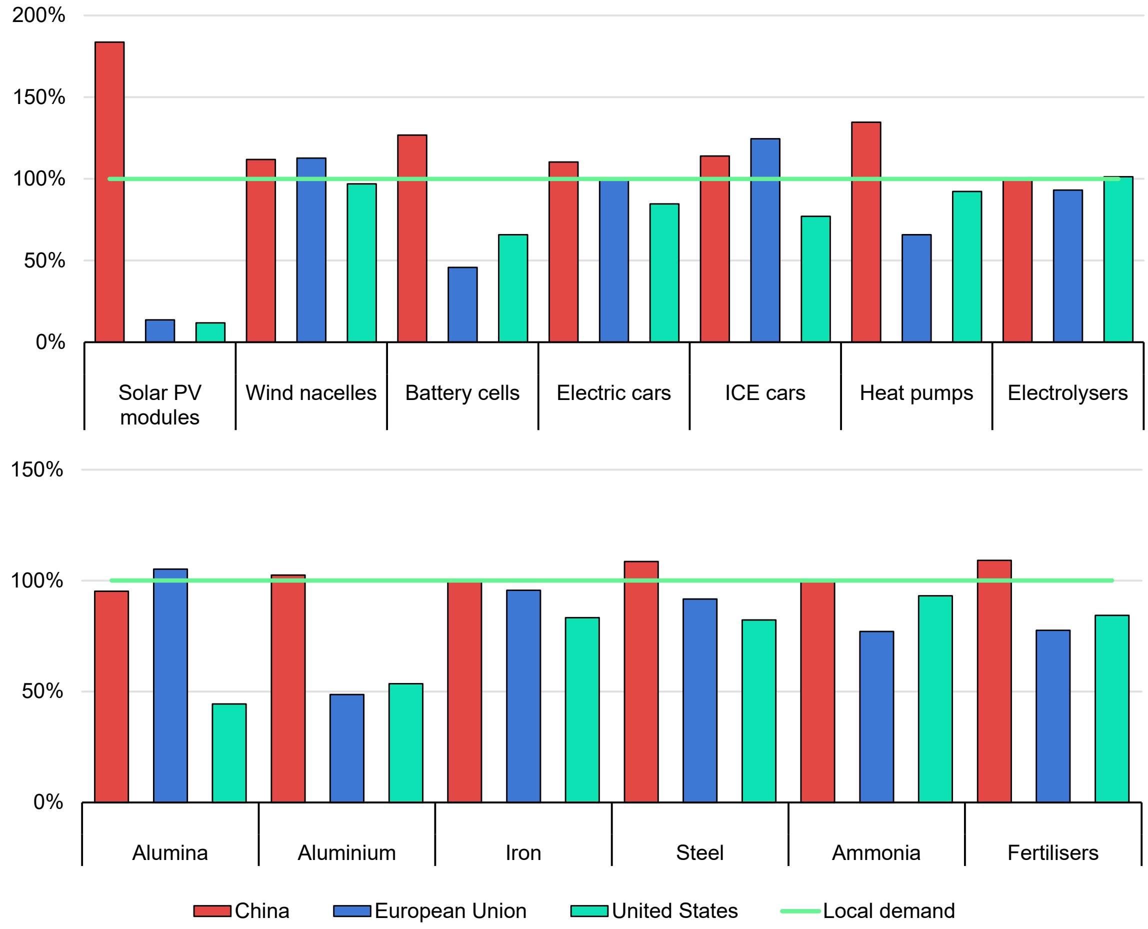
Note: RoW = Rest of World. "Electric cars" values are calculated based on 2023 production numbers, adjusted according to the utilisation rates of car assembly plants in the region.
Source: IEA analysis based on IEA (2024a); and IEA (2023b).

Manufacturing capacity for clean technologies and materials today is highly concentrated geographically, with China the largest single producer in all cases.

At the end of 2023, China held around 85-98% of battery manufacturing capacity, depending on the component, 80-95% of that for solar PV, 50-65% for wind, just under 60% for electrolysers and close to 40% for heat pumps. The European Union and the United States generally account for the rest, with Japan and India accounting for a significant share of capacity in a few cases. India and other countries in the Asia Pacific region are emerging as increasingly important manufacturers, although capacity is not always developed by domestic companies, with Chinese firms increasing their presence in the region. Since 2021, geographic concentration of manufacturing capacity in China has even increased in several cases, such as for battery cathodes (from 70% in 2021 to 90% in 2023), battery cells (80% to 85%), polysilicon (80% to 90%), solar PV modules (75% to over 80%), wind blades (50% to 60%), wind nacelles (55% to 65%), and electrolysers (35% to almost 60%). Similarly, not much has changed since 2021 with regard to the manufacturing of materials, with China remaining the leading producer. China accounted for 30% of global output of ammonia and fertilisers, and 50-60% of alumina, aluminium, iron, and steel in 2023.

China's production of clean energy technologies, as for most other manufactured goods, generally far exceeds domestic demand, with the surplus available for export markets (see below). Around 40% of the country's output of solar PV modules and about one-fifth of that of battery cells was available for exports in 2023; the share was about 12% for wind nacelles and 10% for EVs. By contrast, the European Union and the United States are reliant on imports to meet their full demand, especially in the case of solar PV and batteries, with some exceptions, such as wind nacelles and electrolysers (Figure 1.12). The European Union was a net exporter of internal combustion engine (ICE) vehicles in 2023, and produced just as many electric cars as were sold in the region. For materials, production in China is generally in line with or slightly in excess of domestic demand. The picture for the European Union and the United States for materials is similar to that for clean energy technologies, with production generally falling short of demand, with the exception of alumina in the European Union, for which production is in excess of regional demand.

Figure 1.12 Production of selected clean energy technologies and materials relative to domestic demand by country/region, 2023



IEA. CC BY 4.0.

Notes: Battery cells are for both electric vehicles and stationary storage. Steel includes crude steel as well as semi-finished and finished products.

China is a net exporter of key clean energy technologies, while the European Union and the United States rely heavily on imports to meet domestic demand.

The resilience of clean energy technology supply chains can be jeopardised by strong reliance on a very limited number of component suppliers. For example, an explosion at a polysilicon facility in China in 2020 put 8% of global polysilicon production capacity out of operation (IEA, 2022b). This was the largest of four polysilicon plant closures in 2020, the others resulting from flooding or technical problems. While each incident occurred at a different time, together they led to an estimated 4% decline in annual production in an already-tight polysilicon market, contributing to the near tripling of prices between 2020 and 2021. Vertical integration of supply chains can, in principle, enhance the resilience of supply chains – China's wind turbine manufacturers were more resilient to commodity price fluctuations in 2022 in part due to vertical integration – though it may lead to greater dependence on a small number of suppliers (IEA, 2023c).

Box 1.3 What do we mean by EVs and electric cars?

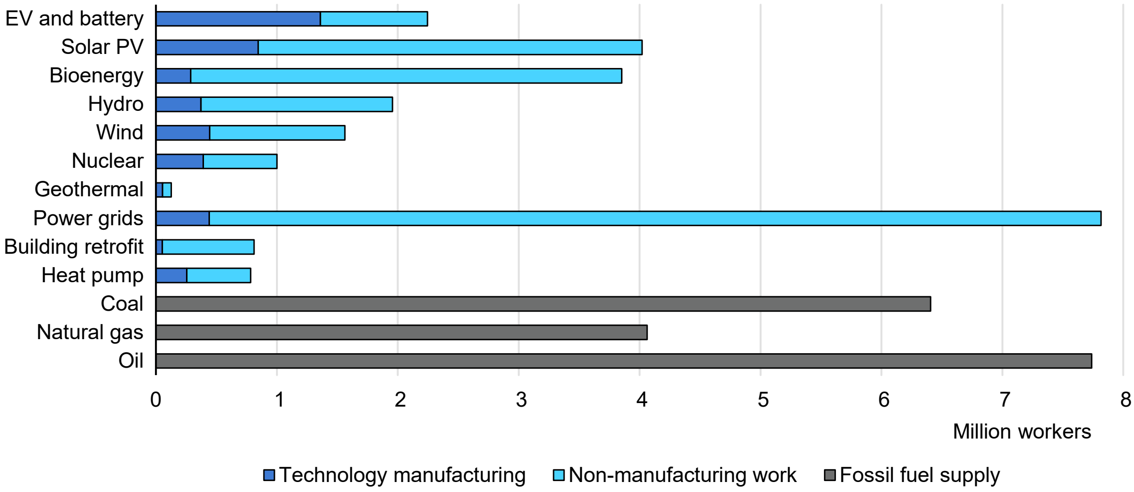
In this report, references to **electric cars** or **electric vehicles** (**EVs**) follow IEA's standard convention. EVs include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), but exclude fuel cell electric vehicles, and specifically refer to electric passenger light-duty vehicles, which include electric cars and pick-up trucks. However, due to the manufacturing differences between BEVs and PHEVs these technologies are treated separately in modelling trade flows, with only BEVs being included in the Manufacturing and Trade (MaT) model, while PHEVs are modelled using 2023 trade patterns and BEV MaT results (see Annex).

When discussing **battery** demand, production, trade and manufacturing capacities, PHEV and BEV batteries are included. This ensures that our modelling of battery supply chains matches total car battery demand, even though PHEV trade is not modelled directly through MaT. Similarly, trade in other vehicle types, such as two- and three-wheelers, buses and commercial vehicles are not modelled explicitly in the MaT model, but the associated battery demand and corresponding production are estimated using 2023 trade patterns. Total vehicle battery demand, together with that for stationary storage, is used to model the production of and trade in batteries and cathode and anode active materials.

Employment

Manufacturing of clean energy technologies is an important source of employment (IEA, 2023d). Clean energy in total currently employs over 33 million people worldwide, with manufacturing accounting for about one-fifth. It has provided more jobs than fossil fuel-related industries since 2021. Non-manufacturing work includes raw materials extraction, construction, installation, utilities, professionals, wholesale and transport. Of the some 5.5 million people that work in the solar PV and wind sectors worldwide, 1.3 million are involved in manufacturing (Figure 1.13). EVs and their batteries account for more than 2 million jobs, of which 60% are in manufacturing, while heat pumps account for almost 800 000 jobs, with one-third in manufacturing. Employment in clean technology manufacturing is expected to increase rapidly as global clean energy transitions advance. By comparison, nearly 6.5 million people are employed in the coal industry, 4 million in natural gas supply and close to 8 million in oil (excluding power generation).

Figure 1.13 Energy employment in selected technology areas, 2022



Notes: EV = electric vehicle. “EV and battery” excludes stationary battery storage. “Bioenergy” excludes waste and traditional use of biomass. “Power grids” refers to transmission and distribution, and stationary battery storage. Non-manufacturing work includes raw materials extraction, construction/installation, utilities, professional services, wholesale and transport. Manufacturing jobs include the final product and direct components (e.g. solar PV includes wafers and cells, while batteries includes cathodes and anodes). Non-manufacturing jobs in the EV and battery category include jobs installing batteries in EVs, but not EV-related jobs such as mechanics or sales, which are not estimated by the IEA. Fossil fuel supply includes upstream (raw materials extraction), midstream (manufacturing of equipment and oil refining) and some downstream activities (wholesale, transport and professional services), but excludes fossil fuel combustion for power generation or distribution.

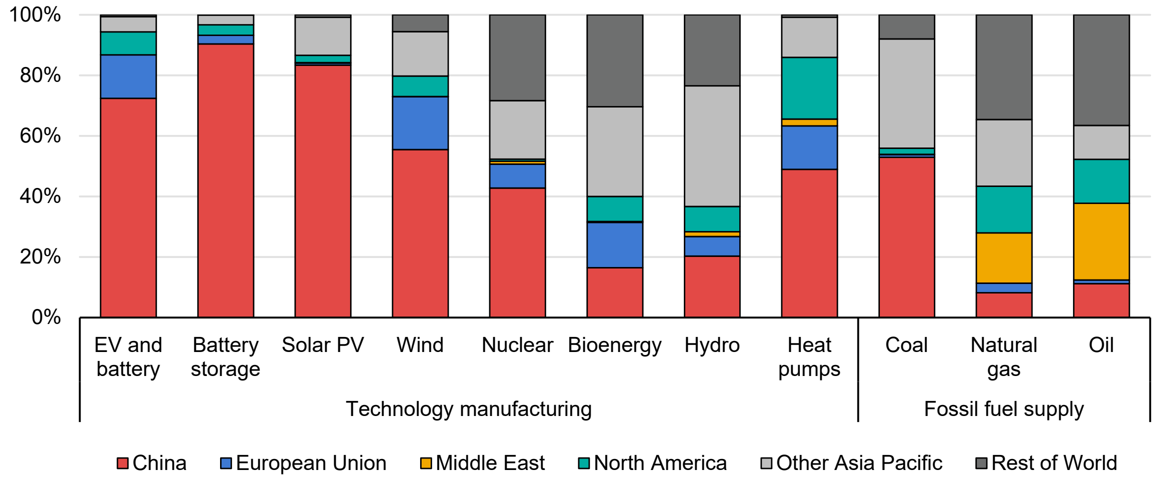
Source: Adapted from IEA (2023d).

Manufacturing of clean energy technologies is a major source of employment, with around 3 million jobs globally in EVs and batteries, solar PV, wind and heat pumps.

Clean energy manufacturing jobs are typically very concentrated geographically. In general, manufacturing sectors in EMDEs tend to be more labour-intensive per unit produced than in advanced economies, where mechanisation, automation and other productivity-enhancing measures have been adopted to a greater extent. Most of these jobs are in China: 75% in EVs and battery manufacturing, 85% for solar PV, 55% for wind and 50% for heat pumps (Figure 1.14). Even in the nuclear industry, over 40% of manufacturing jobs are now located in China. By contrast, jobs in the oil and gas industry are concentrated in the Middle East and the United States, with only 10% of jobs in China. Similarly, only about 25% of the manufacturing jobs in ICE vehicles are in China, compared to more than 15% in the European Union, 12% in India and 7% in both Japan and the United States.

The nature of energy jobs is also changing as the clean energy transition advances, with newly created jobs in the clean energy sector requiring different skills and qualifications. As jobs in fossil fuel supply and in manufacturing the equipment and vehicles that use them are displaced, retraining and reskilling will be important to ensure a fair transition. Many fossil fuel workers already possess similar skillsets to those needed in clean energy sectors. Oil and gas workers, for example, are already some of the most highly sought-after employees due to their extensive skills and mobility. Much of the oil and gas workforce possesses skills relevant to bioenergy processing, CCUS, hydrogen production, offshore wind installations and geothermal production. Similarly, many workers engaged in ICE manufacturing are expected to switch to making EVs, especially as a growing number of established Original Equipment Manufacturers offer their own electric models. However, fewer transfers are expected from ICE vehicle supply chains, and fuel storage technology in particular, to EV battery production, since this requires a distinct skillset and is generally carried out by different companies in different locations.

Figure 1.14 Energy employment in selected energy technologies by region, 2022



IEA. CC BY 4.0.

Note: EV = electric vehicles.
Source: Adapted from IEA (2023d).

Most manufacturing jobs for electric vehicles and batteries, renewables and heat pumps are located in China, in contrast to those in the traditional fossil fuel sectors.

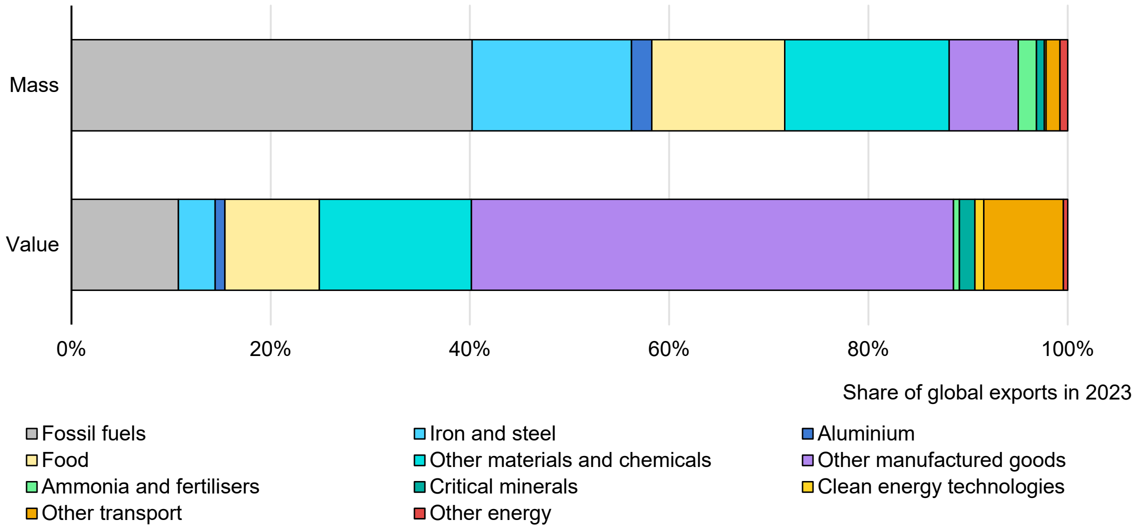
1.2 Trade

Trade volumes and values

Trade has always played a key role in the global economy and the energy sector, with energy sector trade traditionally being synonymous with trade in fossil fuels, though this landscape is now increasingly being shaped by trade in clean energy technologies. Fossil fuels account for nearly 40% of international trade by mass, but in 2023, fossil fuels accounted for only around 10% in value terms. Notably, manufactured goods have a much higher value-to-mass ratio than fossil fuels –

Clean energy technologies made up just 0.2% of total mass traded in 2023, but approximately 1% of total traded value. Other manufactured goods made up just 7% of traded mass, but nearly half of traded value (Figure 1.15).

Figure 1.15 Shares of physical goods in global trade, 2023



IEA. CC BY 4.0.

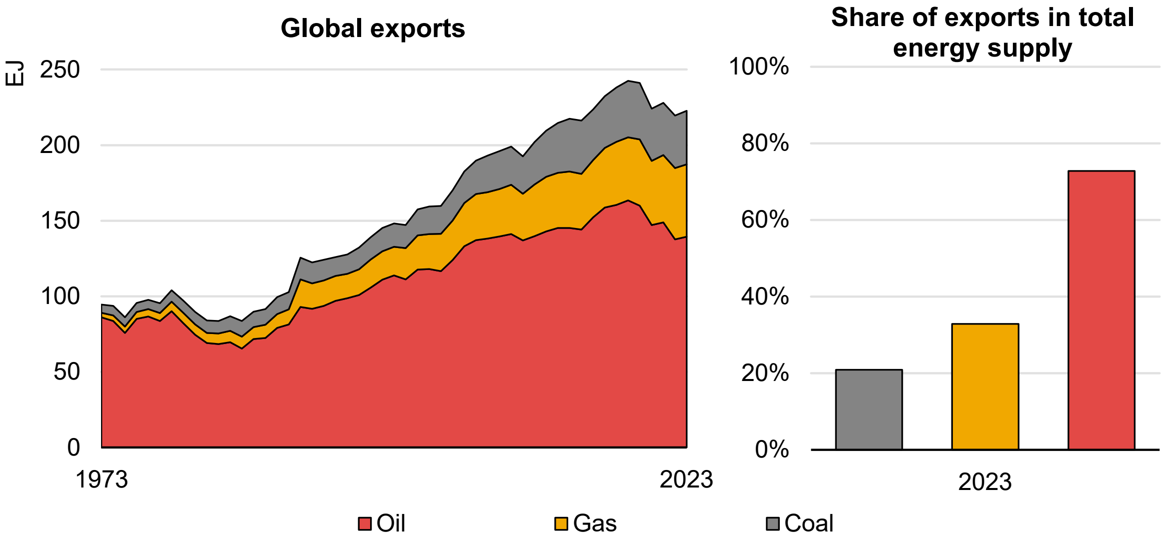
Notes: Clean energy technology includes batteries, electric vehicles, electrolysers, heat pumps, solar PV and wind. Aluminium includes mineral inputs, intermediates (such as alumina and scrap), ingots and semi- and finished products. Iron and steel include mineral inputs, intermediates (such as scrap, pig iron and direct reduced iron) and semi- and finished products. Other energy includes bioenergy, hydrogen, and nuclear fuel. Other manufactured goods include arms and ammunitions, clothing, electronics, machinery, and pharmaceuticals, among others. Other materials and chemicals include cement, chemicals, ethanol, metals, methanol, paper, plastics and rubber and wood. Other transport includes non-electric vehicles including hybrids, aircrafts, ships and other transport equipment.

Source: IEA analysis based on CEPII, (2024); Oxford Economics Limited (2024b); and IEA (2024e).

Fossil fuels account for 40% of international trade by mass, but only 10% in value.

Rising energy demand, in particular, has historically led to increasing trade of fossil fuels. Between 1973 and 2023, global exports of oil and oil products increased by 60%, reaching more than 24 billion barrels in 2023. For coal, exports increased more than sixfold, reaching 1.2 Gt of coal equivalent (Gtce), while natural gas exports expanded more than fifteen-fold to 1.3 trillion cubic metres (tcm). In aggregate, fossil fuel exports in mass terms increased by 160% over 1973-23, reaching 5.8 Gt. Today, exports make up around 20% of global coal supply, 30% of that of natural gas and 75% of that of oil products (Figure 1.16).

Figure 1.16 Global fossil fuel exports, 1973-2023 and share of exports in total energy supply, 2023



Source: IEA analysis based on IEA (2024d); IEA (2024d); IEA (2024e); and CEPII (2024).

Oil continues to dominate international trade in fossil fuels, though gas exports have risen fastest since the 1973 oil crisis.

Fossil fuel production today is concentrated in North America, the Middle East, China and Russia, and countries have diverse relationships to production, consumption and export. The United States, for example, is one of the largest producers of oil and gas while being also the largest consumer of both. It is a net importer of crude oil, a net exporter of oil products and hydrocarbon liquids, and is developing liquefied natural gas (LNG) infrastructure to boost natural gas exports. Overall, the United States ranks among the three largest gross exporters (but not *net* exporters) for gas, oil and oil products. On the other hand, China tops global coal production, while also being the largest coal consumer and coal importer. Conversely, the Middle East exports much greater quantities of oil than it consumes.

Clean energy transitions hold the potential to drastically reduce the reliance of many countries on foreign sources of fossil fuels through electrification, efficiency gains and the use of domestic renewable energy sources. This has major implications for energy security and the economy. For example, net imports of fossil fuels for EU member states amounted to around USD 450 billion in 2023, equal to nearly 2% of GDP. In past decades, many countries have sought to develop alternative technologies to reduce their reliance on foreign supplies of fossil fuels, such as biofuels in Brazil, wind power in Denmark and unconventional oil and gas in the United States. The development of LNG technologies was also partly motivated by the desire to mitigate geopolitical risks by enabling more flexibility for trade partners and diversification of suppliers, and to address impracticalities related to fixed-route pipelines. The development of flexible transport modes for the supply of alternative fuels such as hydrogen, ammonia and methanol could also avoid reliance on fixed-route pipelines in instances where these are impractical or prone to geopolitical risks or unreliable supply-demand relationships at either end. On the other hand, electrification increases exposure to local power prices, which can vary across regions to a greater extent than those of fossil fuels as a result of local electricity supply, infrastructure and market design.

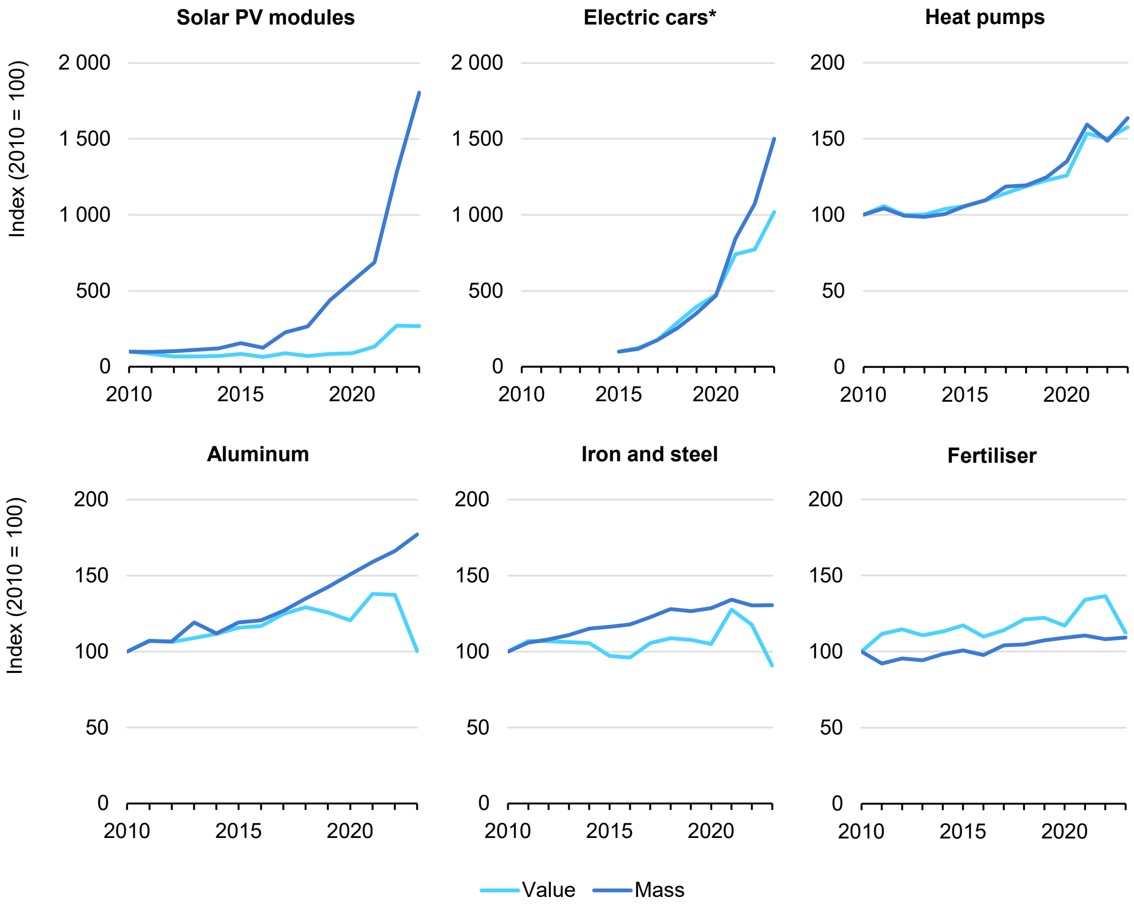
In 2023, international trade was worth a record USD 31 trillion in total, of which around USD 24 trillion was trade in goods, and the remainder was trade in services. In 2023, gross trade in iron and steel, alumina and aluminium, and their mineral inputs, as well as ammonia and fertilisers accounted for USD 1.3 trillion. For the six clean energy technology supply chains covered in this report, international trade was worth around USD 200 billion in 2023.

Trade in clean energy technologies has expanded quickly over the last 10 years, helping to drive the energy transition. Without trade, much of today's deployment of clean technologies would not be possible. Yet the rate of growth in trade varies considerably between the clean energy technologies and associated materials (Figure 1.17):

- **Solar PV**: Between 2010 and 2023, global exports of solar PV modules increased eighteen-fold in volume terms, exceeding 10 million tonnes (Mt) in 2023. At the same time, the rapid decline in module prices has led to the increase in monetary terms to be smaller, roughly tripling over the same period to around USD 54 billion.
- **Electric cars:** Global exports of electric cars jumped nearly twenty-fold over 2015-23, reaching nearly 3 million units and USD 85 billion in 2023.
- **Heat pumps**: Trade in heat pumps has grown less rapidly than trade in the other technologies, as manufacturing capacity has grown significantly in the main demand centres to comply with local standards (Box 2.2) and building designs (Box 2.4). Exports have grown by around 50% since 2010, reaching over USD 10 billion in 2023, with corresponding capacities of more than 25 GW.
- **Materials**: Global exports in volume terms nearly doubled for the aluminium value chain, rose by 30% for the steel value chain, and increased 10% for fertilisers over 2010-23. The traded value of these product groups, on the other hand, does not follow a steady trend, as material commodity prices have been fluctuating over the past decade, which is more common for products upstream in the supply chain than for those downstream, which typically have more stable price trends.

These examples further illustrate the significantly higher value of manufactured goods relative to materials. For the three clean technologies described above, the value-to-mass ratio averages around USD 5 000-10 000/t, compared with around USD 500-1 000/t for the three materials and their precursors.

Figure 1.17 Global exports of selected clean technologies and materials, 2010-2023



IEA. CC BY 4.0.

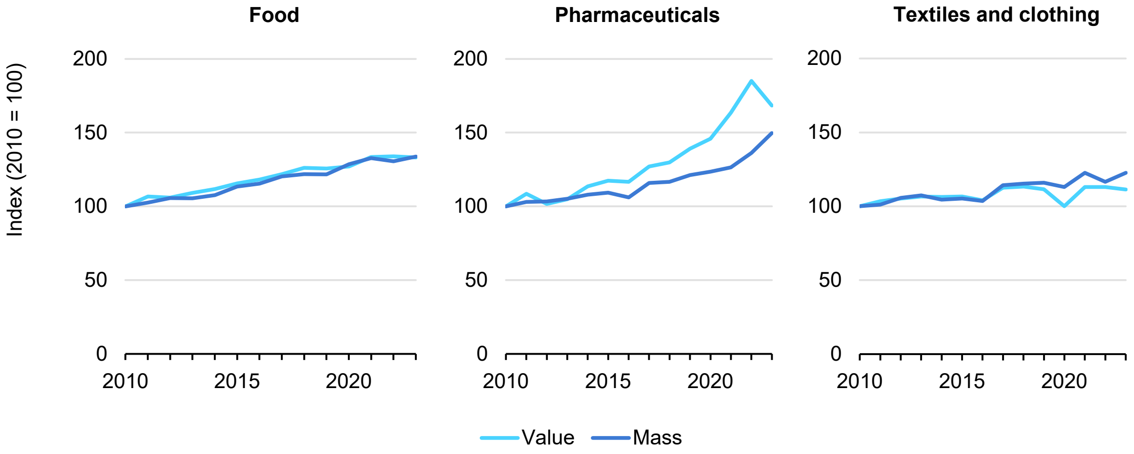
Notes: For electric cars, the index is based on units (not mass) and scaled in 2015 = 100. Aluminium includes mineral inputs, intermediates (such as alumina and scrap), ingots, and semi- and finished products. Iron and steel include mineral inputs, intermediates (such as scrap, pig iron and direct reduced iron) and semi- and finished products. Trade in materials refers to total trade, not just the materials used for manufacturing clean energy technologies. The trade value of the selected technologies reflects only the final exported unit and does not separately account for the value of the materials and components embedded in them.

Source: IEA analysis based on EV Volumes (2024); CEPII (2024); Oxford Economics Limited (2024b); pv-magazine (2024b); BNEF (2024a); SPV Market Research (2024); InfoLink (2024); IEA-PVPS (2024); and RTS Corporation (2024).

Exports of clean energy technologies are increasing rapidly in value and mass terms.

Global exports for several clean technologies have increased more quickly than those of other more established sectors of the economy like food, pharmaceuticals, and textiles and clothing over 2010 to 2023. For these three sectors, trade increased by between 25% to 50% in mass terms over the period – an increase similar to that of the three selected materials and all of their precursors. The volume of trade in clean technologies nonetheless remains small: in mass terms, the combined exports of the three technologies mentioned above, electric cars, solar PV and heat pumps, were around 60% of that of textile and clothing and just above 5% of that of food in 2023.

Figure 1.18 Global exports of selected non-energy goods, 2010-2023



IEA. CC BY 4.0.

Note: Data for 2023 preliminary.
Source: IEA analysis based on CEPII (2024); and Oxford Economics Limited (2024b).

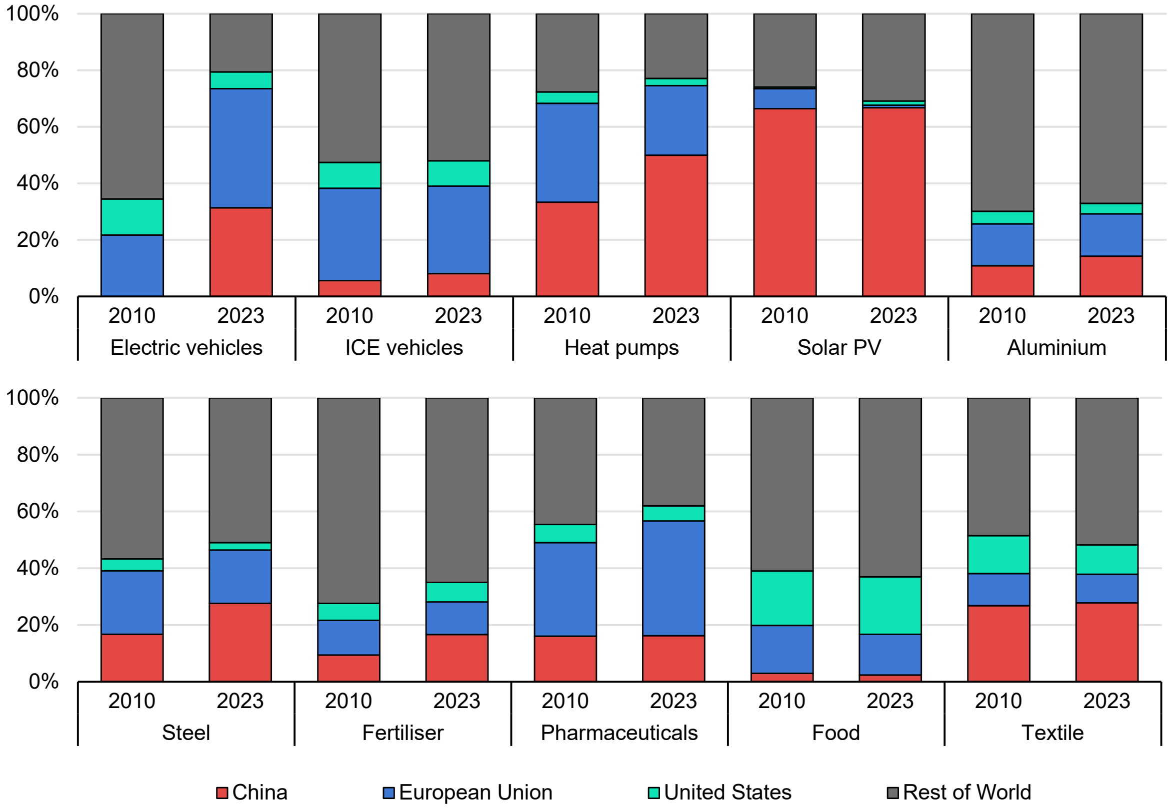
Exports of clean technologies have increased more quickly than most other goods since 2010, including food, pharmaceuticals, and textiles and clothing.

The clean energy transition is having a profound impact on the nature of international energy trade. There is a fundamental difference between fossil fuel trade, in which the goods being traded are *consumed* and then need to be replaced, and trade in mass-manufactured clean technologies, in which the goods being traded are added to the global capacity to *operate* or *produce* energy over a long period (excluding here the case of near-zero emissions materials traded and *consumed* to manufacture other products). For an importing country, fossil fuel trade creates a longer-lasting dependence on the exporter. Disruptions to fossil fuel supply chains can trigger immediate economic difficulties. By contrast, a country importing solar PV modules or EVs does not become dependent on a sustained relationship with the exporting country: installed solar capacity will continue to generate power and EVs will continue to be driven for many years. For these technologies, trade only affects future installations and market growth rather than the operation of the current stock. Consequently, disruptions to clean technology supply chains can affect the pace and cost of the transition. Clean technologies can also involve other types of dependencies, especially in the absence of local manufacturers or service providers, such as for operations (including component replacement, maintenance and updates of digital management systems and cybersecurity) and end-of-life activities (including recycling of materials).

The drivers of energy-related trade are also changing with the clean energy transition. Exports of fossil fuels and other minerals are determined by the availability of natural resources, whereas exports of clean technologies rely more on other factors of production and enabling conditions, such as skills and labour, knowledge and intellectual property, infrastructure, equipment, energy costs and access to capital markets. Government policy can also positively and negatively affect the development of manufacturing capacity.

China is by far the world's largest exporter of clean energy technologies. China's exports of clean technologies and materials have grown significantly over the last decade, supported by ample manufacturing capacity, low-cost production, demand growth outside China and favourable policies (Figure 1.19). In 2023, China's share of global exports of EVs (in units) was over 30%, 65% for solar PV, and 15% for aluminium. China's installed manufacturing capacity has increased rapidly, with capacity potentially available for exports (i.e. once domestic demand has been met) amounting to 650 GW for solar PV and 7 million electric cars, or 70% and 45%, respectively, of total manufacturing capacity in the country in 2023. These trends have raised concerns about the competitiveness of domestic manufacturers in importing countries, particularly in North America and Europe (see below).

Figure 1.19 Export shares by mass for selected products and materials for major exporters, 2010-2023



IEA. CC BY 4.0.

Notes: ICE = internal combustion engine. Estimates, data includes small quantities of re-export. For electric vehicles, the shares are based on units exported. Internal trade within the European Union is not included. Solar PV refers to modules. For steel and aluminium, only exports of ingots, finished products and semi-finished products are considered.

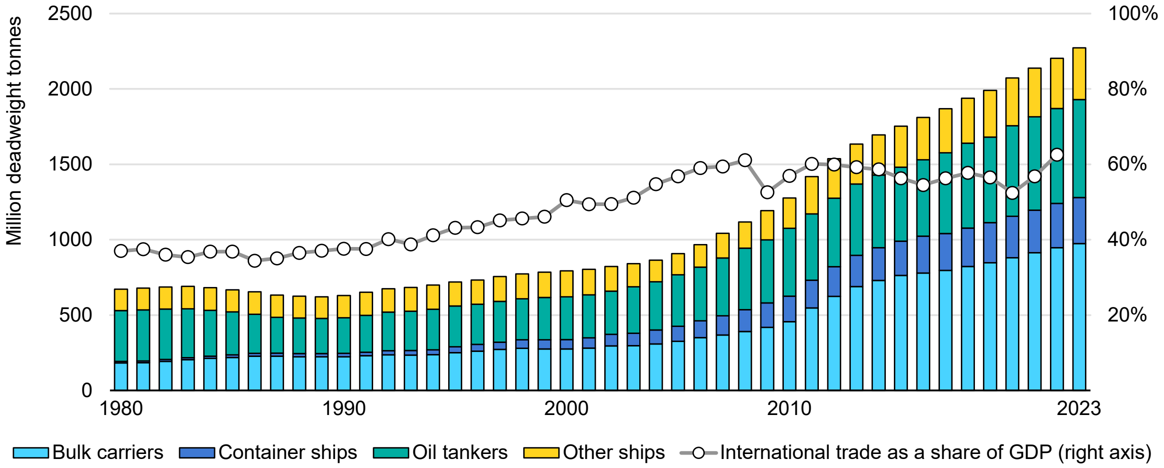
Source: IEA analysis based on CEPII (2024); Oxford Economics Limited (2024b); BNEF (2024a); IEA-PVPS (2024); SPV Market Research (2024); InfoLink (2024); RTS Corporation (2024); and EV Volumes (2024).

China has strengthened its position as the leading exporter of clean energy technologies and materials over the past decade.

Trade routes and maritime chokepoints

Maritime shipping is the primary means of transportation for international trade in fuels, materials and manufactured goods, accounting for around 80% of goods traded globally by mass. Overall shipping capacity has more than tripled over the last 40 years to meet the growth in exports resulting from underlying economic development and globalisation, with the share of trade in global GDP nearly doubling to over 60% between 1990 and 2022 (Figure 1.20). The capacity of all the world's cargo vessels combined increased from around 670 million deadweight tonnes (DWT, the gross carrying capacity) in the early 1980s to 2 300 million DWT by the end of 2023.

Figure 1.20 Global shipping capacity by type of cargo vessel, 1980-2023



IEA. CC BY 4.0.

Notes: Vessel capacity refers to the maximum mass a vessel can carry. Capacity data are for year-end, reflecting merchant cargo vessels. The share of international trade is calculated as the sum of exports of goods and services divided by GDP.
Sources: IEA analysis based on UNCTAD (2024a); and World Bank (2024)

International shipping capacity is growing, particularly for bulk carriers and container ships as materials and manufactured goods are increasingly globally traded.

Oil shipping has traditionally dominated international trade. In the 1980s, oil tankers made up half of global vessel capacity. Container ships, the preferred vessel type for transporting manufactured goods, accounted for only a fraction of global shipping capacity until China emerged as a global manufacturing powerhouse and countries started importing Chinese goods in large quantities in the mid-2000s. By the end of 2023, global vessel capacity had reached around 300 million DWT for container ships (13% of the total) and 650 million DWT for oil tankers (30%).

Bulk carriers, which are typically used to transport dry ores and materials like aluminium, iron and steel, coal and minerals, account for an even greater share of the growth in international shipping capacity, from 180 million DWT (25%) in 1980 to 970 million DWT (45%) in 2023. This is because bulk materials are far heavier than manufactured goods and are typically shipped to manufacturing centres, where they are transformed into final products. Between 2010 and 2023, bulk carrier capacity more than doubled, driven mainly by increased trade in minerals other than coal, while coal trade grew only by around 40% (including non-shipping trade). Nearly 50% of globally exported iron ore is shipped from material production sites in Australia to manufacturing centres in China, and 7% to Japan and Korea. Brazil, the second-largest exporter of iron ore, also predominantly exports to China, with this trade route accounting for around 15% of global exports of iron ore. Similarly, shipments of bauxite from West Africa to China make up over half of global exports, and those from Australia to China account for another 20%.

Clean energy transitions are accelerating this shift. Many clean technologies are mass-manufactured products: their production requires bulk carriers to deliver the raw materials, while their export requires container ships. A greater number of dedicated carriers may also be needed to ship alternative fuels such as hydrogen, ammonia and methanol. In parallel, progressively fewer oil tankers, LNG carriers and bulk carriers for coal will be needed as the world moves towards a low-emissions energy system (see Chapter 5).

This transition is also changing global trade routes, as countries that are fossil fuel exporters today are not the same as the producers of clean energy technologies. The most important trade routes for oil tankers are very different to those for bulk carriers and container ships, which are far more concentrated in Asia. In 2023, the world's most important trade routes were from and to China, accounting for nearly 45% of global shipping via dry bulk carriers, and 30% for container ships. In most cases, shipping took place between China and other countries in the Asia Pacific region, such as through the South China Sea. Shipping between China and the United States and the European Union combined accounted for just 7% of global bulk carrier trade, and 6% for container ships. To compare, the most important oil tanker shipping routes in 2023 started in the Middle East. Exports from the Middle East – which accounted for 40% of global oil tanker trade – supplied countries around the world, including China (10%), the European Union, India, Japan, Korea, and the United States (around 5% each). New trade routes are also emerging as new manufacturing centres develop. Several new ports are being built and existing ones expanded close to where resources are extracted or processed, where technologies are manufactured, or where contents from large cargo ships are transferred to smaller ones for local delivery.

As international trade increases, the risk of severe congestion and of physical supply disruptions at chokepoints – very narrow channels along the main shipping routes – is likely to rise. Shipping routes are subject to natural geographic and geological constraints, and practical alternatives are not always available. The busiest trade shipping route in the world is passing through the Strait of Malacca, which lies between Kuala Lumpur and Singapore. Nearly 100 000 ships pass through the straight every year (over 250 per day), carrying around a fifth of the world's trade in goods and 60% of that in oil. As shipping routes become busier, addressing risks of blockages at these chokepoints will become increasingly important for fossil fuels, clean energy technologies, bulk materials and other goods. These risks are discussed in more detail in Chapter 5, while the policy implications are set out in Chapter 6.

The past few years have provided several obvious illustrations of energy supply shocks. The Covid-19 pandemic, for example, led to a sudden slump in demand for all forms of energy, especially oil (due to reduced mobility), as well as chronic disruptions to supply chains generally, eventually driving up prices once demand started to recover. In 2022, gas markets worldwide, and notably in Europe, were upended by Russia's invasion of Ukraine, resulting in record high gas prices and lower demand. Extreme weather events, accidents, volcanic eruptions, regional conflicts and policy shifts, such as sudden changes in trade rules, have also led to disruptions in energy supplies and the supply chains of clean energy technologies in recent years. Market manipulation such as co-ordinated production limits or anti-competitive pricing can also affect global supply and price.

Clean energy technologies are just as exposed to supply shocks as fuels. The Covid-19 pandemic led to shortages of critical minerals, semiconductors and other materials and components needed to manufacture clean energy technologies. For example, the wind industry, especially in Europe and North America, has faced difficulties recently due to a combination of ongoing supply chain disruptions, higher costs and long permitting timelines, leading to slower project development (IEA, 2023c). The offshore wind sector has been particularly affected by inflation and disruptions in the supply chain, given its dependence on energy-intensive materials and the large size of turbines and farms (IEA, 2023c).

1.3 Competitiveness

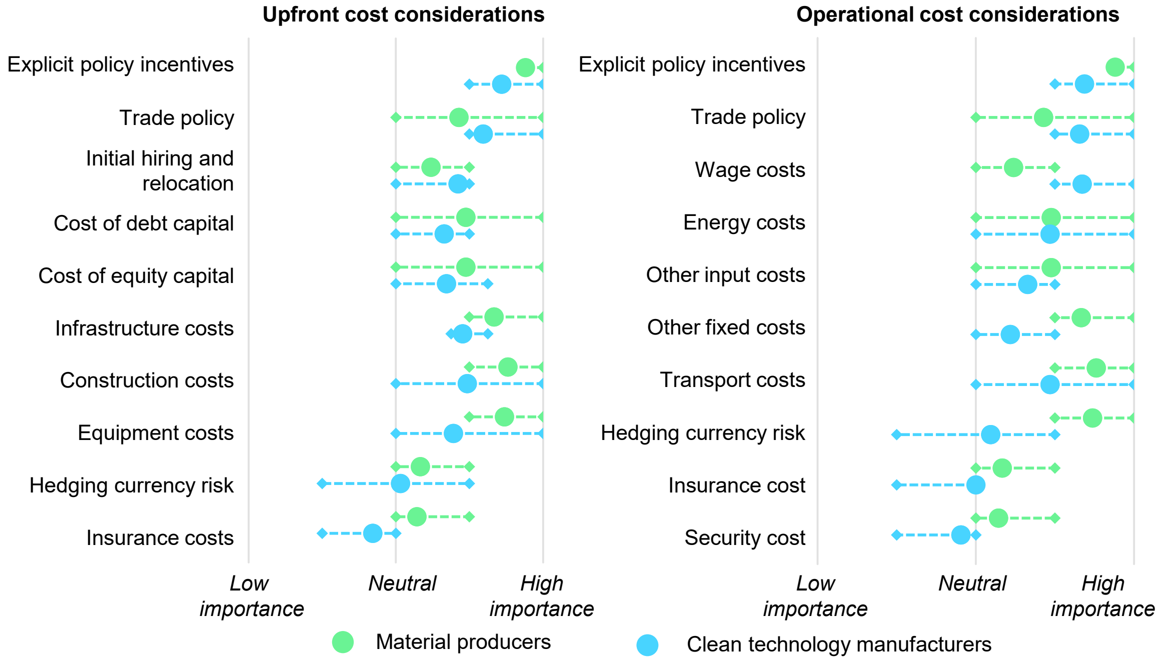
Factors influencing costs

The cost of production is a critical factor influencing investment decisions about whether and where to invest in any type of manufacturing activity. Production costs vary considerably across different clean energy technologies and their associated material inputs, as well as across countries and regions. Innovations in both manufacturing processes and the design of clean technologies themselves can lead to significant reductions in production cost over time. Conversely, improvements in technology performance can justify higher production costs, or components thereof. Trends also differ with respect to upfront costs and operating costs. Some material inputs have experienced sharp swings in price in the last

3 years as a result of supply chain disruptions and commodity price inflation, which can have a strong influence on operational costs. Similarly, sharp increases in interest rates over the past 2 years have led to significant increases in the financing of upfront costs.

The results of an industry survey that we carried out specifically for the purposes of this *ETP* confirm the importance of various types of costs to decision-making about clean energy technologies and related materials (Box 1.4). The survey revealed that investors in both materials production and clean energy technology projects consider government policy incentives and trade policies as the primary factors affecting both upfront investment and operating costs (Figure 1.21). In the case of upfront costs, site construction, equipment and infrastructure costs are given high importance by investors, while energy and wage costs are crucial to operating costs. These latter cost considerations are particularly important for materials production projects.

Figure 1.21 IEA industry survey of the importance of upfront and operational cost considerations for decisions about investing in manufacturing projects



Notes: Circles show the average score on a scale of importance for each subset of respondents, with the dashed lines showing the inter-quartile range of respondent scores.

Sources: IEA analysis based on survey data gathered from 50 companies (see Box 1.4).

Survey participants consistently rated explicit policy incentives as among the most important upfront and operational cost considerations in their investment decisions.

Box 1.4 IEA industry survey on factors influencing firms’ investment decisions

Companies have to weigh several considerations when deciding when and where to deploy their capital. For manufacturing firms, these considerations include both direct cost factors, like the price of energy or labour, as well as more intangible factors like synergies with existing industries and the current state of the innovation ecosystem. Each firm will assess these factors differently, depending on the jurisdiction and sub-sector they are operating in, among other things. Often there is no clear deciding factor, and some degree of instinctive, experiential or subjective judgement is often involved in taking an investment decision.

To gauge how firms assess these factors in deciding on an investment, we conducted an industry survey for the purposes of this report. It was structured using a series of scales and rankings of the relative importance of subsets of considerations with regard to upfront costs and operational costs, including energy and other inputs, employment, innovation and policy factors. In each instance, participants were asked to consider an investment decision in a context with which they were familiar and already have active operations, and then asked whether their responses would be different for a developing country context in which they were not currently operating (see the Annex for the specific questions posed). The survey was not intended to be statistically representative or achieve full coverage of individual industries, but rather to provide a snapshot of how decision makers in the manufacturing sector consider various factors that are less amenable to direct quantification by other means.

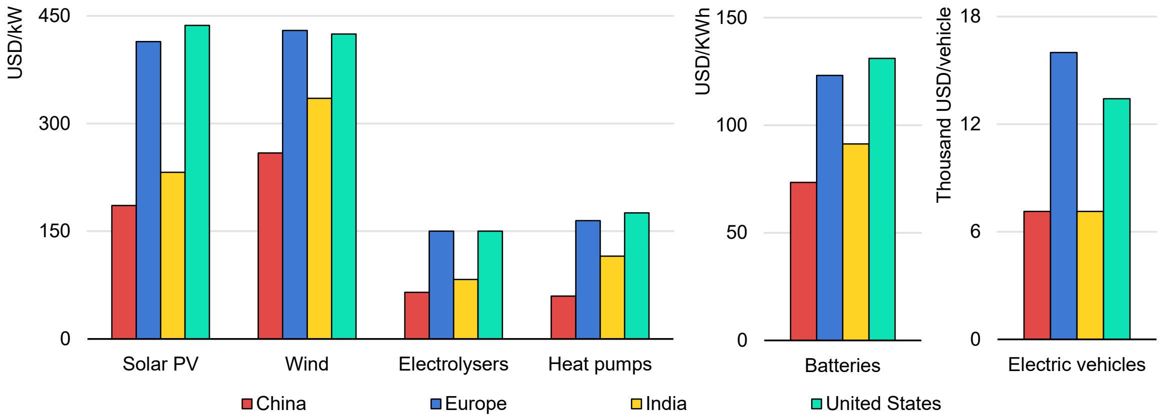
The survey involved 50 respondents spanning all of the clean energy technology and materials manufacturing sectors covered in this edition of *ETP*. Responses were provided by representatives and employees of firms across the world that are actively involved in investments decisions in these sectors, typically staff in the strategy, business development and active project teams.

The industry survey is ongoing. If readers of *ETP-2024* that have not yet participated are interested in doing so, we would encourage them to get in touch with us using the email address etp@iea.org. No firm or individual involved is identified during the analysis and dissemination of the survey data.

Capital costs

Capital costs for manufacturing include the total upfront costs of building factories and installing production equipment, but exclude financing and land costs. Together with the weighted adjusted cost of capital (WACC), a utilisation rate and the period over which the investment is to be depreciated, they are used to compute the annualised contribution of capital expenditure (CAPEX) to total production costs. If clean technology manufacturing facilities are utilised intensively, the contribution of capital costs – via annualised CAPEX – to total production costs is typically less than 20%. But when utilisation rates are lower, as they are for many clean technology manufacturing segments and regions today, the share of annualised CAPEX in total production costs rises, all else being equal. At a utilisation rate of 35% – a level broadly representative of the global battery cell manufacturing industry today, on average – annualised CAPEX can contribute up to 40% of the total production costs across clean technologies, and so can be an important determinant of investment decisions. Capital costs vary markedly between regions, industries and companies, as well as over time. In general, those costs are highest in North America and Europe, and lowest in China (Figure 1.22).

Figure 1.22 Indicative capital costs for selected clean energy technologies by country/region, 2023



IEA. CC BY 4.0.

Notes: Capital costs are shown per unit of annual rated capacity. Solar PV includes polysilicon, wafer, cell and module production facilities; batteries include cell, anode and cathode production facilities; wind includes nacelle, tower and blade facilities. Electrolysers and heat pumps include only the final assembly step. Costs refer to greenfield, non-integrated facilities where these attributes could be isolated in the data and constitute averages across plants of different sizes today. Data gaps were filled using regional multipliers based on differentials in cost for constructing other facilities where more data are available. No explicit policy incentives (e.g. investment tax credits) are applied in this assessment. See the Annex for more details on the scope and methodologies used in this analysis. USD = USD (2023, MER).

Source: IEA analysis based on Wood Mackenzie (2024); BNEF (2024a); IEA (2024a); and Atlas EV hub (2024).

Capital costs for manufacturing facilities vary significantly across technologies and countries, and are generally lowest in China.

Building manufacturing facilities for wind turbines, including nacelles, blades and towers, currently costs USD 250-500/kW for onshore and USD 350-700/kW for offshore components. These facilities require large buildings to house the large components and heavy-duty machinery for manoeuvring them around the site. The steadily increasing size of wind turbines and the need to tailor installations to site-specific conditions has hindered the ability to standardise manufacturing facilities, limiting the scope for lowering costs (as the amortisation of specialised equipment is spread over fewer units), although efforts by manufacturers are underway to increase standardisation of the equipment used in the sector (Memjia, 2023).

Facilities for solar PV manufacturing are almost as capital-intensive as wind turbines, owing to the multiple processing steps and complex nature of the processing equipment needed, particularly for manufacturing cells and wafers. Total capital costs are in the range of USD 190-480/kW. Module assembly, cell and wafer production are more amenable to economies of scale and short cycles of innovation, given the modular nature of the technology. For electrolyser and heat pump production facilities, capital costs are USD 60-240/kW and USD 65-165/kW respectively.

China has the lowest capital costs for manufacturing facilities for all six of the technologies considered here and for all manufacturing steps. Costs in the United States and Europe are between 65% and 195% more expensive per unit of output capacity. Costs in India are around 25-95% higher than in China, but are still significantly lower than in the United States and Europe. These cost differentials reflect differences in underlying labour, material and construction costs. China also benefits from the experience gained in building its large stock of existing facilities, as well as the economies of scale from larger facilities, industrial clusters covering the full value chain, lower interest rates and a deflationary environment. A facility that can be built more quickly at a larger scale and with less uncertainty typically yields cost reductions throughout the construction and procurement process.

Regional average capital cost figures mask some substantial variations in plant-specific costs. In particular, there can be major differences in costs between greenfield and brownfield projects for certain components of clean technology supply chains (all the costs presented here are for greenfield facilities to aid comparability). For example, greenfield facilities for making polysilicon in China – the only region where the distinction can be made based on the data available – cost around two-thirds more per unit of output to build than brownfield facilities. Costs may also vary according to the size of the plant and the degree of vertical integration. A recently announced fully vertically integrated solar PV manufacturing facility in Shanxi, China – which, at 56 GW, will be the largest in the world – is expected to achieve full chain costs of USD 140/kW, compared with a national average figure of USD 185/kW (pv-magazine, 2024c). The regional average figures are also static and aimed at capturing costs of the most recently constructed facilities, thereby concealing any variation in costs over time. In China, for example, capital costs for both solar PV cell and module manufacturing capacity fell by around 35% over the period 2020-23 (on a weighted average cost per unit basis), whereas costs for greenfield polysilicon and wafer production facilities were broadly flat.

In contrast to most clean technology manufacturing facilities, the main facilities used today to make steel, aluminium and ammonia in conventional ways are technologically mature and modifications to their production processes tend to be incremental. For steel and aluminium, capital costs vary according to whether the metals are produced from ore (primary) or recycled materials (secondary); today, around 30% of metallic inputs to steel and 35% to aluminium are recycled scrap. Plants using scrap for production can reduce or avoid the need to process iron ore for steel or refine bauxite into alumina, and so tend to be less capital-intensive to build (although a mixture of scrap and iron use in the same production process is typical in the steel industry). Capital costs also vary according to the type of primary energy input.

Variations in capital costs between regions for a given process route are estimated to be similar to those for clean technology manufacturing. Reliable and comparable information on the costs of material production facilities is limited, even for established conventional production technologies, both because the information is commercially sensitive and because of differences in the methods of production. Steel plants are estimated to cost in the range of USD 650-1 350/tonnes of capacity for a fully integrated conventional facility producing steel from iron ore, and USD 480-850/tonnes for a facility producing from scrap alone.[5] For aluminium, the cost is around USD 6 400-12 000/tonnes for a conventional primary production facility and USD 300-570/tonnes for a secondary facility. Ammonia plants cost in the range of USD 1 400-2 200/tonnes for steam methane reforming.

The capital costs of building facilities that manufacture near-zero emissions materials are expected to be considerably higher than those for recently built plants using conventional technologies, at least initially (Figure 1.23). Technologies to decarbonise these processes, in some instances via entirely new process designs, are under development (IEA, 2023a). Costs for these facilities are largely unknown, as few have been built at scale. Capital costs for steelmaking using a 100% hydrogen-based DRI furnace are expected to be 40-140% higher than for conventional natural gas-based DRI processes, once they reach commercial scale. Yet their costs could fall in the longer term with technical advances. A good example of this is ammonia production based on electrolysis, where the electrolyser system accounts for around 65-80% of the capital cost of the plant at today's electrolyser costs of USD 1 300-2 160/kW, which include installation costs. Halving the installed cost of the electrolyser would lead to a 30-40% reduction in the estimated cost of building the ammonia plant that houses it.

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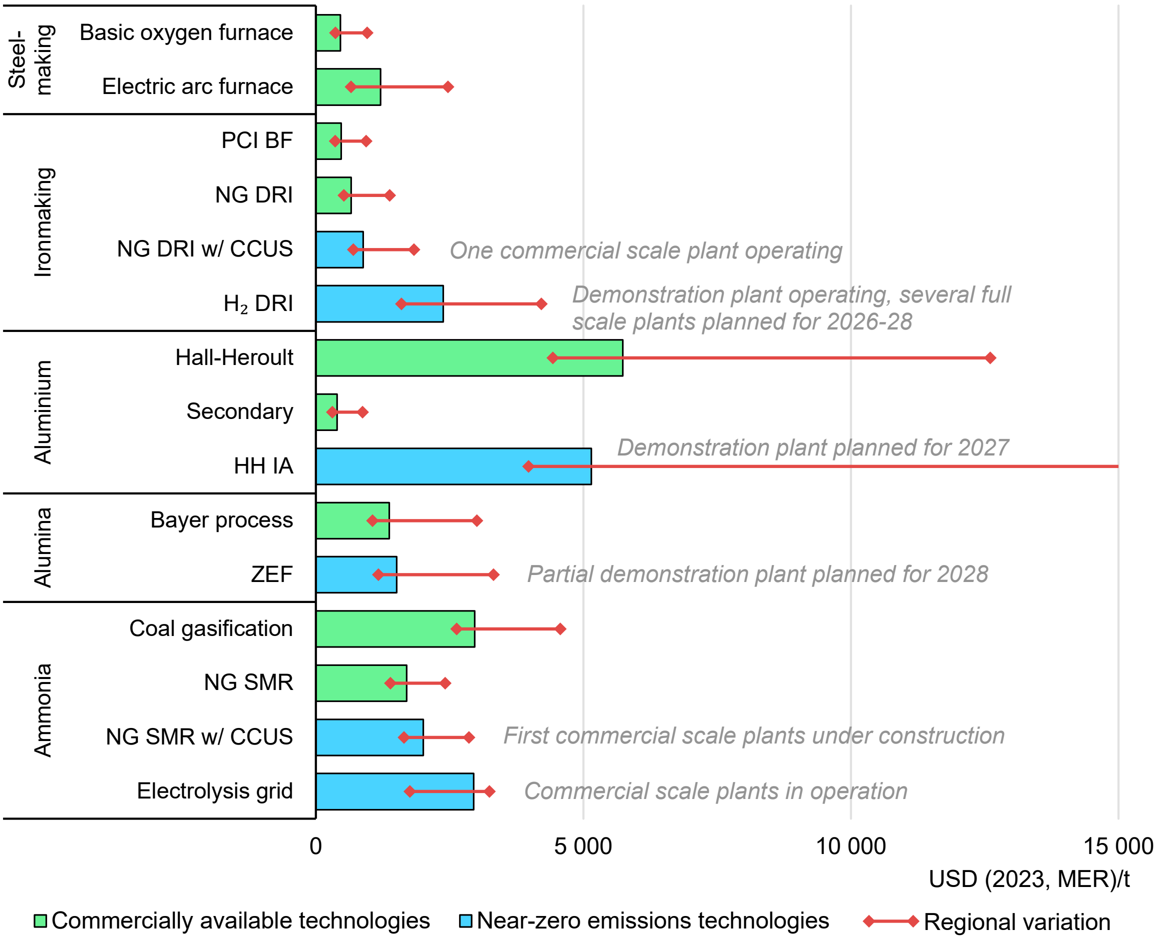
[5] These estimates exclude process units downstream of casting, like rolling and other semi-finishing processes.

Figure 1.23 Indicative capital costs for selected materials production processes, 2023



Notes: PCI BF = pulverised coal injection blast furnace; NG DRI = natural gas-based direct reduced iron furnace; w/ CCUS = with carbon capture, utilisation and storage; H_2-DRI = hydrogen-based direct reduced iron furnace; HH IA = Hall-Heroult process with inert anodes; ZEF = alumina refining with zero emissions fuels; NG SMR = natural gas-based steam methane reforming process. The cost for those near-zero emissions technologies that are today under development either at prototype, demonstration or early commercialisation stage, show estimated capital costs on commercialisation. Bars represent the median CAPEX while error bars show estimated ranges of costs between regions, reflecting variation in engineering, procurement and construction costs. For near-zero emissions technologies, error bars are used to illustrate uncertainty. Hydrogen electrolyser costs are included for the H_2 DRI and ammonia electrolysis routes. All estimates presented are for greenfield facilities, excluding land costs.

Near-zero emissions technologies for materials production generally involve much higher upfront investments than their conventional technology counterparts.

The main drivers of differences in capital costs between regions and between plants within a given region are similar for both clean technology and material manufacturing facilities:

- The regulatory environment: Some countries have lower environmental protection standards, such as the need for environmental assessments and safety standards for workers, as well as less stringent zoning rules that require manufacturing plants to be built in more remote or expensive locations. The predictability of the regulatory environment also influences costs, as changes without sufficient notice can cause delays and require larger contingencies.

- Explicit policy incentives (see below): Besides the direct impacts of lowering the cost to a firm of constructing a manufacturing facility, financial support for upstream industries in the same market can lead to lower production costs for key materials needed to build factories in some countries. Some materials, like cement, are not widely traded due to the high unit costs of transport, and so local prices can vary substantially across regions.
- Cost of capital (financing costs): Access to loans with lower interest rates or being able to raise cheap equity reduces the overall cost of building a manufacturing facility. At the project level, the cost of capital reflects the degree of risk an investor is prepared to take in providing the capital. The cost of capital can vary substantially, notably across countries and regions, and today generally varies by a factor of four for clean technology manufacturing between some advanced economies and the least developed EMDEs.
- Economies of scale: For example, the solar PV plant being built at Shanxi in China (see above) will be 15 times larger than the global average facility, with capacity to produce more than the European Union's annual demand for solar PV modules, resulting in full chain capital costs around one-quarter lower than the average for the country (pv-magazine, 2024b).
- The degree of facility integration: More complex, integrated facilities for materials and technologies can have higher capital costs per unit of capacity but they generally lead to higher efficiencies and lower production costs. For example, a steel plant with better heat integration may be more expensive to build, but can lower overall production costs through higher operational efficiency and reduced exposure to intermediate product prices fluctuations.
- Brownfield versus greenfield facilities and the cost of land: Greenfield plants are almost always more expensive to build, so if a country is already endowed with a large capacity in a given industry, with the requisite infrastructure, permitting and other requirements already in place, the cost per unit of adding or replacing capacity is usually lower.
- Technology and innovation: A more digitalised and refined construction industry can deliver projects at lower cost by reducing the likelihood of mistakes, making it more efficient to adapt and update design changes, and achieving higher levels of mechanised processes on-site. A higher degree of automation can reduce labour and energy costs.
- Labour costs, including wages and benefits like health insurance and employer social contributions: These costs vary substantially across regions, affecting the relative cost of construction of manufacturing plants.

Levelised cost of production

Levelised cost is a commonly used metric for comparing the cost of producing a particular good in different locations using different methods. In this report, the levelised cost of production (LCOP) is defined as the total cost of producing one unit of output, such as 1 MW of solar modules, 1 MWh of battery cells or 1 Mt of steel, taking into account all the upfront and ongoing costs incurred over the lifetime of the investment. Those costs include capital expenditure (CAPEX), as well as fixed and variable operating cost (OPEX), including inputs of energy, materials, upstream components and labour. Upfront CAPEX is annualised over the economic lifetime of the facilities according to the prevailing cost of capital in each region and for each manufacturing sectors. While the metric provides a convenient way of comparing regions and examining the different contributors to production cost, direct comparisons between the costs of different outputs can be misleading. For example, a tonne of steel can do a very different job to a tonne of aluminium, and a kW of wind – once installed – can have a very different capacity factor to a kW of solar PV.

At high utilisation rates, component and material costs are the main contributors to the LCOP of the clean energy technologies examined in this report, typically accounting for upwards of half the total production cost (Figure 1.24). Variable OPEX makes up more than 80% of the LCOP for solar PV, wind, battery, heat pump and electrolyser manufacturing. At 85% utilisation and a financing cost of 5-20% (depending on the region), our modelling shows that CAPEX makes a modest contribution to the overall levelised cost of manufacturing clean technologies, accounting around 10-25% of the cost of producing solar PV modules, 5-15% for batteries, 1-10% for heat pumps, 5-15% for wind turbines and 10-35% for electrolysers.[6] When utilisation rates remain high, the impact of regional variation in CAPEX on LCOP is relatively small, and regional differences in LCOP are largely driven by differences in variable OPEX, and in particular, energy and labour costs. Conversely, if factories are utilised less intensively, overall costs increase, and the share of CAPEX in the total LCOP rises, and becomes a greater contributor to regional variation in LCOP.

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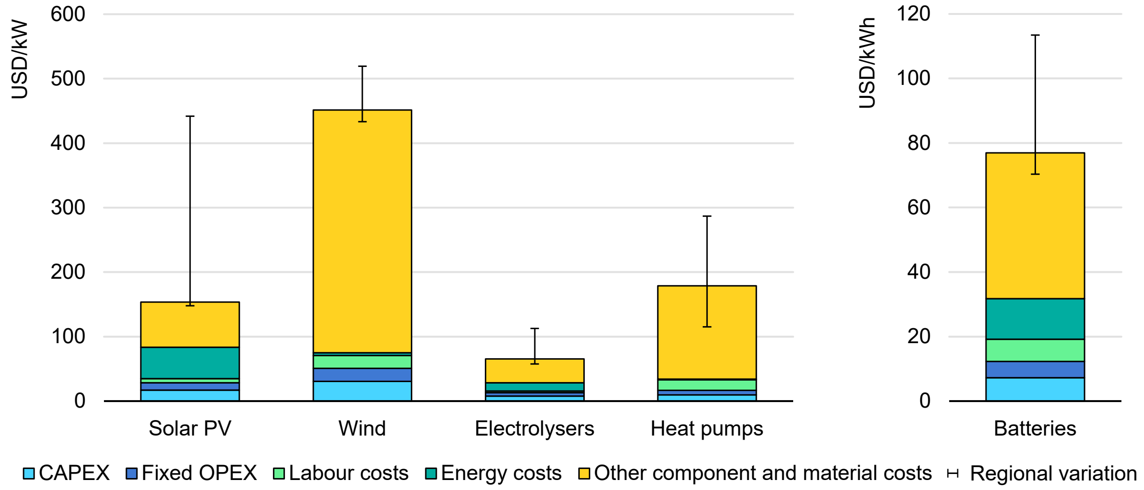
[6] For final clean technology products like PV modules and batteries, the CAPEX contributions of the precursor components (i.e. PV cells, wafers and polysilicon for PV modules, and anodes and cathodes for batteries) were taken into account, which are embedded in the components' cost.

Figure 1.24 Global average levelised cost of production by cost factor for selected clean energy technologies and regional variation, 2023



Notes: The solid black lines indicate the range across regions while columns represent the global production-weighted average in 2023. Other component and material costs refer to the costs of upstream components used in the production of a clean technology (e.g. compressors in heat pumps) or the costs of materials used as inputs (e.g. aluminium for solar modules). Electrolysers refer to the stack of an alkaline system; heat pumps refer to the final assembly step (averaging the production cost of air-to-air and air-to-water units). Battery refers to cells and to the 2023 world capacity-weighted battery chemistry. A utilisation rate of 85% and a lifetime of 25 years is used for all equipment. See the Annex for more details on the scope and methodologies used in this analysis. USD = USD (2023, MER). Costs shown here are exclusive of explicit financial support (e.g. tax credits in the Inflation Reduction Act), but may include financial support embedded in individual cost components (e.g. fossil fuel subsidies).

Sources: IEA analysis based on NREL (2017); NREL (2019); NREL (2023); Wood Mackenzie (2024); BNEF (2024a); IEA-PVPS (2024); BNEF (2024b); IEA (2024a); IEA (2024g); Argonne (2024); JETRO (2024); Dai et al. (2019); and Frith, Lacey, & Ulissi (2023).

When factories are utilised intensively, energy, material and other variable operating costs together account for more than 80% of the levelised cost of production for key clean energy technologies.

The relative contribution of CAPEX and OPEX to LCOP varies markedly across the five technologies assessed here.

- Solar PV: The wide range of LCOP between regions is largely due to the proportionally large contribution of energy to final costs and the large variability of energy costs. For example, industrial electricity prices in China are on average around three times lower than in the European Union. Polysilicon production is the most energy-intensive step, followed by wafers; together, their energy consumption accounts for around 20% of the total module costs. The cost of materials, including large-volume materials (like aluminium), critical minerals (like silver) and the initial silicon used for the polysilicon production, is also a significant factor, especially at the production steps for cells and modules.
- Wind: About 80% of the total cost of producing wind turbines, including the nacelles, blades and towers, come from materials and upstream components. The contribution of energy is very small as the manufacturing process mostly involves the assembly of parts, which uses little energy. While relatively similar, the cost shares differ slightly for each component: labour plays a larger role in blade

manufacturing than in producing nacelles or towers, whereas materials and upstream components have a larger impact on the costs of nacelles and towers.

- Batteries: The cost of manufacturing batteries includes the production of anodes and cathodes, which are then assembled into battery cells. As with solar PV, the overall LCOP of battery cells varies significantly across regions due to the importance of energy inputs, which can account for up to 15% of the total cost, when factoring in the energy consumption for anodes, cathodes and cell production. The scale of production, the degree of supply chain integration and materials costs also contribute to this regional variation, as the shares of different battery chemistries vary across regions; for example, China produces more lithium iron phosphate (LFP) batteries, which involve the use of more abundant materials that are therefore cheaper.[7]
- Electrolysers: As with the other technologies, the main contributors to the LCOP of electrolysers are materials, components and energy inputs. Our estimate of the global average LCOP relates to a large stack and is based on a high utilisation rate of 85%, which is higher than current rates.
- Heat pumps: The contribution of upstream components to the LCOP of heat pumps is higher than for all the other clean technologies, as manufacturing heat pumps consists mainly of the assembly of different parts (see Box 1.5).

Box 1.5 Cost competitiveness of heat pump manufacturing across regions

Technological differences in the type of heat pumps deployed in different markets make cost comparisons between countries difficult. The cost of components such as compressors or heat exchangers represents the largest share of manufacturing cost for heat pumps. Costs can vary significantly across different heat pump types and different efficiency levels, which may require different technical specifications. In addition, manufacturers that produce their own components and/or can benefit from economies of scale have a strong competitive advantage. These factors partially explain the significant cost gap between technologies and across regions. For example, an air-to-air heat pump for a ducted system manufactured in the United States can cost twice as much to produce per kW as an air-to-air split system manufactured in China, with up to 70% of the difference in cost being driven by component and material costs (Figure 1.25).

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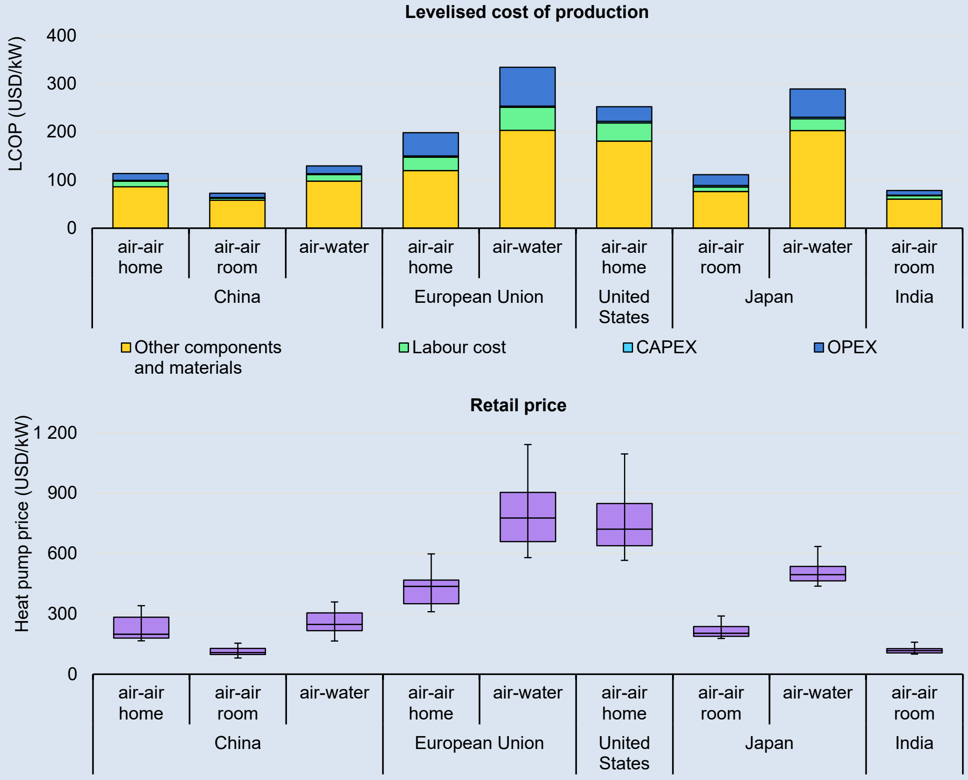
[7] The effect of different chemistry choices, which can further enlarge the production cost gap between different regions, is not reflected in the estimates of LCOP shown here, as they are based on 2023 capacity-weighted average battery chemistry used worldwide.

Figure 1.25 Levelised cost of production for heat pumps and retail price in selected countries/regions by type, 2023



IEA. CC BY 4.0.

Notes: air-air home = air-to-air central heat pumps for the whole household; air-air room = air-to-air reversible air conditioners for a room; air-water = air-to-water units for the whole household. LCOP = levelised cost of production. For Japan, air-water units are intended as water heaters with tanks. USD = USD (2023, MER). Costs shown here are exclusive of explicit financial support (e.g. tax credits in the Inflation Reduction Act), but may include financial support embedded in individual cost components (e.g. fossil fuel subsidies).

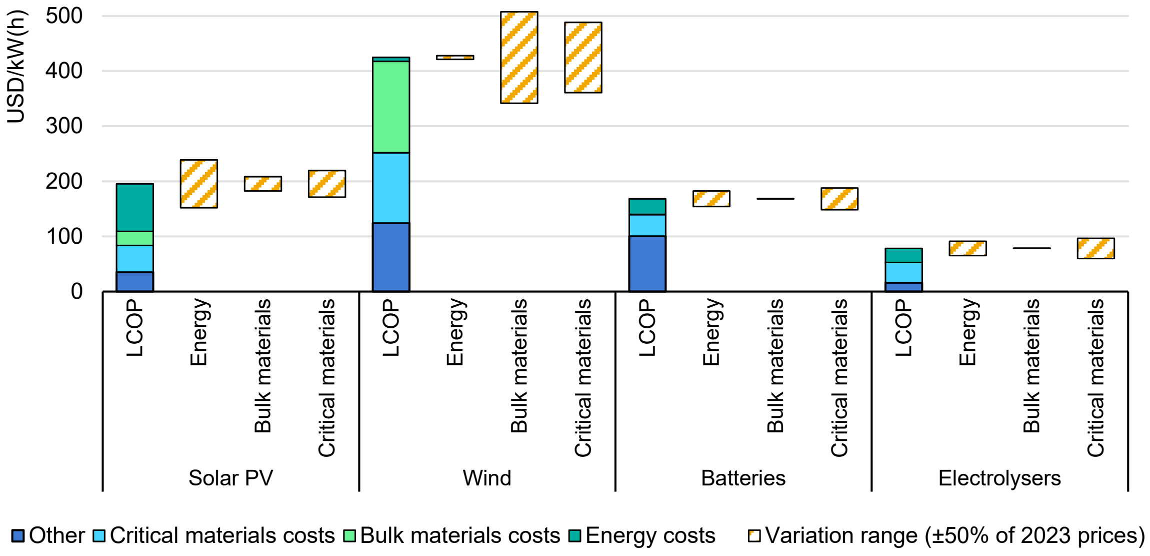
Source: IEA analysis based on JETRO (2024).

Despite these regional differences in production costs and a clear competitive advantage for some countries, heat pumps – except small reversible air conditioners – tend to be mostly produced locally and not traded extensively. This is partially linked to the need to comply with local standards and regulations (see Chapter 2). Another factor is the share of the heat pump unit cost in the total heat pump installation cost. Although imported heat pumps may sometimes be significantly cheaper, when installation costs and ancillary services (e.g. control systems) are also factored in, the relative savings may be small and, therefore, have only a limited impact on the consumer's choice of unit.

There is scope to reduce heat pump production costs, for instance via enhanced digitalisation and automation of some production processes, or via strategic partnerships on producing certain components. Installation costs could also be cut, for instance by developing more modular, easier-to-install units and by training more installers.

Energy costs are most important for solar PV, electrolysers and batteries. The price of electricity – the main form of energy for the clean technology manufacturing industry – varied by a factor of ten between regions in 2023, with Europe having the highest prices and the Middle East the lowest (in some cases, reflecting subsidies for fossil fuels). The prices of materials also vary significantly across regions, but generally to a lesser extent than for energy. There is some scope for lowering the cost of materials through more material-efficient products, such as frameless PV modules or newer chemistries in battery cells. There is a strong incentive for manufacturers to seek ways of reducing reliance on materials that are most vulnerable to price volatility, such as lithium for making batteries.

Figure 1.26 Sensitivity of the levelised cost of production to the costs of energy and materials for selected clean energy technologies, 2023



IEA. CC BY 4.0.

Notes: LCOP = Levelised cost of production. The variation represents the range of costs with a variation of +/- 50% of the 2023 price of each production input. Bulk materials refers to steel and aluminium. "Critical materials" refers to copper, lithium, cobalt, neodymium, silver and other minerals. "Other" refers to other components of the levelised costs such as CAPEX or fixed OPEX. USD = USD (2023, MER). Costs shown here are exclusive of explicit financial support (e.g. tax credits in the Inflation Reduction Act), but may include financial support embedded in individual cost components (e.g. fossil fuel subsidies).

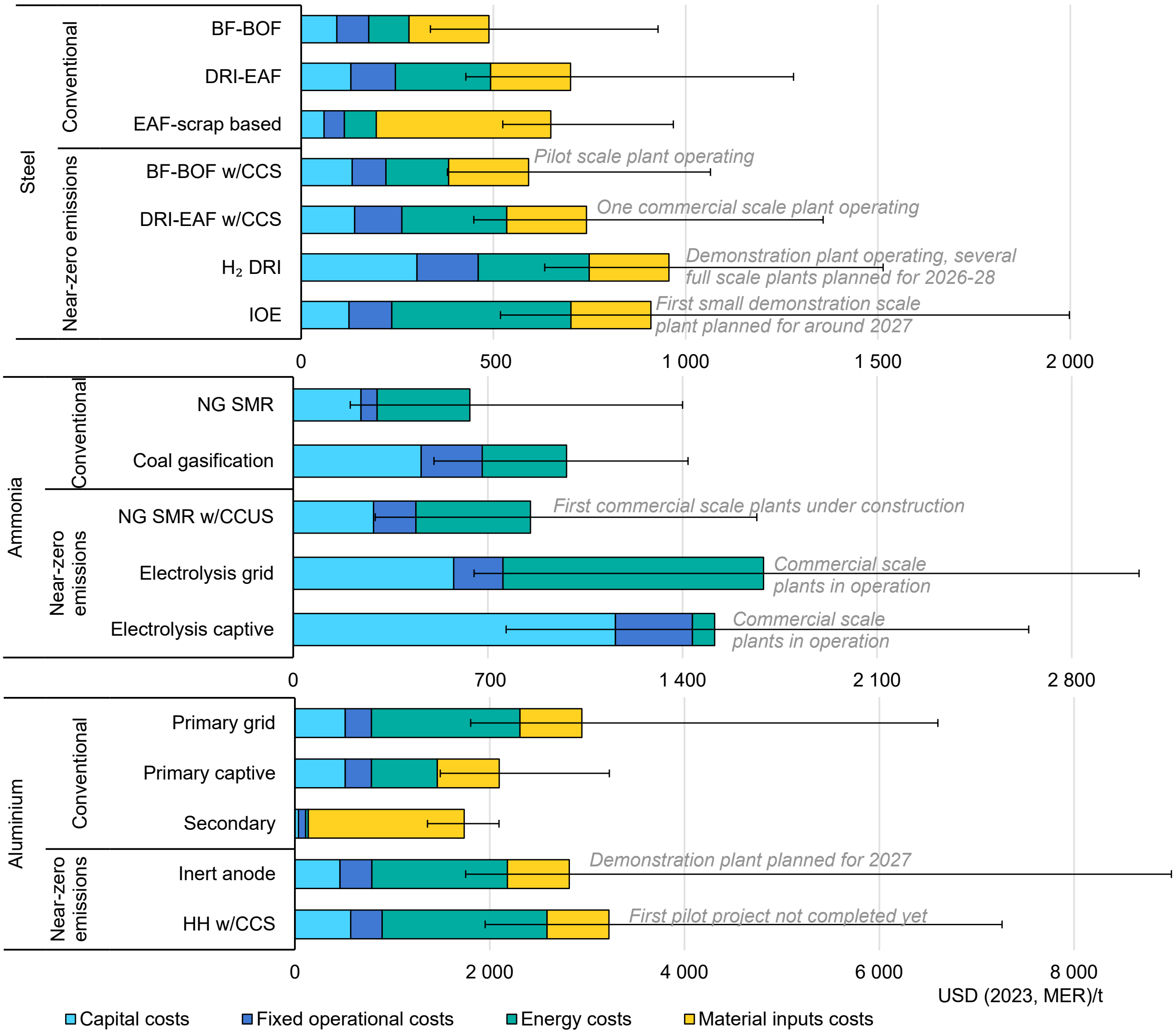
Sources: IEA analysis based on NREL (2017); NREL (2019); NREL (2023); Wood Mackenzie (2024); BNEF (2024a); IEA-PVPS (2024); BNEF (2024b); IEA (2024a); IEA (2024g); Argonne (2024); JETRO (2024); Dai et al. (2019); and Frith, Lacey, & Ulissi, (2023).

Variations in critical mineral prices have the biggest impact on manufacturing costs, energy prices most affect solar PV and electrolysers, and bulk material costs wind.

The LCOP for materials varies substantially between production routes as well as regions (Figure 1.27). Compared with clean technologies, the contribution of CAPEX to the LCOP for the three main materials covered here are relatively higher:

- Steel: The global average LCOP of steel production is broadly similar for the three main conventional production routes in use today, with their regional ranges of price variation overlapping to a considerable extent. The prices of iron ore and scrap – which are inter-related as they are inputs for the same final product – heavily influence overall production costs, typically accounting for 30-70% of the total, with scrap-based production being at the upper end of the range. The blast furnace-basic oxygen furnace (BF-BOF) technology uses coal as its primary energy input, which varies much less in price between countries than natural gas, the main energy input to the direct reduced iron (DRI) electric arc furnace (EAF) route (although this technology is also used with coal in India). Near-zero emissions technologies for steel production could, in the future, reduce their cost premium compared to conventional routes to around 5-15%, if the main energy inputs (electricity for the hydrogen-based DRI) and enabling infrastructure (CO_2 transport and storage in the case of the CCUS-equipped routes) are available at low cost.
- Ammonia: The variation in LCOP between production routes and between regions is also important for ammonia, given that the steam methane reforming (SMR) route is the dominant mode of production globally. As natural gas is both the primary feedstock and energy input in SMRs, typically accounting for half of the LCOP, there are wider regional price differences for natural gas-based ammonia production than for coal-based production. Production based on coal gasification is virtually all based in China. Among the main near-zero emissions technologies being pursued for ammonia production, the SMR with CCUS route has the same cost drivers as its unabated SMR counterpart, whereas the electrolysis route entails a shift to electricity as the sole energy input. For electrolysis installations, a process arrangement with captive variable renewable electricity leads to much lower electricity costs, but also a potentially lower capacity factor for the plant, resulting in a higher share of CAPEX in the LCOP, relative to grid-connected installations.
- Aluminium: There is a significant difference in LCOP between primary and secondary conventional routes for aluminium production based on grid electricity. However, at least half of the primary aluminium plants operating worldwide utilise captive, low-cost sources of electricity, notably hydropower in Canada and Europe, coal-fired plants in China and gas-fired plants in the Middle East (International Aluminium Institute, 2024). By contrast, differences in cost for the secondary route are mainly due to the price of scrap aluminium, which in turn is affected by the cost of primary production. The LCOP of aluminium using near-zero emissions technologies is highly uncertain, given the early stage of their development, but could theoretically achieve similar production costs to conventional primary routes once they reach commercial scale.

Figure 1.27 Levelised cost of production for selected materials by technology

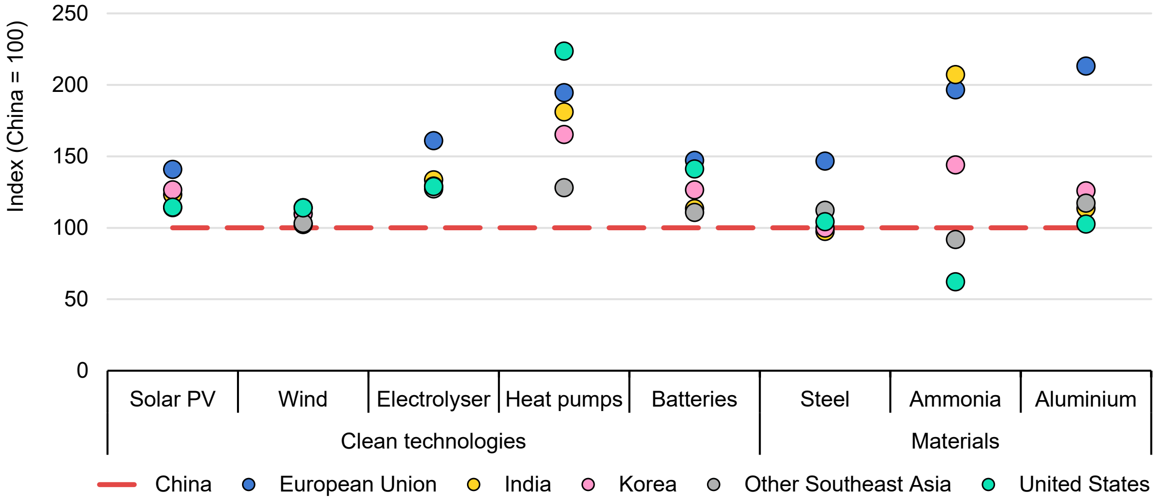


Notes: SMR = Steam Methane Reforming; EAF = Electric Arc Furnace; DRI = Direct Reduced Iron; BF = Blast Furnace: BOF = Basic Oxygen Furnace; CCS = Carbon Capture and Storage; IOE = Iron Ore Electrolysis; HH = Hall-Heroult process. Bars show the levelised cost using median regional costs for best available technology energy performance. Error bars represent regional variation together with cost uncertainty for near-zero emissions technologies for materials production. Near-zero emissions technologies refer to technologies that are today under development either at prototype, demonstration or early commercialisation stage and show estimated capital costs on commercialisation. Energy costs based on regional end-user prices for industry, including taxes and charges. Their ranges are as follows: USD 10/GJ for natural gas (1-30/GJ); USD 5/GJ for coal (0.5-10/GJ); USD 100/MWh for grid electricity (30-300/MWh); USD 30/MWh for captive electricity (20-40/MWh). Costs shown here are exclusive of explicit financial support (e.g. tax credits in the Inflation Reduction Act), but may include financial support embedded in individual cost components (e.g. fossil fuel subsidies).

Near-zero emissions technologies for materials production usually involve higher costs than their conventional counterparts, even once they reach commercial scale.

Regional cost differences are generally more pronounced for materials than for clean energy technologies, with the LCOP again being among the lowest in China for steel and aluminium, but lower in the United States and other Southeast Asian countries for ammonia, thanks to low natural gas prices. US production costs for aluminium are close to those in China, again thanks to cheap energy. Regional variations in the LCOPs, excluding any explicit financial support, result mainly from differences in operational costs, notably energy and labour, which generally constitute the largest share of the total costs.

Figure 1.28 Levelised cost of production for selected clean energy technologies and materials by country/region, 2023



IEA. CC BY 4.0.

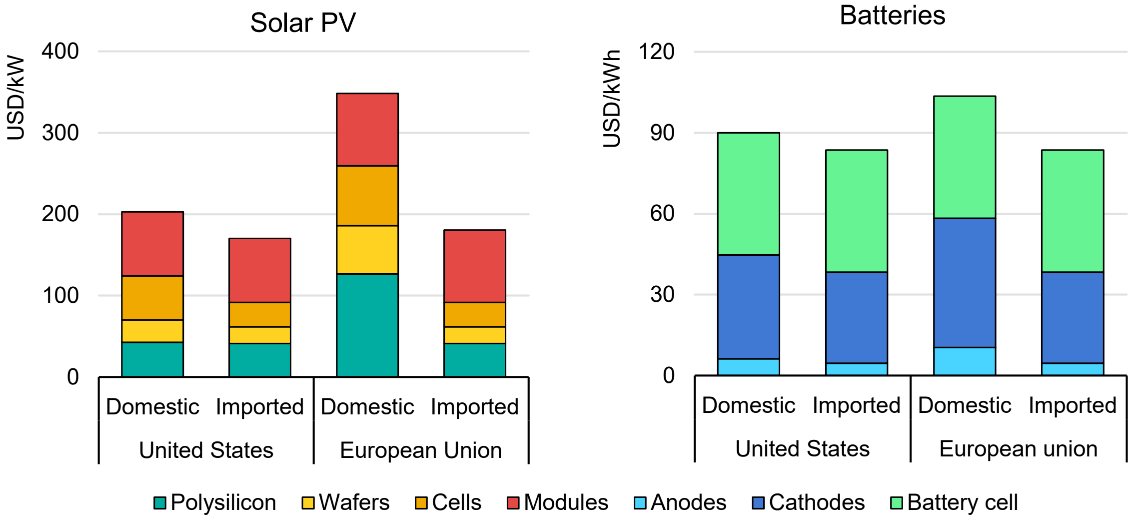
Notes: For solar PV and batteries, costs relate only to the last manufacturing step, with components such as cathodes or PV cells assumed to be imported from China. For the other clean technologies and materials, production is fully local. LCOP for steel refers to blast furnace-basic oxygen furnace (BF-BOF) technology; ammonia refers to steam methane reforming (SMR); aluminium refers to the Hall-Heroult process using electricity from the grid. Costs shown here are exclusive of explicit financial support (e.g. tax credits in the Inflation Reduction Act), but may include financial support embedded in individual cost components (e.g. fossil fuel subsidies).

Sources: IEA analysis based on NREL (2017); NREL (2019); NREL (2023); Wood Mackenzie (2024); BNEF (2024a); IEA-PVPS (2024); BNEF (2024b); IEA (2024a); IEA (2024g); Argonne (2024); JETRO (2024); Dai et al. (2019); and Frith, Lacey, & Ulissi, (2023).

China has the lowest production costs for all clean energy technologies and most materials.

In the United States and, to an even greater degree, in the European Union, the LCOP for solar PV modules and batteries depends heavily on whether the components are produced domestically or imported. EU production costs for solar PV using components produced within the region are twice as high as those using components imported from China and around a quarter higher in the case of batteries (Figure 1.29). The cost differentials in both cases are much smaller in the United States, largely due to lower energy costs.

Figure 1.29 Levelised cost of production for batteries and solar PV modules by origin of components in the United States and the European Union, 2023



Notes: Domestic refers to the production cost using components produced entirely within the country/region; imported refers to the production cost using components imported from China and only the last production step happening locally. Tariffs, shipping cost, profit margins of components, and financial support are excluded. USD = USD (2023, MER).

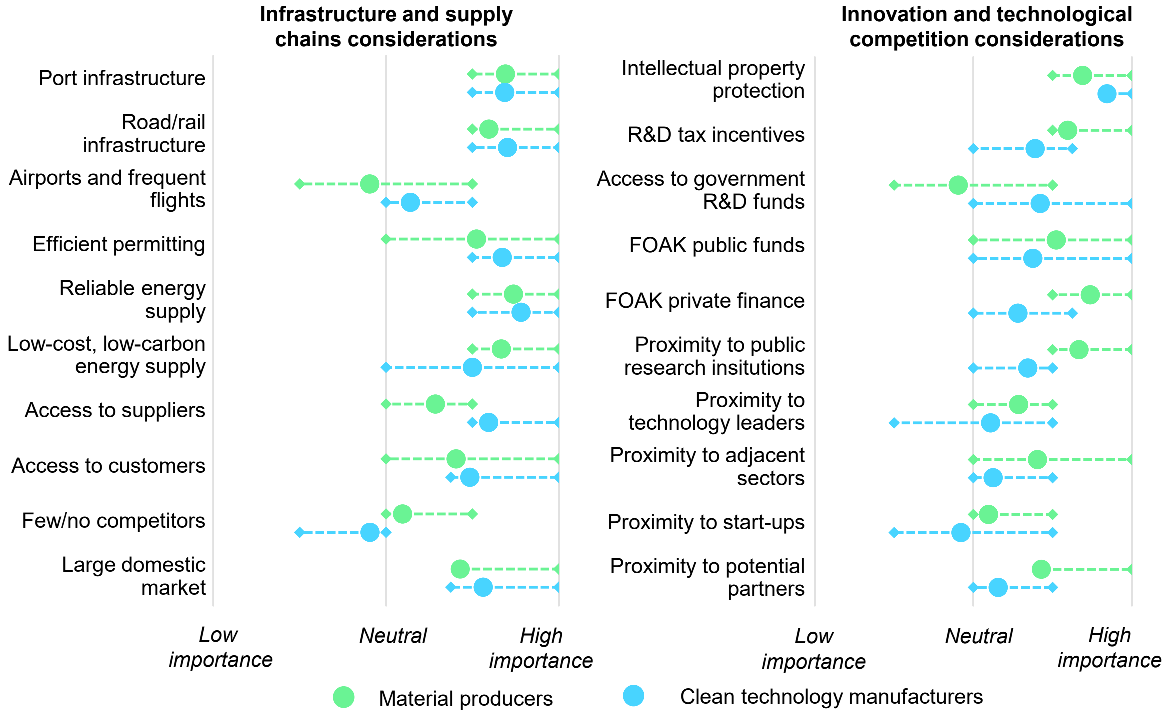
Sources: IEA analysis based on NREL (2017); NREL (2019); NREL (2023); Wood Mackenzie (2024); BNEF (2024a); IEA-PVPS (2024); BNEF (2024b); IEA (2024a); IEA (2024g); Argonne (2024); JETRO (2024); Dai et al. (2019); and Frith, Lacey, & Ulissi, (2023).

Manufacturing solar PV modules using domestically produced components costs around twice as much as using imported components in the European Union.

Other factors influencing competitiveness

While cost competitiveness is, in most cases, the main factor driving decisions to invest in manufacturing of clean energy technologies and associated materials, a number of other factors can also have a major influence. This includes non-cost factors such as good transport infrastructure, access to reliable and affordable energy supplies, and access to both markets and suppliers. The results of the IEA survey of manufacturers indicate that (Figure 1.30) these factors are all critical. In this section, we focus on two of the most important factors: domestic market size, and the existing industrial base in a country. In reality, all these factors both influence and are influenced by broader cost drivers, so understanding their relative importance can be difficult.

Figure 1.30 IEA industry survey of the importance of selected considerations for investment decisions on manufacturing



Notes: FOAK = First of a kind. Notes: Circles show the average score on an importance scale for each subset of respondents with the dashed lines showing the inter-quartile range of respondent scores.
Source: IEA analysis based on survey data gathered from 50 companies (see Box 1.4).

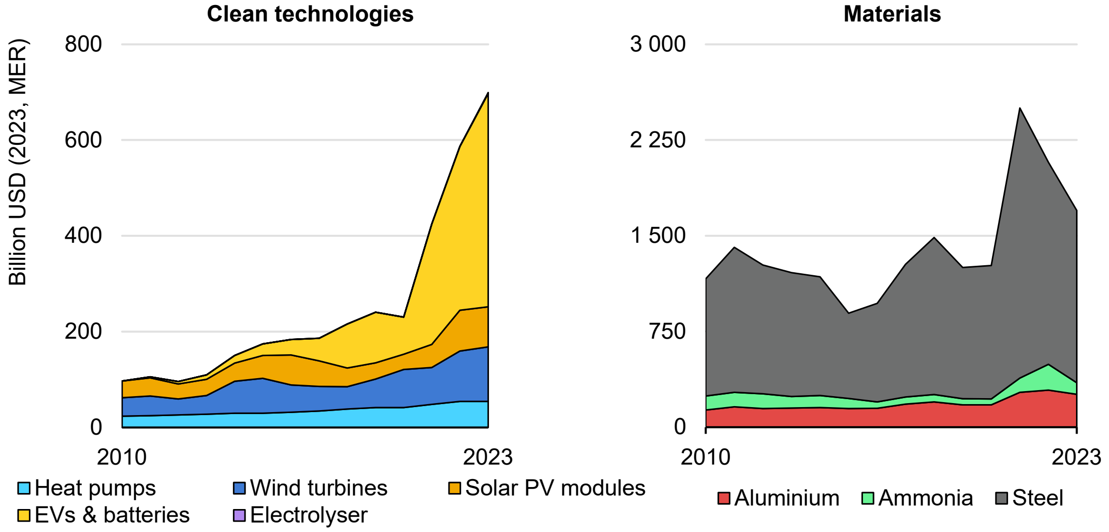
Transport infrastructure, access to reliable and affordable energy supplies, and access to both customers and suppliers are critical drivers of investment in supply chains.

Domestic market size

The size of the domestic market for any given product is important as local markets are easier to access physically, leading to lower transport costs relative to supply from another country. They are also less vulnerable to changes in trading arrangements between countries. Feedback loops between the final customer and producer can be shorter and more direct, enabling products to be tailored to consumer needs. The markets for all the main clean energy technologies have been growing strongly over the past decade, though they still remain smaller, in absolute terms, than heavy industrial sectors like steel. The combined global market size of key clean technologies has nonetheless surpassed that of aluminium or ammonia (Figure 1.31).

The markets for clean energy technologies and materials are interlinked, as increasing demand for technologies increases the demand for materials; for example, increased wind turbine production leads to higher demand for steel, while increased solar PV production boosts demand for aluminium. Similarly, demand for materials can increase demand for clean energy technologies, such as electrolysers to produce hydrogen-based DRI steel, or for solar PV and wind to produce the electricity needed for materials production. Nonetheless, these technologies still account for only a small share of the total demand for materials. For example, aluminium demand related to the production and installation of solar PV accounts for less than 5% of global aluminium demand today.

Figure 1.31 Market size for selected clean energy technologies and associated materials, 2010-2023



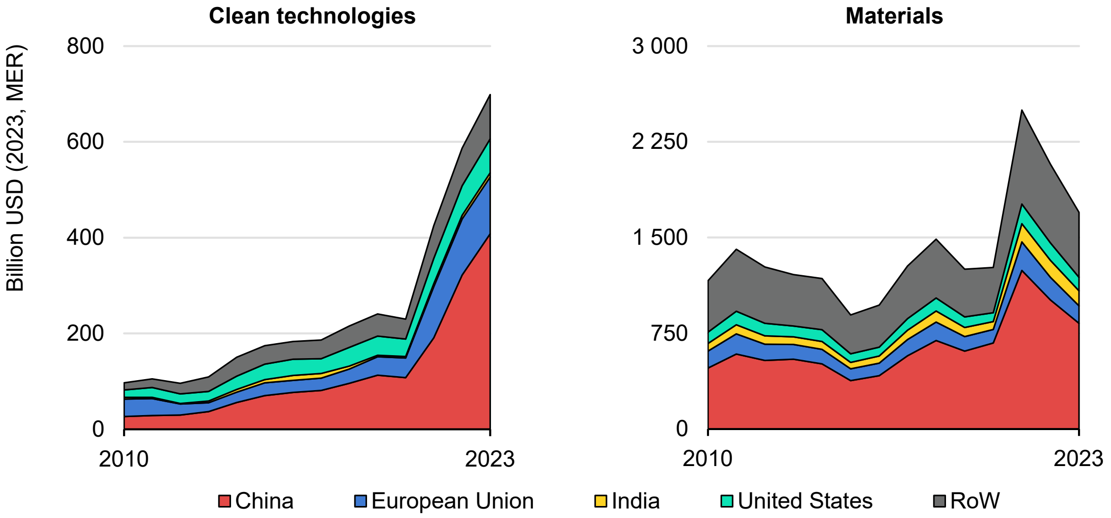
IEA. CC BY 4.0.

Notes: EVs = electric vehicles (including batteries). Heat pumps are residential only. Wind turbines include towers, nacelles and blades. Electrolysers refer to the stack.
Source: IEA analysis based on Bloomberg terminal data.

The markets for clean energy technologies have been growing strongly over the past decade, though they remain smaller compared with heavy industry.

Clean technology markets saw two periods of relative stagnation over the 2010-2013 and 2015-2017 periods, before they soared from 2020 in the wake of the Covid-19 pandemic. The strongest growth in recent years has been in EVs and their batteries, with most of this growth coming from China and advanced economies. More established technologies – solar PV, wind and heat pumps – saw a slowdown in market growth in 2023. For solar PV, this was due to decreasing prices counteracting unprecedented capacity additions. For wind and heat pumps, demand was dampened amidst policy uncertainty and increasing financing costs (IEA, 2024f).

Figure 1.32 Market size for selected clean energy technologies and associated materials by country or region, 2010-2023

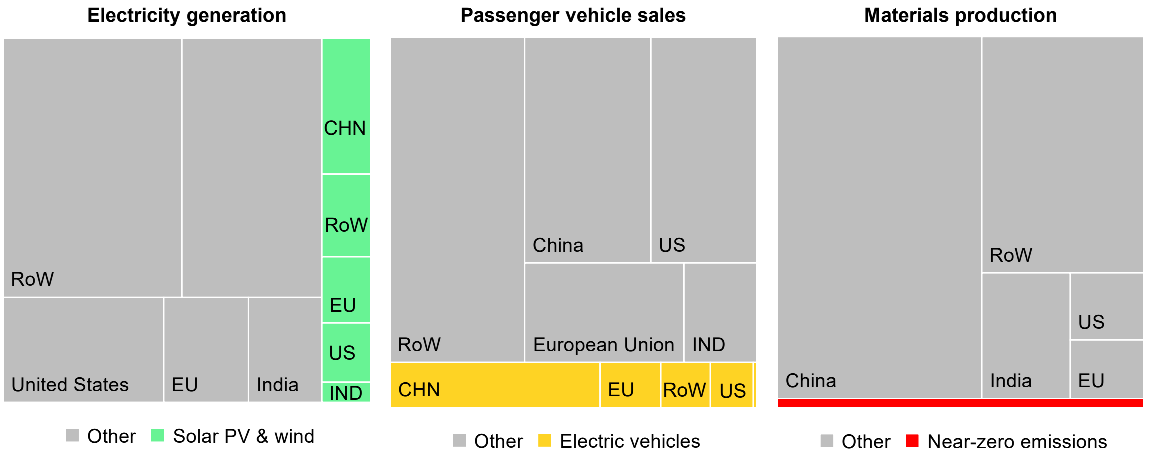


Notes: "RoW" = rest of World. Clean energy technologies include solar PV, batteries, electric vehicles, wind turbines, heat pumps and electrolysers; materials include steel, aluminium and ammonia.
Source: IEA analysis based on Bloomberg terminal data.

The regional distribution of the global market for clean energy technologies has shifted markedly since 2010, with China now the biggest market, ahead of the European Union.

The regional distribution of global demand for clean energy technologies has changed significantly over the last decade or so: Europe was the biggest market in 2010, but has since been surpassed by China (Figure 1.32). Since the mid-2010s, China's capacity has been ahead of Europe's, but growth in China and Europe has remained close in relative terms. In 2023, total sales in China exceeded those in Europe by roughly USD 300 billion, or 250%. Clean energy technologies and near-zero emissions materials production only account for a small share in their wider markets (Figure 1.33). In 2023, solar PV and wind power accounted for just 13% of the global market for power generation equipment, and EVs just 12% of the market for passenger cars. The share of near-zero emissions technologies in the overall production capacity for the three bulk materials is a mere 0.2%. This suggests there is still room for the fast-paced growth of the past decade to continue.

Figure 1.33 Shares of selected clean energy technologies and materials in total market, 2023



IEA. CC BY 4.0.

Notes: CHN = China, EU = European Union, IND = India, RoW = Rest of World, US = United States. Other electricity generation includes electricity generation from fossil sources, nuclear, hydro and biomass. Other passenger vehicle sales include internal combustion engine and hybrid passenger vehicles sales. Materials production includes ammonia, aluminium and steel production.

Clean energy technologies and near-zero emissions materials only take a small share of their respective markets today.

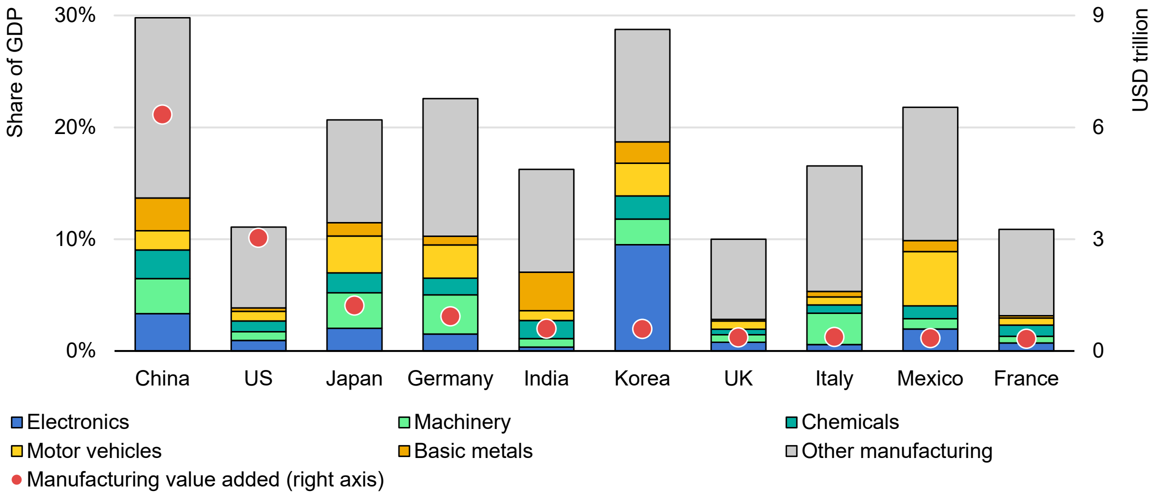
Existing industrial base

The existing industrial base in a country, supported by robust infrastructure, is also a crucial factor in deciding to invest in new manufacturing and materials production facilities. The structure of a country's economic and industrial base is the result of competitive advantages, specialisations, and industrial and trade policies and strategies accrued in the past, as well as its broader history, geography and culture, among other factors. The existence of a strong industrial base gives confidence to investors by reducing perceptions of risk to the financial viability of industrial activities and the adequacy of supporting infrastructure, services and policy. Several advanced economies have developed their industrial bases for more than a century, whereas much of the industrial base in China and some other emerging economies has only existed for a few decades or less.

The clean energy transition provides an opportunity for countries with a strong existing industrial base, backed by supportive government policies, to leverage that advantage in developing new clean technology sectors. In general, the most advanced economies have tended to transform themselves over time to a consumption- and services- driven economic model, while emerging economies, often with lower labour costs, better access to mineral resources, and cheaper energy, have been the primary drivers of industrialisation in recent decades. The share of industry in GDP is particularly high in China, at around 30%. The contribution of manufacturing in advanced economies is generally much lower, ranging from 10% to 17% in France, Italy, the United Kingdom and the United States. But there are major exceptions: Germany, Korea and Japan all have high shares of manufacturing in their value added today, amounting to 20-30% of GDP. There are also signs of reindustrialisation in some countries, notably the United States, where access to cheap natural gas has boosted investment in energy-intensive industrial activities. If effectively implemented, these activities could possibly slow down or reverse the long-standing decline of the share of manufacturing in GDP in the last 20 years.

Among countries with a strong existing industrial base, the composition of manufacturing output varies considerably, with major implications for the attractiveness of investing in clean energy technology manufacturing. In particular, the importance of the automobile industry is a major determinant of opportunities for investing in the manufacturing of EVs, as well as batteries and their components. Although much smaller in absolute terms than in China and some other countries, the contribution of manufacturing of motor vehicles to total economic value added is highest in percentage terms in Mexico, at around 5%, in large part thanks to its competitive cost base and proximity to the large car markets in the United States and Canada, with which it has free trade agreements (FTAs) (Figure 1.34).

Figure 1.34 Sectoral composition of manufacturing value added as a share of GDP for the top ten manufacturing countries, 2023



IEA. CC BY 4.0.

Notes: US = United States, UK = United Kingdom. Manufacturing value added by sector is shown as a share of national GDP (approximated as total value added across the whole economy) for each country.

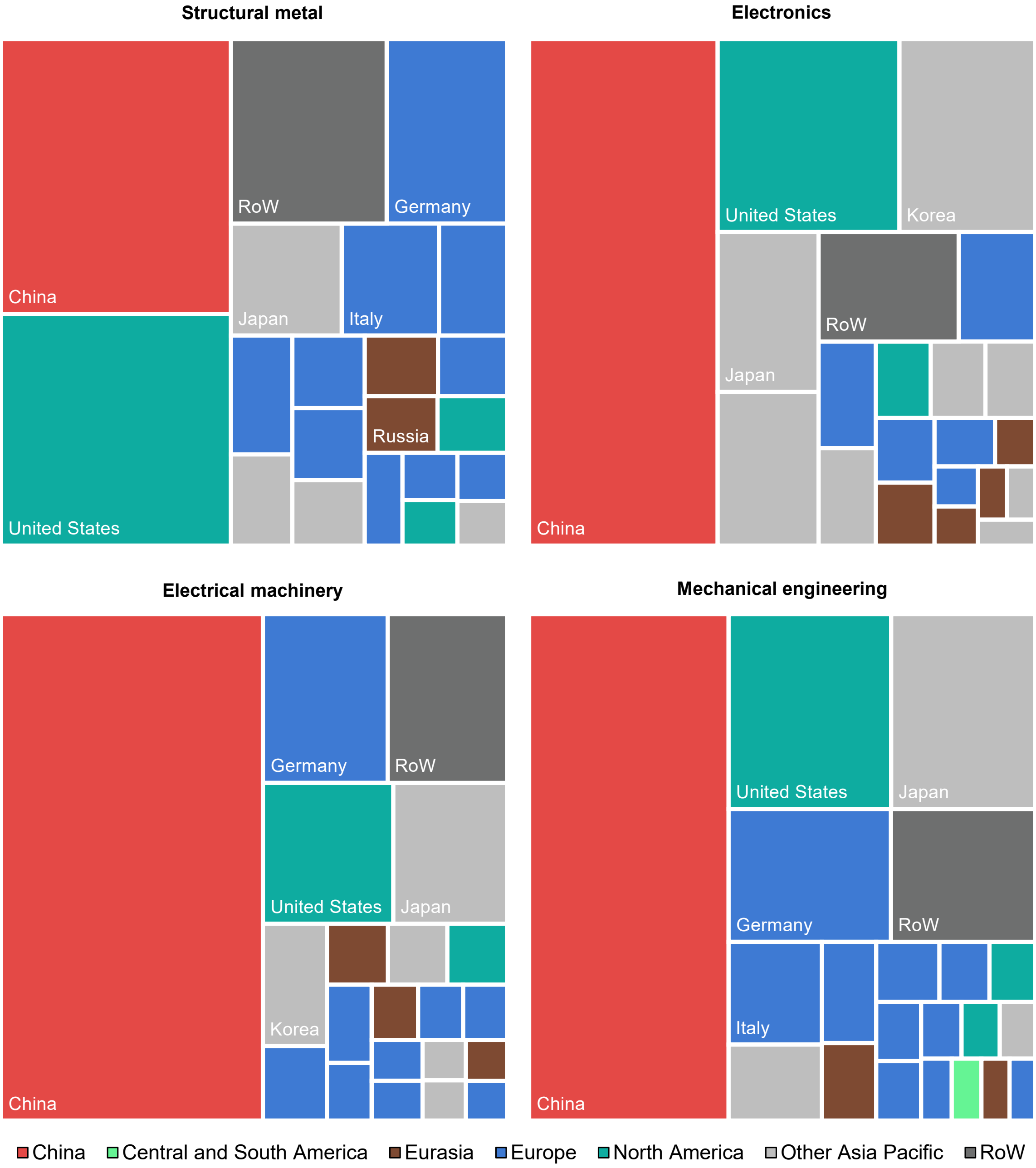
Sources: IEA analysis based on Oxford Economics Limited (2024a).

The composition of manufacturing output varies among the leading industrial nations, with implications for the attractiveness of investing in clean energy technologies.

A strong presence in adjacent manufacturing sectors can also confer an advantage for investing in clean technologies. The electronics industry, which plays a major role in the supply chains of several clean technologies, is an important contributor to China's economy, though the sector's share of GDP is highest in Korea. Similarly, the chemical industry, which provides a wide range of inputs for several clean technologies, is a key source of economic output for China, Korea, Japan, India and Germany. In advanced economies, these industries have usually been built up over several decades, though there are cases of these industries shrinking away. For example, at its zenith, Imperial Chemicals Industries was once the largest manufacturer in the United Kingdom, but the entire chemical industry now accounts for roughly 0.5% of GDP. The reverse is true too, as demonstrated by the rapid emergence of a range of manufacturing industries in China. In 2023, in volume terms, China led in all sub-sectors; European and Asian countries excluding China tended to produce more electrical machinery; Asian countries and North America more electronics; and all three regions were roughly on par for mechanical machinery (Figure 1.35).

While the overall size of the manufacturing sector provides an indication of a country's competitive strength, it does not provide an indication of the quality of its output or the competences and skills of its workforce, as certain industries may be insulated from competition with imports by trade policies or other factors. The role a given sector plays in a country's economy, volumes of exports and metrics of revealed comparative advantage (the relative importance of a product in a country's exports, compared to that product's share in world trade), or RCA, can provide an indication of how well an industry performs in a country compared with the rest of the world. However, such metrics are imperfect, as they include any financial support provided to these industries, which as described below, is often difficult to measure and isolated.

Figure 1.35 Geographic distribution of value added in key sectors of relevance to clean technology manufacturing, 2023

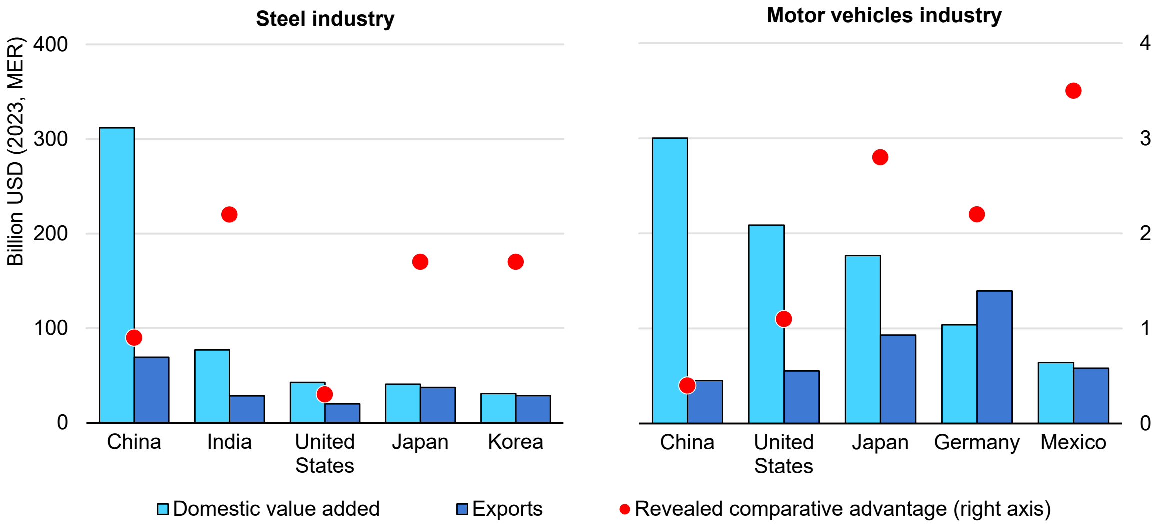


Notes: RoW = Rest of World.
Sources: IEA analysis based on Oxford Economics Limited (2024a).

While China leads in all sub-sectors, other regions all have sizeable industrial activity in either electronics, machinery or structural metal.

This can be demonstrated by contrasting two different but closely inter-related industries – automobile manufacturing and steel production. The top five producer countries each have very different ratios of exports to total domestic value added, and different values of RCA (Figure 1.36). The higher the value of RCA, the more competitive the country's exports (UNCTAD, 2024b). China's very large steel industry is less export-oriented than those of India, Japan and Korea, with the vast majority of the steel it produces being consumed domestically. Despite being the biggest exporter of steel globally, China's steel industry has a substantially lower value of RCA than these countries. The fraction of steel exports in China's total exports is lower than the fraction of steel in total global exports, resulting in an RCA value slightly lower than 1. This implies that steel exports feature less prominently in China's overall exports than the global average, and that its relative comparative advantages lie elsewhere. In contrast, India has the highest RCA value among the top five exporting countries in 2021, signifying that steel plays a more important role in India's total goods exports than it does in global exports. This indicates that at the sectoral level, India's steel industry is more competitive at exporting steel than the global average.

Figure 1.36 Domestic value added and exports for the steel and automobile industries in selected countries, 2021



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Notes: RCA = Revealed Comparative Advantage. The RCA presents the relative importance of a product in a country's exports compared to that product's share in world trade.
Sources: IEA analysis based on Oxford Economics Limited (2024a); UNIDO (2024); UNCTAD (2024b); and CEPII, (2024).

China's motor vehicle manufacturing industry is two to three times larger in value added terms than those in Germany and Japan but is relatively less export-oriented.

For example, Germany and Japan's ICE-dominated automotive industries are highly export-oriented. Even in 2023, when Germany's car industry faced higher input prices as a result of the surge in natural gas prices, the value of its exports was even higher in absolute terms than the domestic value added for the sub-sector. While accounting for a smaller share of global exports, Mexico's automotive sector has an even higher RCA than either Japan's or Germany's in 2021. The automotive sector of all three countries has a much higher RCA than those of the two leading car manufacturing countries globally – China and the United States. These countries' car industries primarily serve their gigantic domestic markets, and are, in some cases, protected from competition with import tariffs. A key difference between the latter two is that China's automotive sector already comprises a much higher share of EVs (35% of cars produced and nearly 40% of sales in 2023) compared with the United States (under 15% and around 10%).

1.4 Industrial strategies and policies

Government policies can have a major impact on the cost competitiveness of firms producing clean energy technologies and materials in different countries and, therefore, the relative attractiveness of investing in them. Part of the regional differences in manufacturing costs described in the previous section are explained by inherent or natural advantages, such as differences in energy costs that stem from differences in geography. Policies, however, including production and deployment incentives, measures to boost innovation, regulatory instruments, carbon pricing, and trade measures, can also play a major role in determining production costs and the attractiveness of investing in any given country (see Figure 1.37).

Industrial strategies, comprised of industrial policies – defined as interventions intended to improve structurally the performance of the business sector – were particularly popular in the aftermath of the Second World War, but began to lose their appeal in the mid-1960s as mainstream economics highlighted distortions caused by government intervention (OECD, 2023a). Despite this shift, industrial strategies never disappeared, though their role became less publicly emphasised. Recent economic crises, heightened geopolitical tensions and the urgent need to accelerate climate action have led to a revival of more explicit and interventionist industrial strategies in both advanced economies and EMDEs.

Governments' energy and climate policies are increasingly intertwined with industrial strategies, and vice versa. In general, they aim to guide capital towards locations and assets in their jurisdictions that would not otherwise receive it. While trade policies are not always considered to be part of industrial strategies, the latter always affect trade.

Figure 1.37 Industrial strategy policy instruments

Direct support to producers

Reduce production costs

Capital costs
- Grants
- Tax breaks
- Concessional finance
- Loan guarantees

Operational costs
- Output-linked financial support
- Discounted energy
- Workforce support

Demand support

Reduce price for consumers
- Purchase grants
- Consumer tax incentives

Guarantee end-user demand
- List of favoured suppliers
- Local content requirements

Innovation support measures

Resource Push
- R&D funding
- Access to research facilities
- Education and training

Knowledge Management
- International and domestic networking
- Intellectual property regimes

Market Pull
- Deployment goals
- Public procurement
- Other demand support (see above)

Socio-political support
- Consensus-building processes
- Public information campaigns

Regulatory instruments

Regulation
- Carbon pricing: carbon tax, emission trading systems (ETS)
- Emission intensity standards
- Energy intensity standards
- Other performance and product quality regulations
- Chemical and material restrictions
- Biodiversity and land use regulations
- Other environmental standards
- Recyclability criteria
- Labour and human rights standards
- Carbon border adjustment mechanisms (CBAM)

Regulatory institutions and enforcement processes
- Standardisation and measurement
- Certification and accreditation for compliance
- Regulatory co-operation with other countries

Trade instruments

Import tariffs and quotas

Non- tariff measures

Export restrictions

WTO and preferential trade agreements (between two or more countries)

General policy environment and other indirect measures

Anti-trust and competition laws

Fiscal and tax policies

Inward investment regime

Labour and workforce policies

Electricity market regulations

Other market rules

Infrastructure planning

Digital and data governance

Industrial strategies comprise a range of measures, including direct support to producers, support to innovation, and regulatory and trade instruments.

Most of the world's major economies have announced industrial strategies focused on manufacturing clean technologies and materials. While some strategies are still aspirational and have yet to be translated into firm policies, others are already being implemented, including in the form of various types of direct financial support, and in many instances with the aim of cultivating or strengthening domestic industries to reduce reliance on imports. The Inflation Reduction Act (IRA) in the United States, the Net-Zero Industry Act (NZIA) as part of the EU Green Deal Industrial Plan and Japan's GX Promotion Strategy are recent examples of different types of industrial strategies (see Table 1.1). Other countries, including China, have long-established mechanisms for industrial policy support for clean energy technologies, and specific targets for their outcomes.

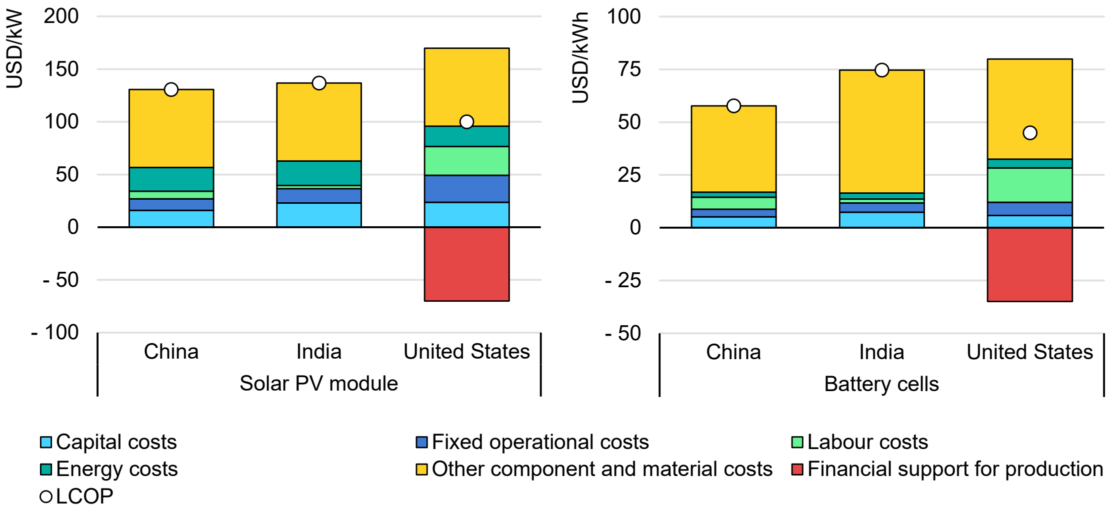
Table 1.1 Selected industrial strategies and policy packages targeting clean energy technologies or materials manufacturing

Jurisdiction	Name	Prominent features for manufacturing
United States	Inflation Reduction Act (IRA)	Provides financial support including investment and production tax credits and grants for clean energy technology manufacturing and industrial decarbonisation, including requirements for domestic value additions.
European Union	Net-Zero Industry Act (NZIA)	Sets manufacturing capacity targets for clean energy technologies and their components, promotes resilience through supply diversification, implements more efficient administrative and permitting processes, and supports innovation through regulatory sandboxes. It does not include direct financial support but aims to facilitate faster access to finance.
Japan	GX Promotion Strategy	Aims to promote a stable energy supply and decarbonise the energy sector while maintaining economic growth, including through carbon pricing. Sovereign Japan Climate Transition Bonds will be issued over the next decade, to be repaid with revenues from carbon pricing.
Canada	A Made-in-Canada Plan	Provides economic investment tax credits across a range of technologies to support the transition to net zero, including CCUS, clean technology adoption, clean hydrogen, clean technology manufacturing and clean electricity. In addition, the 2024 budget provides tax credits for EV supply chains.
China	14th Five Year Plan 2021-2025	China has a "dual circulation" strategy aimed at reducing reliance on exports for economic growth by boosting domestic consumption, while maintaining its participation in the global economy, particularly through the Belt and Road Initiative. China's 14th Five Year Plan targets clean energy as one of the key areas for competitive funding.
India	Make in India	Aims to transform India into a global manufacturing hub, reducing imports and creating opportunities for export-led growth. To support these goals, production-linked incentive (PLI) schemes have been introduced, including for clean energy technology manufacturing.

Jurisdiction	Name	Prominent features for manufacturing
Korea	Industrial Supply Chain 3050 Strategy	Aims to reduce the import dependence on a single country to 50% by 2030 for 185 key goods, including batteries and cathode and anode materials, vehicles, silicon wafers and urea. A range of incentives are being considered.
Australia	Future Made in Australia Act	Aims to boost clean energy technology manufacturing and industrial decarbonisation, including through tax incentives and streamlined approvals to accelerate projects in strategic critical minerals, hydrogen and clean energy manufacturing.
South Africa	Just Energy Transition (JET)	Aims to achieve the country's decarbonisation goals, while boosting upstream manufacturing, localising clean energy value chains and creating jobs.
Brazil	Nova Indústria Brasil	Aims to promote industrialisation through various missions, including one on energy transition. It features a prominent role for the Brazilian Development Bank (BNDES) and the Innovation Agency (FINEP), including mechanisms such as public procurement and local content requirements.
Malaysia	New Industrial Master Plan 2030	Aims to bolster the manufacturing sector, targeting among other sectors, advanced materials, EVs, renewable energy and CCUS. The plan sets a target of 6.5% annual growth in the manufacturing sector.
Saudi Arabia	Vision 2030	Aims to diversify the economy and reduce domestic dependence on oil, with a target to increase non-oil exports from 16% to 50% in non-oil GDP. It includes initiatives such as the "Made in Saudi" programme, which aims to boost the competitiveness of locally made products.
Kazakhstan	Third Modernization of Kazakhstan: Global Competitiveness	Aims to transform Kazakhstan into one of the top 30 most developed countries by 2050. With respect to manufacturing, this includes promoting advanced technological integration, increasing productivity and enhancing global competitiveness by leveraging innovation and new technologies.

Recently introduced financial support schemes for the manufacturing of clean energy technologies under the IRA in the United States and the PLI scheme in India are significantly changing the relative cost of production between countries. For example, the LCOP for solar PV modules is lowest in China, when explicit financial support measures are excluded (see previous section). However, if financial support such as the US 45X advanced manufacturing production credit of USD 70/kW for manufacturing solar PV modules is included, the LCOP in the United States would be around USD 100/kW – lower than in China or India (Figure 1.38). The picture is similar for battery cells.

Figure 1.38 Impact of Inflation Reduction Act financial support for production on the manufacturing cost of solar PV modules and battery cells, 2025



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Notes: LCOP = levelised cost of production. Embedded financial support for energy inputs and other cost components, including access to cheaper finance, which may be present in the different cost components, are not explicitly included as financial support elements in this analysis. The disaggregated costs of capital, fixed operational costs, labour and energy also include the disaggregated costs of producing the main components of the solar PV module supply chain, which include polysilicon, wafers and cells. Battery cells uses the 2023 world capacity-weighted battery chemistry.
USD = USD (2023, MER).

The IRA's production tax credits for solar PV modules and battery cells make technologies manufactured in the United States competitive with those made in China.

As capital costs represent a relatively small proportion of the LCOP of clean energy technologies when factories are utilised intensively (see section on cost competitiveness above), financial support for investment would have a smaller impact on the LCOP than that for production. In practice, however, access to financial support for investment, often topped up by regional governments, may influence the location of production facilities, including within a country, particularly when access to finance is a constraint. This is particularly important for smaller, emerging companies, such as clean technology start-ups, which tend to incur higher risk premiums than established companies for private investors.

Given that financial support for production can quickly mount up and have a significant impact on a country's budget, measures need to be carefully designed to avoid wasteful overspending and economic rents for firms (OECD, 2023b). In addition, overly generous financial support can lead to short-term investment booms, but there is a risk that production facilities close one the support is withdrawn, if the support is not well-aligned with future domestic market needs and export potential. In the absence of sustained demand, companies dependent on subsidies may struggle to remain in business.

Direct support to producers

Direct industrial policy support comprises various mechanisms such as direct financial transfers, tax incentives, risk-sharing initiatives, demand-side support and innovation incentives (Table 1.2). These measures can be combined to encourage investment in production capacity or to attract investment to specific regions within a country. Most of these measures aim to reduce consumer prices by offsetting some of the costs faced by producers, by shifting part of these costs to the government, but there are exceptions. In regions with high input costs, such as energy or materials, reducing capital costs alone may not be sufficient to make production competitive, and a broader policy framework may be needed. Demand guarantees or restrictions on foreign competition can help to establish emerging industries, but can actually lead to higher prices if they are maintained over extended periods of time without clear performance criteria.

Table 1.2 Forms of direct support to producers that can be components of industrial strategies

Aim of measure	Impact	Examples of policy tools
Reduce manufacturers' capital costs	By funding or otherwise bearing some of the capital costs, governments lower the costs of production faced by producers, allowing them to offer consumers lower prices.	Grants, investment tax incentives, concessional finance (debt or equity), loan guarantees, below-market rates for land or other assets, export controls on key production inputs.
Reduce manufacturers' operational costs	By funding or otherwise bearing some of the operational costs, governments lower the costs of production faced by producers. Governments can also pay producers based on their output, allowing producers to offer consumers lower prices.	Production tax incentives, output or performance-linked payments (including contracts-for-difference), public procurement, below-market prices for energy inputs or other utilities, financial support to workers, labour tax incentives.
Reduce prices for consumers	By offering financial support to consumers, the effective price is at a lower level than would be expected given producers' costs, raising demand. Support can sometimes be restricted to a subset of products, such as those from domestic producers or producers in an FTA region.	Purchase grants (including rebates), consumer tax incentives.
Guarantee or bolster end-user demand	In exceptional cases, governments could restrict competition by allowing a producer a monopoly (or oligopoly) position in a domestic market, for example for a time-limited period. In nascent industries, governments may choose to favour domestic suppliers through regulation.	Lists of regulated favoured suppliers, local content requirements.

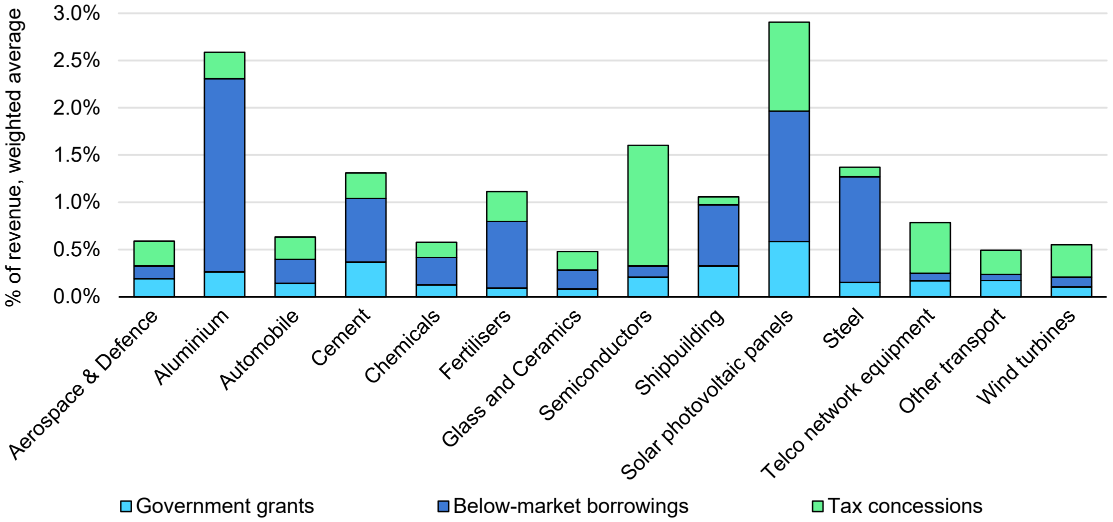
Aim of measure	Impact	Examples of policy tools
Boost longer-term competitiveness through innovation	Supporting innovation in manufacturing and product design raises the probability of cheaper output that allows producers to offer lower prices, or higher quality products that raise demand.	R&D, demonstration and entrepreneurship grants, venture equity and debt, access to public laboratories and other facilities, support to knowledge networks, R&D tax incentives, R&D loans, prizes, loan guarantees to demonstration projects, regulatory sandboxes, intellectual property protection.

Evaluating production costs exclusive of any financial support is difficult because the benefit conferred on producers by the various measures can be hard to quantify. Assessing the benefit conferred by grants, where they are declared or revealed, is much easier than for tax incentives and discounted finance. This is because a counterfactual or benchmark is required to evaluate what the costs would have been without the financial support. In the case of the costs of capital, the appropriate benchmark can differ across firms or projects, even within the same sector or country. For example, a large firm with low levels of debt might be able to secure a lower interest rate on a new loan than a smaller, more indebted one, which creates a range of benchmark values. The benefits of equity finance at lower than market rates of returns are particularly hard to quantify as judgements about the investor appetite for companies receiving government equity are required.

Financial statements can sometimes reveal ex-post the benefits of a given support measure or combinations thereof. Despite the lag between the time when a government support measure is announced or implemented and the time at which the financial statements of a company are published, this type of analysis has the benefit of being able to capture the actual impact for the firms that receive the support, including that provided by federal, provincial and municipal governments. In practice, company financial information is not always available for non-listed firms and gathering it can be resource-intensive, so sampling may need to be used, which can lead to doubts about the representativeness of the sample. In addition, the interactions between different financial support measures and trade policy measures make analysis even more complicated.

Such analysis has been undertaken by the OECD for the solar PV and wind turbine manufacturing industries, showing that financial support is already relatively high compared with other sectors (Figure 1.39). Worldwide, tax concessions in the solar PV industry were estimated to have amounted on average to more than 0.9% of revenues over the period 2005-22 – the highest share of any major manufacturing sector besides semiconductors – government grants for almost 0.6%, and below-market borrowing for almost 1.4% over the period 2005-22. Total support to the wind turbine industry amounted to almost 0.6% of revenues, more than 60% of which was in the form of tax concessions.

Figure 1.39 Estimated rate of financial support provided by governments across selected manufacturing sub-sectors, 2005-2022



Notes: Data are expressed relative to the sales revenue of the firms covered in the study over the period 2005-22.
Source: OECD, (2024c).

Solar PV and aluminium manufacturing are estimated to be among the sub-sectors that have received the highest rate of financial support in the past two decades.

The estimates of overall financial support to firms in the form of government grants, below-market borrowing and tax concessions suggest that they amount to around 0.5-3% of total corporate revenue. While these figures may sound low, earnings after tax in manufacturing operations often represent a small share of total revenue (low single digit percentages are not uncommon) for these low-margin, high-volume businesses. In practice, this support can have a significant impact on a firm’s financial performance and its ability to raise money and/or make subsequent investments; in some cases, it could determine whether the firm makes a profit or not. Furthermore, some of the industries examined have gigantic revenues globally. The steel industry for example produces around 2 billion tonnes of steel globally. Assuming an average market price of USD 730/tonne for semi-finished products, this equates to global revenue of almost USD 1.5 trillion, meaning single digit percentages could equate to tens of billions of government support or foregone tax revenue.

While nearly all governments provide support to their manufacturing industries in one form or another, the OECD finds that firms in China receive more support overall than firms based in other jurisdictions covered in the analysis. Grants and below-market borrowings make up an estimated 3% of the revenues of firms based in China, compared with less than 0.2% in OECD countries 0.6% for India-based firms, and 0.5% for firms based in the other jurisdictions covered over the period 2005-22.

Regulatory instruments

Regulations are a key component of industrial strategies: they help direct investment towards certain types or qualities of goods and can favour the producers who make them. They typically include, but are not limited to, environmental regulations to minimise emissions, energy and other resource consumption and waste, such as vehicle emission standards or energy efficiency standards for appliances and equipment; performance regulations to ensure that products meet specific quality, safety and durability criteria; and labour and safety regulations to protect workers' rights and conditions, such as compliance with the International Labour Organization (ILO) Convention on child and forced labour or the European Union's Corporate Sustainability Due Diligence Directive, which is of particular concern for critical minerals. While regulations are essential to ensure safety, environmental sustainability and quality, they can create barriers to market entry, distort competition and hinder international trade if they are not harmonised or if they are applied unevenly across regions.

Quality and safety standard-setting, product specifications and benchmarking metrics, conformity assessments, and the associated certification and accreditation processes are sometimes referred to as “quality infrastructure”.[8] These instruments, especially standards, promote innovation by providing a framework for sharing industry knowledge, reducing transaction costs by limiting the number of product variants, ensuring compatibility and increasing consumer confidence. They are particularly important for scaling up market-ready technologies and supporting innovation by enabling more focused R&D. While industry typically takes the lead in setting standards, governments and regulators have a critical role to play in co-ordinating, streamlining and reducing the length and complexity of certification and approval systems.

The effectiveness of standards is maximised when they are harmonised locally, regionally and internationally, as this reduces technical barriers to trade and promotes technology spillovers across regions. However, standardisation policies must be carefully designed to maintain flexibility, as overly rigid standards can inadvertently become regulatory barriers and slow down innovation. International

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[8] In this context, the term refers to the regulatory and institutional infrastructure that assures quality, and is unrelated to other uses that refer to the quality of physical infrastructure, such as transport or electricity sectors assets. The International Network of Quality Infrastructure defines it as “the system comprising the organisations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety and environmental soundness of goods, services and processes”.

standard-setting processes also need to engage with less mature markets to facilitate trade with these regions and ensure wider participation in the development of new technologies. International standards are largely developed and published by the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the International Telecommunications Union (ITU) through a consensus process based on the principles set by the World Trade Organization (WTO)’s Technical Barriers to Trade (TBT) committee. The WTO TBT Agreement promotes the use of international standards by its member countries and provides a framework for the adoption of these standards to ensure that they do not create unnecessary barriers to trade.

Carbon pricing – through emissions trading or taxation – acts as both a regulatory and a financial incentive, depending on its design.[9] By assigning a cost to GHG emissions, it favours producers of less emissions-intensive goods and encourages other manufacturers to adopt cleaner processes and technologies. Many countries and jurisdictions have introduced carbon pricing, though the form of pricing and level of prices vary. Carbon pricing can have a significant impact on the cost competitiveness of materials produced using near-zero emissions technologies compared with those based on fossil energy. The impact can also change the relative competitiveness of manufacturers of clean energy technologies. By putting a cost on carbon emissions, cleaner technologies become comparatively cheaper, encouraging their deployment.

Carbon pricing, if well-designed, can be an economically efficient means of encouraging investment in clean energy technologies and discouraging fossil fuel use. However, for the jurisdictions introducing the measure, it is not without risk: Differences in carbon pricing between regions can lead to competitive imbalances, with industries in countries with stricter carbon pricing facing higher costs than those in regions with weaker regulations. In addition, by raising production costs, carbon penalties can render domestic manufacturing uncompetitive, leading to site closures and job losses.

The sensitivity of production costs to carbon penalties varies between the three main emissions-intensive commodities considered in this *ETP* and the method of production. Traditional production processes for steel, aluminium and ammonia result in substantial carbon emissions, emitting almost 40% of the world’s industrial CO_2 emissions (around 10% of total energy system CO_2 emissions). If a steel plant equipped with best available technology today, with direct

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[9] Cap-and-trade systems act more as performance-based regulations, especially where benchmarking and free allowances are used, while taxation is more of a purely financial incentive to favour less-emissions-intensive producers.

CO_2 emissions of 1.5 tonnes of CO_2 per tonne of steel, were subject to a CO_2 price of USD 75 per tonne of CO_2, this would increase the cost of production by USD 110 per tonne of steel, or around one-fifth.

There are also potential risks that if is not applied uniformly between trading jurisdictions, carbon pricing may result in so-called "carbon leakage", i.e. industries in countries without carbon pricing may continue to produce using conventional, high-emitting technologies, at lower cost, leading to greater trade of cheaper but also potentially more polluting materials, thereby possibly even leading to higher global emissions. As one means of addressing such concerns, carbon border adjustment mechanisms (CBAMs) have been proposed. CBAMs impose a cost on imported products based on the carbon content of their production and the difference in carbon prices between the exporting and importing countries for selected sectors, ensuring that domestic industries are not disadvantaged by foreign ones with lower or no emissions penalty. For example, the European Union's CBAM, which is expected to enter its definitive phase from 2026, would cover some GHG emissions embodied in imports of cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. It aims to incentivise other countries to take action to reduce their emissions or put a price on them to avoid tariffs on their exports. However, the implementation of CBAMs could be administratively complex and could lead to trade disputes. In addition, some experts have raised concerns about the risk of EU member states simply importing more finished products made with those materials, or intermediary goods, such as alumina instead of aluminium, which will not be subject to the CBAM, at least initially.

In 2023, the WTO announced the launch of a task force on global carbon pricing to ensure that plans to tax imports based on their carbon emissions do not penalise developing countries (Reuters, 2023). Some countries are calling for the Paris Agreement "principle of common but differentiated responsibilities" to promote international co-operation on carbon taxation.

Trade policy instruments

Trade policy instruments can have a big impact on the cost of trading manufactured goods,[10] including clean energy technologies, with far-reaching repercussions for the volume and pattern of international trade. High trade costs associated with the use of policy instruments designed to regulate trade flows can reduce or eliminate the potential comparative advantage of products from certain regions, making their exports uncompetitive with others. While they can protect

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[10] The trade cost refers to the costs that the trader incurs when moving a manufactured product from one country to another. Several aspects will impact trade costs, besides transport cost, such as trade policy barriers, costs to comply with foreign regulations, communication costs, etc.

domestic industries from overseas competition, with the potential to boost domestic production of clean technologies, they may also slow the deployment of those technologies, hold back the clean energy transition and raise costs to consumers and businesses. Policy makers, therefore, need to pay careful attention to the implications of trade policies for the clean energy transition, industrial development and economic growth.

The multilateral trade system today is governed by the WTO, guided by rules set out in its agreements (Box 1.6). While the principle of non-discrimination among trading partners is central, the WTO rules also authorise members to establish preferential trade agreements (PTAs), with provisions that apply exclusively to goods and services traded within the group of participating jurisdictions. PTAs are increasingly prevalent and the share of trade they cover is expanding. Examples include FTAs, like the United States-Mexico-Canada Agreement (USMCA) or the European Union’s customs union. PTAs are often reciprocal and may entail substantive legislative and institutional reforms beyond WTO requirements. The mechanisms for enforcement can be more expedient than those presently available in the multilateral context, such as the WTO’s Appellate Body. Consequently, they have become an important driver of globalisation and economic development (Dadush & Dominguez Prost, 2023), but they present a risk of regionalisation of markets and standards, as each agreement only applies to a subset of countries.

Box 1.6 World Trade Organization (WTO) trade rules

The rules guiding WTO governance of multilateral trade are laid out in agreements negotiated and signed by the bulk of world’s trading nations. The core components of the agreements are as follows:

Principles of exchange of goods, services and intellectual property

1.Trade without discrimination: This covers two main rules of the WTO:

- Most Favoured Nation (MFN) Treatment: WTO members must treat all trading partners equally. If a country grants trade advantages, such as lower tariffs, to one member, it must extend the same treatment to all other WTO members.
- National Treatment: Imported goods and services are treated equally to those produced locally once they have entered the market.

2. Predictability through binding commitments and transparency: WTO members commit to tariff binding at certain levels and agree not to raise them above those levels without negotiating with other trading partners to compensate for any loss of

trade. They must also publish their trade rules, maintain clear communication and notify the WTO of any changes in trade policy.

3. Freer trade gradually, through negotiation: WTO facilitates negotiations on the reduction of tariff and non-tariff measures across its member countries to support freer trade.

4. Promoting fair competition: WTO rules on MFN and national treatment, anti-dumping, subsidies and countervailing measures are designed to promote fairness in trade.

5. Special and differential treatment provisions: This gives special rights to developing countries and allows developed countries to treat developing countries more favourably than other WTO members. These include, for example, longer implementation periods and technical assistance.

Dispute Settlement Mechanism

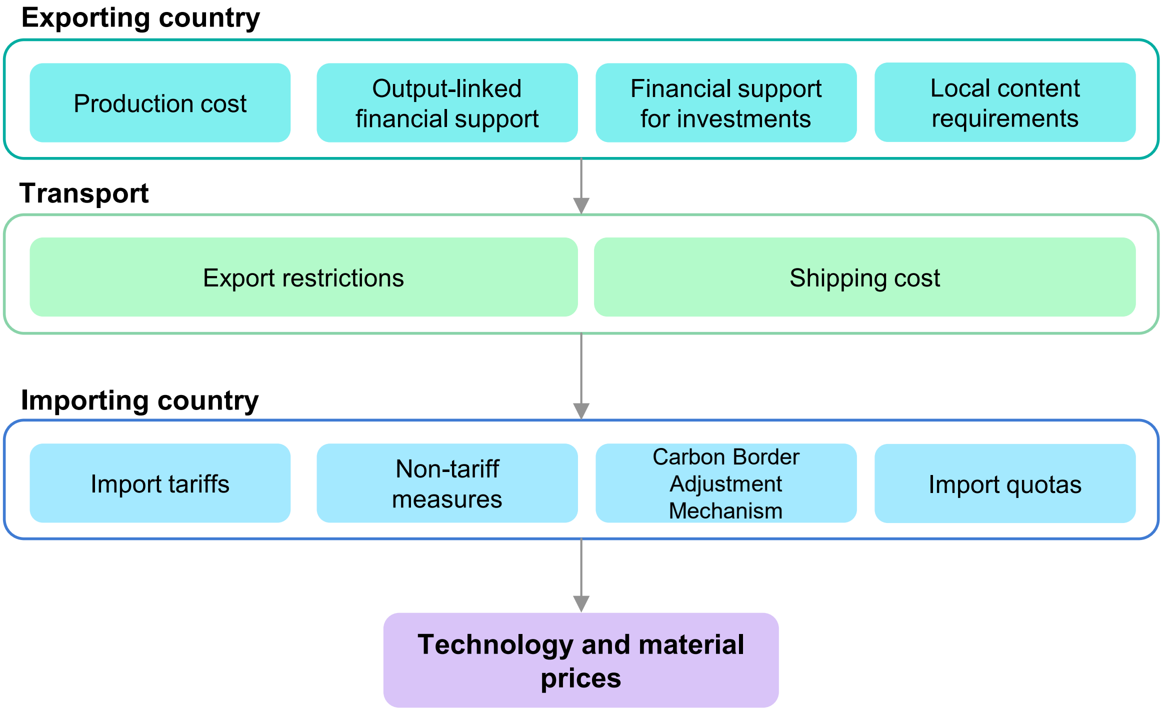
The WTO is responsible for enforcing the rules of trade established in the agreements and for resolving any conflicts associated with it. It provides a formal process for resolving trade disputes between countries based on WTO rules rather than through unilateral actions.

Trade Monitoring

All WTO members are subject to periodic reviews, which include reports from both the member country and the WTO Secretariat. Additionally, the WTO conducts regular monitoring of global trade measures. Members are also required to notify the WTO about laws in force and measures adopted.

Trade liberalisation aims to lower trade barriers. At the multilateral level, discussions have long been underway on the potential for reducing tariffs on environmental goods in order to lower the cost of renewable energy production, though no formal agreement has yet been reached (WTO, 2024a). In 2020, 50 members of the WTO launched the Trade and Environmental Sustainability Structured Discussions initiative with a view to launching dedicated discussions on “how trade-related climate measures and policies can best contribute to climate and environmental goals and commitments while being consistent with WTO rules and principles” and exploring opportunities for “promoting and facilitating trade in environmental goods and services to meet environmental and climate goals, including through addressing supply chain, technical and regulatory elements” (WTO, 2023a).

Figure 1.40 Key factors influencing the trade of manufactured goods



Notes: The figure does not illustrate profit margins. While non-tariff measures may be imposed by the importing country, costs can be incurred in both the exporting and the importing countries. The exporting country can also impose some non-tariff measures. Export restrictions include tax and volume-based restrictions, as well as export licensing.

The prices and quantities of traded goods are influenced by a wide range of industrial and trade policies that affect their competitiveness in the global marketplace.

Explicit trade policy instruments include export taxes and restrictions on exported volumes, import tariffs, and NTMs such as quantity restrictions (quotas), and various types of technical barriers (Figure 1.40). These measures affect the costs of manufacturing and resulting prices in different ways (Table 1.3). Unlike direct financial support to producers, trade policy measures generally raise consumer prices relative to a scenario without intervention, passing on part of the higher domestic production costs to consumers rather than to the government. However, these price effects can sometimes be justified by policy objectives such as supporting employment or promoting nascent industries.

Table 1.3 Trade policy measures that can be components of industrial strategies

Mode of action	Typical initial reallocation of capital	Measures
Raise the cost of imports	By adding costs for importers, the prices they can offer to consumers rise and higher-cost domestic producers become more competitive.	Import tariffs, NTMs (including costly compliance with local standards and testing), carbon border adjustments.
Exclude certain imports from the market	By restricting access to the market for imports, higher-cost domestic producers are at less risk of being undercut by lower-priced goods, which can help to secure domestic demand for their output.	Import bans, import quotas, local content requirements (including for local labour input).

Notes: NTMs = non-tariff measures. Export restrictions, as applied to manufacturing inputs, and which could lower domestic prices while raising international prices, are included in Table 1.2 as a means of lowering operational costs.

Import tariffs – customs duties levied on imported products[11] – are a widely used measure to influence international trade. They raise fiscal revenues and protect local industries from foreign competition. Tariffs are sometimes used to influence trade relationships and negotiations, including to retaliate against trade practices that are perceived to be unfair. After decades of steady decline in the use of tariffs following the implementation of the General Agreement on Tariffs and Trade Uruguay Round Agreement in 1995, and the negotiation of various PTAs, the use of tariffs has recently grown.

Tariffs often result in higher prices for final consumers. If a tariff is imposed on clean energy technologies without additional action to boost the competitiveness of domestic production, it may simply increase their cost to consumers, which risks slowing their deployment (IISD, 2021). Import tariffs on most clean energy technologies and associated materials have risen in recent years, though they have fallen in some cases since 2021 (Figure 1.41). On a global weighted average basis, tariffs on clean energy technologies were highest for EVs, at around 9%, in 2023. Tariffs on the other main technologies ranged from 4% for wind nacelles and heat pumps to more than 6% on battery cells and solar PV modules. Global weighted average tariffs on aluminium, steel and nitrogen-based fertilisers were below 6%.

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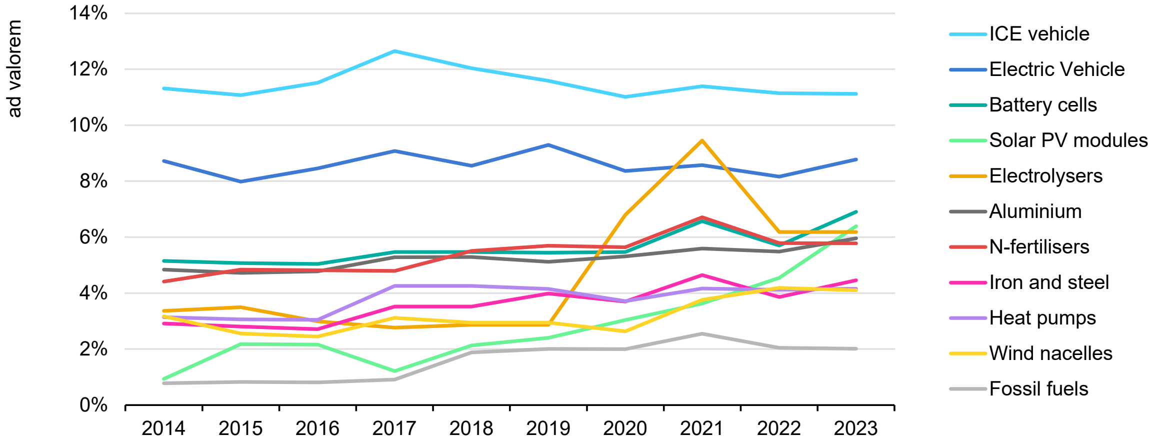
[11] There are four main types of tariffs: ad valorem tariffs, which are calculated as a percentage of the value of the product; specific tariffs, which are calculated on the basis of the physical quantity of the imported good; compound tariffs, which combine both ad valorem and specific tariffs; and tariff rate quotas, which apply lower tariff rates to imports within a certain quantity and higher rates to imports above that quantity.

Figure 1.41 Weighted average global import tariffs on selected energy technologies and related materials



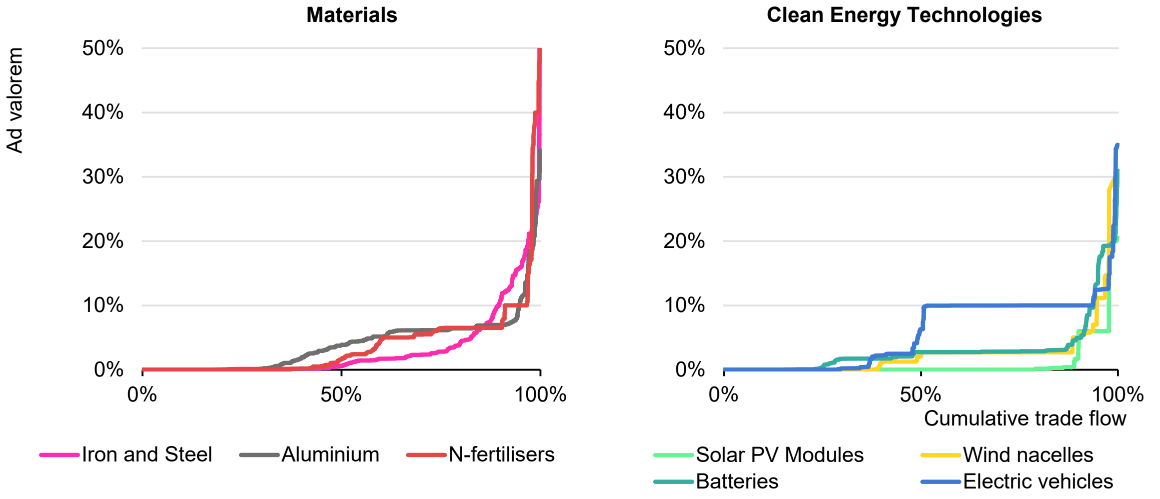
Notes: ICE vehicle = Internal combustion engine vehicle; N-fertilisers = nitrogen-based fertilisers. Specific tariffs are not included. Bilateral ad valorem import tariffs at the HS6 digit-level are aggregated weighted by the actual trade volumes in monetary terms. Tariffs for aluminium and iron and steel reflect those for trade in finished and semi-finished products.

Source: IEA analyses based on WTO (2024b); and CEPII (2024).

Weighted average global import tariffs for the leading clean energy technologies and materials are below 10%, with the highest tariffs levied on vehicles.

Nearly 90% of the trade of solar PV modules, 50% of wind nacelles and 30% of batteries had a tariff that was set at, or close to zero in 2022, but a growing share of global trade is being subjected to higher tariffs (Figure 1.42). Among the advanced economies, average tariff levels generally declined from roughly 4.5% in the mid-1990s to about 2% in 2015 (IMF, 2022), contributing to an increase in trade. However, for clean energy technologies and materials, this trend has already reversed, with a sharp increase in bilateral tariffs in some cases. On average, import tariffs on clean energy technologies in emerging economies are several times higher than those in advanced economies, increasing the cost of imported clean energy technologies (UNCTAD, 2022). In instances where they are imposed and trade is maintained, tariffs can have a significant impact on the final costs for consumers. For example, a 100% tariff on solar PV modules today would cancel out the decline in technology costs seen over the past five years. The knock-on impact on electricity generation costs using the panel would likely be small though, as the solar PV modules themselves make up just 20-30% the total installation cost of the power plant.

Figure 1.42 Ad valorem tariffs applied to the global trade flows of selected materials and clean energy technologies, 2022



IEA. CC BY 4.0.

Notes: N-fertilisers = nitrogen-based fertilisers. Specific tariffs are not included. The cumulative trade flow is calculated over trade value and the maximum cumulative trade flow represented in the Figure is 99.8%. Tariffs for aluminium and iron and steel reflect those for trade in finished and semi-finished products.

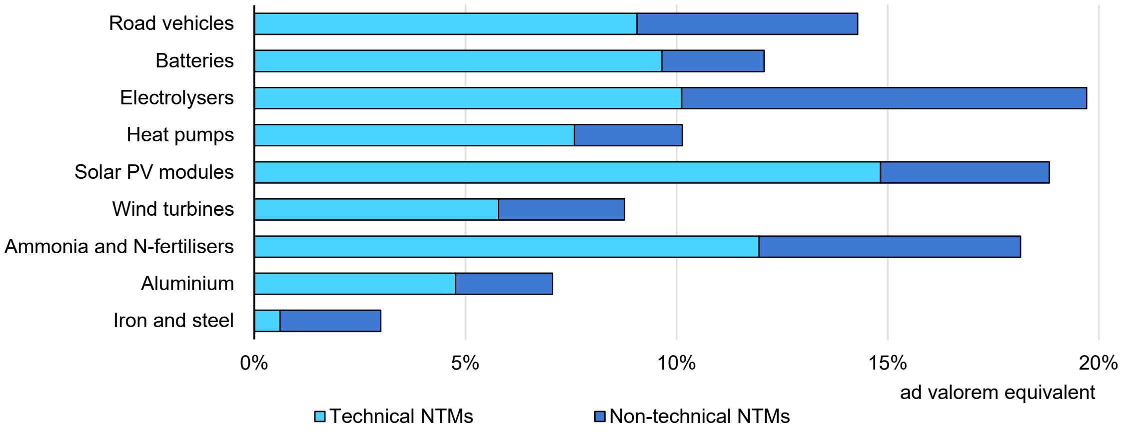
Source: IEA analyses based on WTO (2024b); and CEPII (2024).

Most trade is subject to ad valorem tariffs of less than 10%, while the bulk of trade in clean energy technologies and materials is subject to minimal tariffs.

Import tariff policies differ enormously between countries. In some cases, they are very high, but have little impact on the average global weighted tariff for certain technologies, as they effectively prevent any significant volume of imports. In the United States, for example, tariffs on imports of EVs from China under Section 301 were recently raised from 25% to 100%, but the measure is not expected to have any major impact on trade in the short term as imports to the United States were already minimal. In August 2024, the European Union disclosed a draft decision to impose countervailing duties of up to 36.3% on imports of BEVs from China, on top of the existing 10% tariff. Given that China supplied more than 21% of the EU BEV market in 2023, the new import duties are expected to impact the competitiveness and growth of Chinese imports in the coming years. How well Chinese manufacturers can absorb these tariffs will determine their ability to maintain or expand their exports to the EU market (see Box 3.4).

In addition, NTMs can potentially have a major impact on the volume, prices or both, of internationally traded goods. They include regulations and technical specifications, such as those that aim to overcome or reduce the impact of negative externalities (e.g. GHG emissions) or information asymmetries (e.g. ingredients in a product that are potentially harmful to human health). They tend to increase the cost of production and trade, particularly if they differ significantly between countries. It is therefore beneficial to ensure that they are designed and implemented effectively in order to minimise their impact on costs of production and trade.

Figure 1.43 Estimated ad valorem equivalents of non-tariff measures for key energy technologies and products



IEA. CC BY 4.0.

Notes: NTMs = non-tariff measures. N-fertilisers = nitrogen-based fertilisers. Price-based ad valorem equivalent estimation of non-tariff measures. Technical NTMs include regulations on safety, quality and environmental standards, such as sanitary and phytosanitary measures, and technical barriers to trade that require products to meet specific technical standards, such as safety, labelling and performance. Non-technical NTMs include trade policies such as quotas, licensing and customs procedures that are not related to product specifications. The NTMs for aluminium and iron and steel reflect the NTMs for trade in semi-finished products. Road vehicles include internal combustion engine vehicles and electric vehicles.

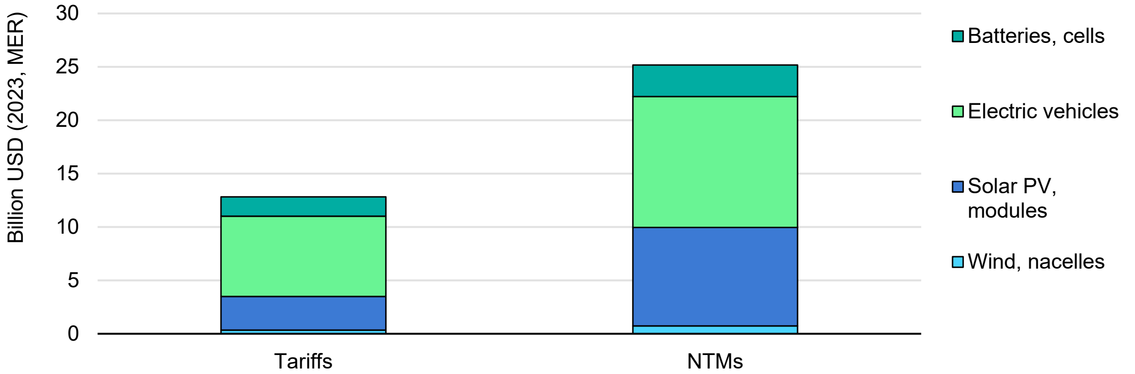
Source: NTMs are estimated based on Kravchenko (2022). Bilateral ad valorem import tariffs at the HS6 digit-level are aggregated and weighted by the actual trade volumes based on WTO (2024c); and CEPII (2024).

Non-tariff measures represent a larger share of the cost of manufactured energy products than in materials like aluminium and steel.

There is scope for reducing the impact of NTMs. WTO studies (WTO, 2023b) suggest that full implementation of the Trade Facilitation Agreement (WTO, 2014) alone could reduce the total cost of trade (including transportation) by an average of 14.3%.

Tariffs and NTMs have a large impact on trade costs for clean energy technologies. We estimate that, globally, they reached almost USD 40 billion in 2023 for EVs, battery cells, solar PV modules and wind nacelles alone, with EVs accounting for over 50% of the total (Figure 1.44). The bulk of the costs relate to NTMs, amounting to about USD 25 billion, incurred both by exporters and importers. These trade costs are equivalent to around 25% of the investment spending in manufacturing facilities for those technologies in 2023.

Figure 1.44 Global trade cost of selected clean energy technologies and materials



IEA. CC BY 4.0.

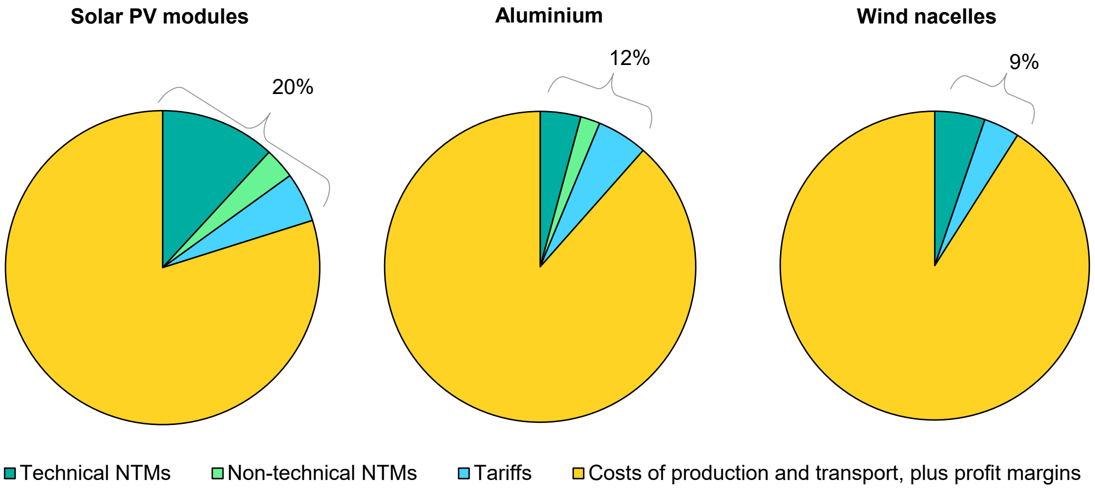
Notes: NTMs = non-tariff measures. Trade costs are calculated as the sum of ad valorem tariffs and the estimated ad valorem equivalent of non-tariff measures, multiplied by the reported trade flows between countries. Transportation costs are not accounted for in this Figure.

Source: IEA analysis based on WTO (2024b); Kravchenko (2022); and CEPII (2024).

The cost of non-tariff measures for EVs, battery cells, solar PV modules and wind nacelles is larger than the cost of tariffs, though tariffs are increasing.

Explicit import tariffs and the cost of NTMs now represent a significant share of the international prices of several leading clean energy technologies and their associated materials. For example, we estimate that, in total, they account for around 20% of the global weighted average import price of solar PV modules, 9% of that of wind nacelles and 12% of that of aluminium (semi-finished products) (Figure 1.45).

Figure 1.45 Global weighted average share of import tariffs and non-tariff measures on import prices of solar PV modules, aluminium and wind nacelles, 2023



IEA. CC BY 4.0.

Notes: NTM = non-tariff measure. Aluminium prices reflect those faced by semi-finished products.

Sources: NTMs are estimated based on Kravchenko (2022). Bilateral ad valorem import tariffs at the HS6 digit-level are aggregated and weighted by the actual trade volumes based on WTO (2024c); and CEPII (2024).

Tariffs and non-tariff measures account for 9% to 20% of global average import prices of solar PV modules, aluminium and wind nacelles.

Beyond the reduction of tariff and non-tariff measures, regional agreements play a critical role in fostering collaboration and co-operation to improve transparency in policies and development of new global markets. With industrial strategies gaining momentum across the world, there is also a role for governments to co-ordinate the different policies being implemented to avoid fragmentation with an objective to accelerate the development of clean energy technologies. In 2022, the G7 presidency launched the Climate Club initiative to accelerate climate action and industrial decarbonisation through co-ordination of industry policy instruments across its member countries to ensure a smooth transition. International organisations such as the International Monetary Fund (IMF) and the WTO have recently collaborated to promote a multilateral dialogue on trade and industrial policy to understand the effectiveness and spillovers of enacted measures and to develop a common understanding of co-operative solutions. Moreover, monitoring platforms such the Joint Subsidy Platform launched by the WTO, IMF, World Bank, and the OECD aim to enhance transparency on the use of financial support and to facilitate dialogue on best practices.

Innovation support measures

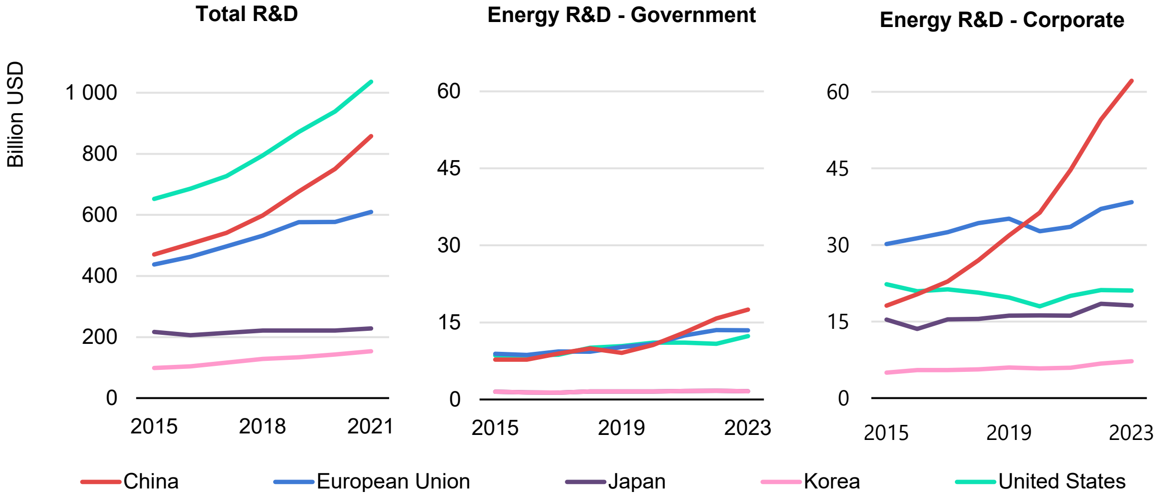
Enhancing the innovation capabilities of domestic manufacturers (and potential manufacturers) can be an important component of industrial strategies (see Table 1.2). A strong innovation ecosystem can bring important benefits to investors and, for emerging technologies in particular, can have an important influence over investment decisions. Innovation – including R&D, demonstration projects and continuous optimisation – has facilitated the market uptake of all clean energy technologies. As the IEA industry survey highlights, public funding or financial support for innovation are an important driver of private investment in innovation for clean energy technologies. Technology innovation support measures have particular characteristics that are explored in this section.

Innovation policy is vital to ensure competitiveness is maintained over time, by creating a supportive ecosystem that encourages R&D, fosters collaboration between industry and academia, and provides the necessary financial incentives and regulatory frameworks to accelerate technological progress. Innovation in the clean energy sector is often slower than in fast-moving sectors such as software, where innovation cycles are shorter and less capital-intensive. Clean energy innovations, particularly in hardware such as solar panels, wind turbines and electrolysers, require significant investment, long development times and extensive testing to meet safety and performance standards. Innovation policies must, therefore, be designed with patience and a long-term perspective, providing stable support for early-stage research as well as mechanisms for scaling up and commercialising new technologies over time (IEA, 2022c).

Innovation support measures are targeted policies, programs or interventions intended to accelerate the development and diffusion of new clean energy technologies. These measures tend to be multifaceted in their approach and aim to provide resources, reduce barriers and create incentives that facilitate innovation (IEA, 2024h). They include resource push components (e.g. increased R&D spending), market pull components (e.g. targets and incentives for consumers), together with enhanced knowledge management (e.g. intellectual property protections) to foster information-sharing and collaboration, and socio-political support to build public and political goodwill. While there is an increasing variety of measures used by governments to promote innovation, the most widely used option is R&D funding. Spending on R&D by governments and the private sector has increased significantly over the past two decades. The United States remains the leader in R&D spending, but China is catching up (Figure 1.46). Over the past 20 years, China has increased its R&D expenditure almost fifteen-fold. By 2021 (the last year for which comprehensive data is to hand), China's R&D expenditure was almost equal to that of the European Union, Japan and Korea combined.

As a share of GDP, total R&D spending has increased only moderately in most advanced economies over the past two decades, while in China it has almost tripled. Global spending specifically on energy R&D has increased by more than 40% over the last 5 years, driven mainly by a doubling in China, while increases in other regions have been smaller. Although energy R&D spending as a share of GDP remains lower than in the early 1980s, a period marked by a similar energy crisis and a drive for supply diversification, some regions have seen growth since 2015. Over the past 5 years, Japan, Korea and the European Union have moderately increased their energy R&D investment as a share of GDP, while the United States has reduced its share. Meanwhile, China increased its energy R&D expenditure as a share of GDP around 70% over this period. China overtook the European Union in 2020 to become the biggest spender on energy R&D as it focuses on developing next-generation technologies in order to retain its global market dominance. While the relative pace of growth in energy R&D by governments and companies has been similar over the past 5 years, in absolute terms, around 75% of the increase in spending came from companies, aimed at strengthening their long-term competitiveness and cutting GHG emissions. In 2023, four-fifths of the USD 50 billion spent by governments on energy R&D targeted clean energy.

Figure 1.46 Spending on R&D in selected countries/regions, 2015-2023



IEA. CC BY 4.0.

Notes: Spending covers current and capital expenditures by companies, research institutes, university, and government laboratories. Data on total R&D only available up to 2021.

Source: IEA analysis based on OECD (2024d); and IEA (2024i).

R&D spending has increased significantly over the last decade, with the United States remaining the overall leader, but China now leads in the energy sector.

The location of manufacturing sites during the earlier stages of technology development is linked to innovation capacity, which provides a significant first-mover advantage. However, as technologies mature and companies prioritise market access and cost reductions, manufacturing often shifts to other regions, decoupling from the initial R&D centres, which nonetheless need to keep on innovating in order to maintain a competitive advantage. This trend is particularly pronounced for modular technologies that have low transportation costs and can be easily relocated (NREL, 2017).

In addition to the risk that R&D does not lead to a commercial technology, there is therefore also a risk to governments of a failure to reap the full benefits of the scale-up and commercialisation that occurs as result of public spending on R&D because of the offshoring of any commercial technologies that are eventually developed. New and improved technologies, such as those that are cheaper and more efficient, can enable companies to gain market share and increase demand for their products. This demand can come both from competitors and from alternative technologies that provide similar services. However, without continuous innovation, the risk is higher that production becomes uncompetitive if financial support for manufacturing a technology is removed. Linking financial support to innovation support can limit this risk, thereby reducing future requirements for public funding of manufacturing in strategically important sectors. There are significant domestic economic benefits to be gained from public support for innovation in clean technology manufacturing. Firstly, innovation ecosystems cannot be easily relocated, allowing countries to specialise in particular technologies. Protecting intellectual property and services is an important consideration, even if some manufacturing sites are located away from R&D centres. Energy innovation may also have spillover effects on other sectors beyond those initially targeted, including non-energy-related sectors, through technology transfer and development of a skilled workforce.

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Chapter 2: Global outlook

Highlights

- Trade is a critical enabler of clean energy transitions. The value of trade in clean energy technologies rises in all three scenarios used in this report, but at varying rates. In the Stated Policies Scenario (STEPS), it rises from USD 200 billion in 2023 to USD 575 billion by 2035, more than half of the value of trade in natural gas today. It reaches over USD 700 billion by 2035 in the Announced Pledges Scenario (APS), and further grows to over USD 1 trillion in the Net Zero Emissions in 2050 Scenario (NZE Scenario). The dividends of trade would be higher if tariffs were lower: tariffs on renewable energy systems and components average twice those applied to fossil fuels today.
- Growing trade in clean technologies will have a major impact on trade balances. In the STEPS, the United States' net imports of clean energy technologies grow to USD 150 billion in 2035, but this is offset by an increase in fossil fuel exports. In the European Union, net imports of clean energy technologies, one-third of which come from China, reach USD 140 billion in 2035, fully offsetting the gains from lowering the fossil fuel import bill.
- In China, the cost of fossil fuel imports today is more than five times higher than its clean technology export revenues. Fossil fuel imports and clean technology exports come into balance just before 2050 in the STEPS, but that is achieved by 2035 in the APS thanks to more ambitious climate policies that cut fossil fuel demand and import needs. In India, the Production Linked Incentive Scheme and measures to meet the country's 2070 net zero emissions target help the country to become a net exporter of clean technologies before 2035 in the APS.
- More climate ambition does not automatically mean more clean energy technology trade, as climate goals need to be balanced with those for energy security, trade and industrial development. In the NZE Scenario, a fair and inclusive transition means that more capacity is co-located with demand in emerging markets and developing economies (EMDEs). As a result, global trade in clean technologies is around 5% lower by 2050 than in the APS.
- Total investment needs for clean technology manufacturing are unlikely to be a barrier to the transition. At USD 150 billion, global average annual investment over 2024-35 in the APS is actually lower than the level seen in 2023, but getting capital to the technologies and countries where it is needed will be a major task. More than 20% of the required investment in clean technology manufacturing is in EMDEs (besides China) in the APS and this share is 30% in the NZE Scenario. In contrast, global annual investment in near-zero emissions materials production needs to grow steeply, from USD 4 billion today to USD 88 billion on average over 2036-50 in the APS, and over USD 90 billion in the NZE Scenario.

This chapter sets out the results, at the global level, of a first-of-its-kind analysis of the outlook for the manufacturing of and inter-regional trade in clean energy technologies and their material inputs, based on a new IEA modelling framework adeveloped specifically for this report. We start by setting out the methodological approach informing our analysis of the manufacturing of six key clean energy technologies and their components – electric vehicles (EVs)[1], batteries (cells, anodes and cathodes), solar PV (modules, cells, wafers and polysilicon), wind turbines (towers, nacelles and blades), heat pumps and electrolysers[2] – that are central to the clean energy transition. The analysis also covers three key materials and chemicals – steel, aluminium and ammonia – and their precursors. Using our scenario approach, the chapter sets out the prospects for demand for those technologies and materials, and its principal drivers. It then presents in detail the outlook for manufacturing these technologies and materials in different scenarios, and the consequences for trade, taking account of energy, climate and industrial policy goals. It also sets out the implications for investment and CO_2 emissions.

2.1 Methodological approach

For this edition of *Energy Technology Perspectives (ETP)*, the IEA has developed a new manufacturing and trade (MaT) Model, which projects investments in the manufacturing of clean energy technologies and the key materials used in making them, as well as the resulting bilateral trade flows, based on the optimisation of overall manufacturing and trade costs under different scenarios to 2050 (see the Annex for more detailed documentation). The model determines manufacturing locations and trade patterns based on cost, within a set of constraints. Overall import costs include production costs (both capital and operational costs) and the cost of transporting a given commodity between modelled countries and regions, including freight and insurance costs, export taxes, tariffs and non-tariff measures (NTM). Transport costs are linked to the shipping model embedded in the IEA's Global Energy and Climate (GEC) Model, which projects energy demand by fuel for international and domestic shipping operations by vessel type and scenario (see Chapter 5).

Demand for each of the finished technology products (the final step of a given manufacturing supply chain) is derived from the IEA's GEC Model, while demand for intermediate technology components is determined by the MaT Model based on the upstream steps in the manufacturing supply chain. For example, the model determines the location of manufacturing centres for EVs, which drives the demand for battery cells in each region. Demand for materials is determined based on a set of macroeconomic drivers, including population and the value added of

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[1] In this publication, EVs refer to battery electric passenger cars, including plug-in hybrids (see Box 1.2).

[2] Water electrolysers for hydrogen production.

relevant economic subsectors, and integrates the impact of energy and material efficiency measures derived from the GEC Model (IEA, 2024d).

A set of constraints are incorporated into the MaT Model to reflect practical considerations. They include minimum and maximum utilisation rates for manufacturing facilities, based on observed conditions; project announcements for future clean energy technology manufacturing and for near-zero emissions production of materials based on detailed research and validation (which serve as upper bounds for regional installed capacity in the short term); local content requirements; government policies; and existing trade patterns. The constraints also take account of a detailed assessment carried out for *ETP-2024* of current enabling conditions for manufacturing investments in emerging markets, where capacity is often limited today (see Chapter 4).[3]

Scenario-based modelling

As in previous *ETP*s, the detailed projections of trends in manufacturing and trade are presented for different scenarios, which vary mainly according to assumptions about government policies affecting energy use and supply, and the overall pace of the clean energy transition. Three scenarios are used in this report:

- The **Stated Policies Scenario** (STEPS) is designed to provide a sense of the direction the energy system is heading in, based on a detailed review of the current policy landscape. The STEPS looks closely at what governments are actually doing to reach their current targets and objectives across the energy economy. Outcomes in the STEPS reflect a detailed sector-by-sector review of the policies and measures that are already in place or that have been announced. It is not automatically assumed that the aims of these policies will be met; rather they are incorporated in the scenario only to the extent they are underpinned by adequate provisions for their implementation. Aspirational energy or climate targets are not taken into consideration. This scenario also takes account of projects that have been announced to build manufacturing capacity for clean energy technologies and associated materials for which funds have been committed, i.e. they have reached the stage of a final investment decision (FID).

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[3] We do not explicitly model broad, cross-cutting or "horizontal" policies that support the wider industrial ecosystem, such as those related to innovation and competition, infrastructure investments, intellectual property frameworks and access to finance. As these enabling policies are crucial components of a comprehensive industrial strategy, their indirect effects are captured through an assumed differential pace of manufacturing capacity growth. The model assumes that some degree of inertia remains, meaning that countries with limited industrial capacity today would create a manufacturing capacity at a slower rate compared to those with an established industrial base (see Box 2.1).

- The **Announced Pledges Scenario** (APS) assumes that governments meet, in full and on time, all the climate-related commitments they have announced, including longer-term net zero emissions targets and Nationally Determined Contributions under the UN Framework Convention on Climate Change, as well as commitments in related areas such as energy access and industrial policy. It does so irrespective of whether these commitments are underpinned by specific policies to secure their implementation. Pledges made in international I and initiatives on the part of businesses and other non-governmental organisations are also taken into account wherever they add to the ambition of governments. In addition, the scenario takes on board all the manufacturing projects that have been announced, including preliminary plans.

- The **Net Zero Emissions by 2050 Scenario** (NZE Scenario) is a normative scenario that sets out a pathway to stabilise global average temperature at 1.5°C above pre-industrial levels. The NZE Scenario achieves global net zero energy sector CO_2 emissions by 2050 without relying on emissions reductions from outside the energy sector. In doing so, advanced economies reach net zero emissions before emerging markets and developing economies (EMDEs). The NZE Scenario also meets the key energy-related UN Sustainable Development Goals, achieving universal access to energy by 2030 and securing major improvements in air quality.

The detailed regional projections of demand, manufacturing and trade flows are presented solely for the STEPS and APS, as those scenarios are based on actual policies and official statements about policy commitments. We present only global or aggregated projections for the NZE Scenario, as it is a normative scenario, i.e. it depicts what the world could do collectively to achieve a stated global outcome.

None of these scenarios should be considered a prediction or forecast. Rather, they are intended to offer insights into the impacts and trade-offs of different technology choices and policy targets, and to provide a quantitative framework to support decision-making in the energy sector, and strategic guidance on technology choices for governments and other stakeholders. The scenarios and results are consistent with those presented in the *World Energy Outlook 2024* (IEA, 2024c).

The base year of analysis is 2023 and projections are made in annual time steps to 2050. In the discussion of results, global and regional demand for clean energy technologies and materials is presented until the end of the projection period. For manufacturing and trade, the detailed discussion of results by technology and region is limited to 2035, given that this is the time horizon for which detailed information about planned manufacturing projects and policy incentives is available. Where practical and helpful for decision makers, manufacturing and trade results for 2050 are presented at a global level to indicate the long-term direction of travel.

Industrial strategies and policy instruments

As countries have advanced in setting climate targets and developing policies to work towards them, attention has shifted towards developing the industrial capabilities needed to meet those targets. A growing number of countries have now set targets or goals for manufacturing clean energy technologies. Policy instruments that have already been implemented are taken into account in the STEPS. In contrast, aspirational targets for manufacturing that have not yet been translated into concrete and predictable policy instruments are considered only in the APS (see Table 2.1).

Table 2.1 Selected industrial strategies and policy packages targeting clean energy technologies or materials manufacturing by scenario

Country	Stated Policies Scenario	Announced Pledges Scenario
United States	Inflation Reduction Act (IRA)	Proposed financial support schemes in the IRA where tax credit rules are not yet finalised (45V clean hydrogen production tax credit)
European Union	The European Green Deal	Net-Zero Industry Act (NZIA)
India	Production Linked Incentives (PLI) scheme	Make in India
Japan		Green Transformation (GX) Promotion Strategy
Korea		Industrial Supply Chain 3050 Strategy
Canada	Budget 2023 – A Made-in-Canada Plan Budget 2024 – Fairness for Every Generation	-
Australia		Future Made in Australia
Brazil	Support from the National Bank for Economic and Social Development (BNDES)	New Industry Brazil (Nova Indústria Brasil); MOVER (Green Mobility and Innovation Program)
Chile	-	Electromobility Strategy; Hydrogen Strategy
Kazakhstan	-	Third Modernization of Kazakhstan: Global Competitiveness
Saudi Arabia	-	Vision 2030
Malaysia	-	New Industrial Master Plan 2030
Egypt	-	National Automotive Industry Development Program
South Africa	-	Just Energy Transition Plan; South African Renewable Energy Masterplan (SAREM)

Notes: The scope of the industrial strategies is wider than those covered in this table, but only some features that could potentially have a direct impact on the clean energy technologies and materials covered in this report are modelled in the IEA MaT Model. Financial support policies for energy inputs are not included in this table.

Trade policy instruments

Given the high degree of uncertainty associated with the evolution of import tariffs and export taxes on clean energy technologies and materials, the tax and tariff levels in effect or announced as of the beginning of September 2024 are considered in all three scenarios. This includes any temporary tariffs or exemptions, which are applied according to their scheduled start and end dates when such information is disclosed. This assumption allows for a consistent analysis of the impacts of tariffs on the global deployment and manufacturing of clean energy technologies, without embedding within the results additional uncertainty about their future projected level or extent.

Tariffs on clean energy technologies and materials have increased in the major economies in recent months and years with the aim of counteracting the effect of financial support mechanisms in exporting countries that are perceived as unfair and detrimental to the maintenance of a level playing-field. The recent hike in tariffs in the United States, Canada and European Union on EV imports from China are the most prominent examples of this (see Chapter 1). Several Latin American countries have also followed this approach, with Mexico, Chile and Brazil announcing tariff increases on Chinese steel in Q2 2024 and other countries in the region considering similar tariff hikes (Bloomberg Línea, 2024).

The impact of NTMs[4] is modelled using estimates of their ad valorem equivalent (AVE), which represents the additional cost imposed by the NTM on imports, expressed as an ad valorem tariff that would have the same trade effect as the NTM. The methodology used to estimate the AVE is based on econometric models that take into account the full range of NTMs classified into different types. In the STEPS and APS, the AVE of NTMs on each traded product is assumed to remain at its current level.

As concerns grow over disparities in carbon pricing and the potential for "carbon leakage" from regions with high carbon prices, a growing number of countries are considering carbon border adjustment mechanisms (CBAMs). For regions where CBAMs have been announced and initial steps have been taken towards implementation, such as in the European Union, the objective of these mechanisms is reflected in the APS but not in the STEPS, reflecting uncertainty as to their final arrangements. In the case of the EU CBAM, for example, a review will be conducted at the end of its transitional phase in 2026, including on aspects related to the product scope. For countries that have announced their intention to implement CBAMs but not yet begun implementation, such as the United Kingdom, the goal of these mechanisms is also reflected in the APS. The impact of CBAMs is modelled in each scenario by accounting for differences in carbon prices between exporting and importing countries for steel, aluminium and

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[4] A description of non-tariff measures (NTMs) is provided in Chapter 1.

ammonia. This allows a portion of emissions to be charged a carbon price equivalent to what the materials would have faced had they been produced in the importing country. This analysis does not include the transaction costs associated with the implementation of CBAMs.

Box 2.1 Clean energy technology manufacturing and near-zero emissions materials in the NZE Scenario

The NZE Scenario is predicated on an increased participation of EMDEs in clean energy technology and near-zero emissions materials manufacturing, drawing in many cases on their abundant low-cost renewable energy resources. This drives greater diversification of supply chains in the scenario. Those countries with an existing industrial base, particularly in manufacturing cars, steel, aluminium or ammonia, as well as clean energy technologies, are clearly best-placed to scale up output in the short term. For countries with an existing industrial base in other sectors that have the potential for skills transfer, clean energy technology manufacturing typically starts after 2030. In the least developed countries, where industrial production is currently minimal, it starts after 2040, in view of the long lead times for developing the necessary transport and energy infrastructure and skills to enable manufacturing to take place. Achieving this kind of development hinges on EMDEs putting in place the requisite enabling conditions, including securing financial support and creating a favourable business and investment environment that goes well beyond that depicted in the APS.

In the NZE Scenario, the accelerated deployment of clean energy technologies and near-zero emissions materials requires faster and broader consensus on standardisation and certification. It is assumed that countries work together to reduce NTMs and recognise each other’s standards and regulations, lowering the trade cost impact of NTMs by 20% by 2040 compared with current levels, and reducing the disparity in trade costs between advanced economies and EMDEs for both clean energy technologies and materials.

2.2 Demand

Clean energy technologies

Market size

The emerging clean energy economy is underpinned by a vast set of manufacturing operations. The transition to clean energy has only just begun, yet the global market for the key clean energy technologies covered in this report is already enormous: total sales amounted to over USD 700 billion in 2023 – almost 20% more than in 2022 and three times more than in 2020. China and advanced economies account for the lion's share of the market. China's large clean energy technology market reflects its leading role as an exporter as well as consumer. The global market for electric cars and batteries (including the batteries that power other EVs and stationary storage) accounts for 65% of the total – the result of spectacular growth in recent years; EV sales reached almost 14 million units in 2023 globally (over 85% in China, the European Union and the United States) – an increase of 35% over 2022 (Figure 2.1). Solar PV and wind turbines make up most of the rest.

The market for clean technologies Is set to continue to grow rapidly in the medium term. In the STEPS, which reflects today's policy settings, it nearly triples by 2035, reaching around USD 2 trillion, with China and advanced economies continuing to dominate. In the APS, which takes full account of climate pledges around the world, it reaches over USD 2.5 trillion – 25% more than in the STEPS. More than half of the difference between the two scenarios is due to EMDEs (excluding China)[5], where the gap between policies in place and wider climate ambitions is bigger. In the NZE Scenario, the market for clean technologies reaches USD 3.3 trillion by 2035.

In the long term, the growth of the global clean energy technology market slows down in the STEPS and APS. By 2050, it reaches USD 2.4 trillion in the STEPS and USD 3 trillion in the APS. About 90% of the growth between 2035 and 2050 in the APS comes from EMDEs, with EVs being the biggest driver of this increase. The global market reaches a similar size in the NZE Scenario to that in the APS in 2050 because of a decrease in electric car demand driven by behavioural changes and a shift in road transport modes which offsets the growth in the market size of other clean energy technologies. In 2050, the electric car global market size is about 3% smaller in the NZE Scenario compared to the APS, while that of other clean energy technologies is 20% higher, with the battery (excluding those for cars), wind turbine and heat pump markets being the primary drivers of the growth.

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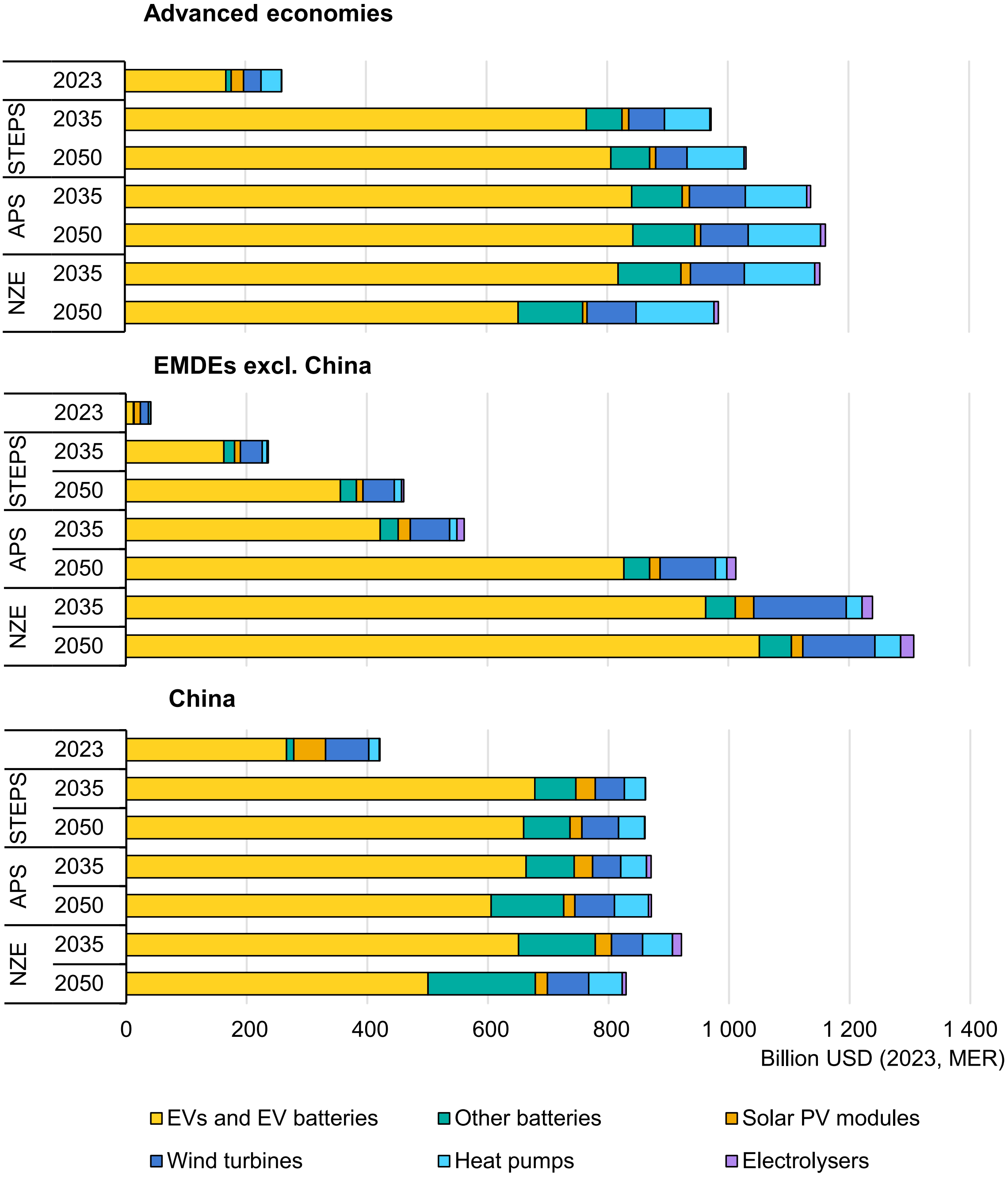
[5] EMDEs exclude China in the rest of this chapter unless otherwise stated.

Figure 2.1 Market size of key clean energy technologies and components by region and scenario, 2023-2050



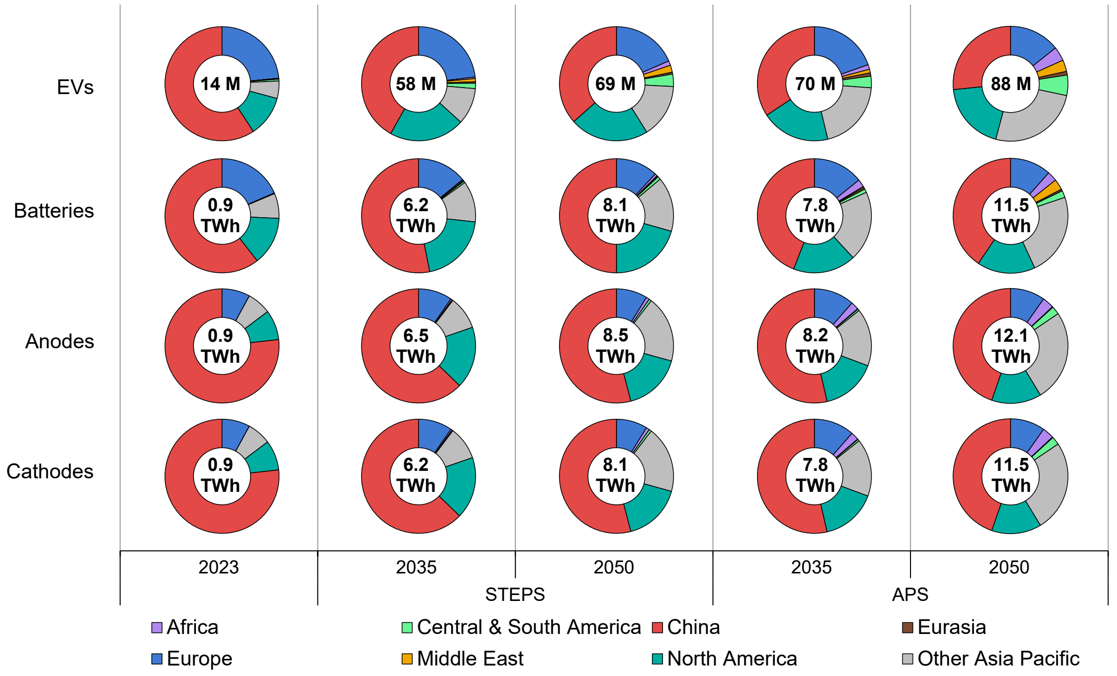
Notes: EMDEs = emerging markets and developing economies; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Market size is calculated as regional demand (by excluding any inventory building) multiplied by global average price. EVs & EV batteries = Electric cars including their battery value. Other batteries = Batteries used for two- and three-wheelers, light commercial vehicles, trucks, buses, and stationary storage. Wind turbines = Wind turbine towers, nacelles and blades. Electrolysers = Electrolyser stack.

The market for clean technologies Is set to continue to grow rapidly in the medium term, led by EVs.

EVs and batteries

Global demand for electric cars grows from nearly 14 million in 2023 to 58 million in 2035 in the STEPS (Figure 2.2). Governments in most advanced economies have put in place a wide range of financial incentives and subsidies to help mass-market consumers to gradually shift to electric cars, such as the Inflation Reduction Act (IRA) tax credit in the United States and purchase subsidies or social leasing schemes in EU member states. Fuel economy standards and, in several regions such as in the European Union and the United Kingdom, future bans on new internal combustion engine (ICE) registrations are also pushing up EV sales. In advanced economies, they reach 28 million in 2035, accounting for 70% of car sales in these markets. This helps to decrease the costs of manufacturing EVs and increase their competitiveness, thereby leading to their more rapid deployment in the rest of the world in the longer term. By 2050, EV sales reach nearly 70 million worldwide, accounting for almost 60% of total car sales. In the APS, more ambitious targets boost EV sales to the level envisaged in the STEPS for 2050 as early as 2035, with sales climbing to almost 90 million, or 80% of total car sales, by 2050.

Figure 2.2 Global demand for EVs, batteries and components by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2050



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; M = million; EV = electric vehicles, specifically passenger cars and pick-up trucks. Battery demand includes all EV types and stationary storage. The number in the middle of the pie chart refers to global demand. A negative (anode) to positive (cathode) electrode ratio of 1.05 is assumed for the final cells, which implies 5% more anode capacity than cathode capacity per cell.

The regional distribution of EV and battery demand becomes more diverse both in the STEPS and the APS, with the share of EMDEs growing rapidly in the APS.

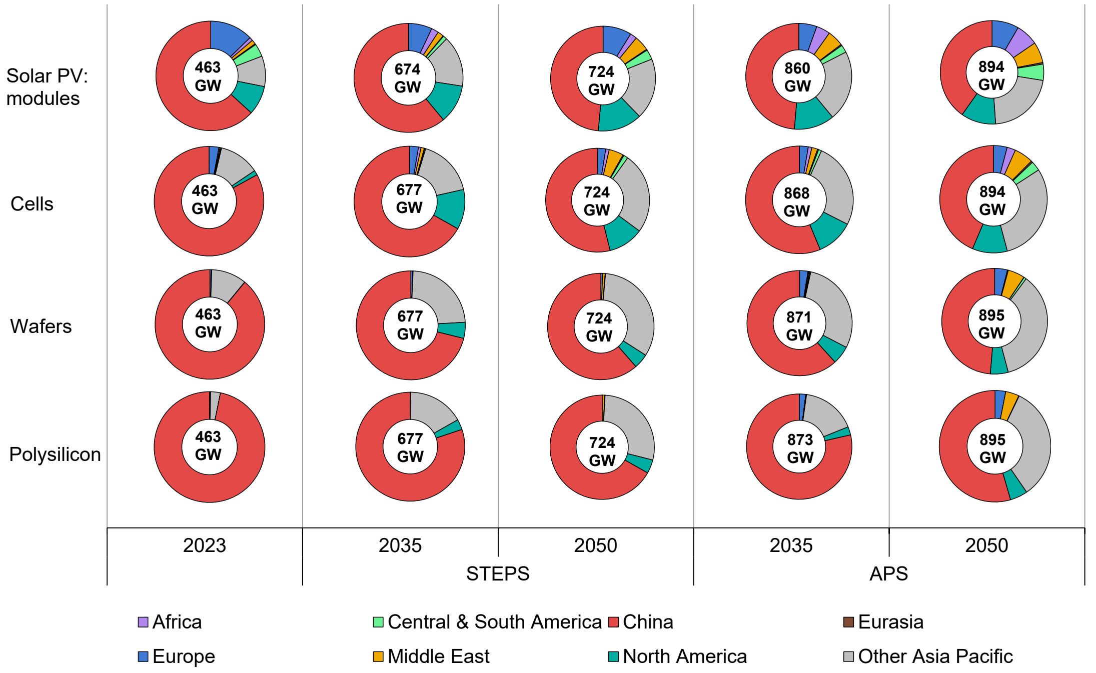
The deployment of EVs remains highly concentrated in China and advanced economies to 2035, but EMDEs take a growing share thereafter in both the STEPS and the APS. In the STEPS, sales in China jump to 24 million by 2035, their share of the Chinese car market jumping from 37% in 2023 to 85% – far exceeding the national target of 50% the same year – driven by their competitive prices. In 2023, even without subsidies, more than 60% of EVs sold in China were cheaper than their ICE equivalents (IEA, 2024a). One reason for this is Chinese manufacturers' access to raw materials and integrated supply chains, with EVs being assembled near battery cell factories and critical mineral processing for cathodes and anodes (see Chapter 3). Deployment in EMDEs takes off later, their share of global sales rising strongly after 2035 as EVs become more competitive in those markets, and markets in China and the advanced economies become saturated. By 2050, EMDEs account for nearly 20% of total EV sales, up from just 3% in 2023. In the APS, deployment of EVs is faster in all regions, with the share of EMDEs reaching nearly one-fifth and one-third of global sales in 2035 and 2050, respectively.

Global demand for batteries is driven largely by EV manufacturing, so their demand grows in parallel in both the STEPS and APS. Stationary storage is a rapidly expanding and crucial sector for decarbonising power grids, contributing to rising battery demand. However, from 2023 to 2035, it is expected to account for only 10-15% of total demand. At the regional level, demand for batteries and EVs diverges, reflecting differences in where the EVs and batteries are made and where they are sold. In 2023, China produced 65% of global electric cars, and 75% of EV batteries, despite domestic demand not being capable of absorbing all of this output. As a result, 12% of its EV production and 17% of its battery production were exported. In both scenarios, China's share of global battery demand drops over the projection period, reflecting the growth in manufacturing of both EVs and batteries in other parts of the world, at first mostly in advanced economies and then in EMDEs. This trend is more marked in the APS due to the faster development of manufacturing capacities in EMDEs, especially in countries with low production costs and an incipient car industry, such as Viet Nam and Morocco. The United States and European Union maintain their shares in global battery demand thanks to improved integration in their battery supply chains supported by industrial policies (see Chapter 3).

Solar PV

Global demand for solar PV modules grows from 460 GW in 2023 to 675 GW in 2035 (an average rate of growth of 3% per year) and 725 GW in 2050 (0.5% per year over 2035-2050) in the STEPS (Figure 2.3). Growth is fastest to 2030 and then starts to decelerate as markets reach saturation. By 2050, solar PV contributes half of the world's nominal power generation capacity. Demand grows even faster in the APS, at an annual average rate of 5% over 2023-35, and 0.3% over 2035-2050, almost peaking by the mid-2030s. Demand for additional installations reaches about 860 GW in 2035 and almost 900 GW in 2050. These projections are slightly higher in *ETP-2024* compared with the 2023 edition, reflecting the momentum of record installations that have taken place recently and the fall in module prices.

Figure 2.3 Global demand for solar PV components by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2050



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The number in the middle of the pie chart refers to global demand. The manufacturing demand for any given year is calculated as the average solar PV installations between that year and the following year.

EMDEs account for a growing share of global demand for solar PV modules and components through to 2050, particularly in the APS.

The main engine of the growth in solar PV demand is China, which accounts for more than half of the global capacity additions between 2023 and 2035 in the STEPS and just slightly less – still almost half – of them in the APS. Chinese demand for modules in 2035 reaches around 415 GW in both scenarios. The rest of the growth in demand to 2035 is split between advanced economies and the EMDEs, with the former having a proportionally higher share in STEPS and the latter in the APS. India is the leading market among EMDEs, accounting for half of the additions in those countries in the STEPS in 2035 and over 35% in the APS. In the longer term, India and other EMDEs take a growing share of the market in both scenarios, reaching nearly 25% in 2050 in the STEPS and 35% in the APS.

This big increase in demand for solar PV worldwide is largely thanks to it being the most competitive way of generating electricity in several regions around the world, pushing deployment beyond national targets in many cases. Module prices have plunged in recent years. The average price worldwide in 2023 was USD 0.18/watt, down almost 80% from a decade ago (BNEF, 2024). In addition, policies supporting the deployment of renewable energy in general, including feed-in-tariffs, net metering, renewable portfolio standards and mandatory targets, and supporting solar PV in particular have been strengthened.

Global demand for upstream solar PV module components – polysilicon for making wafers, which are used to make cells, which are then used to make the modules – is a function of the demand for finished modules. The regional distribution of demand for these components depends on where the downstream manufacturing take place. There is often a lag between the development of capacity for the two, as has been seen in Southeast Asia, which was initially a module-manufacturing hub and has now moved into making cells to supply local module companies. The industry in China is already highly vertically integrated and dominated by large companies.

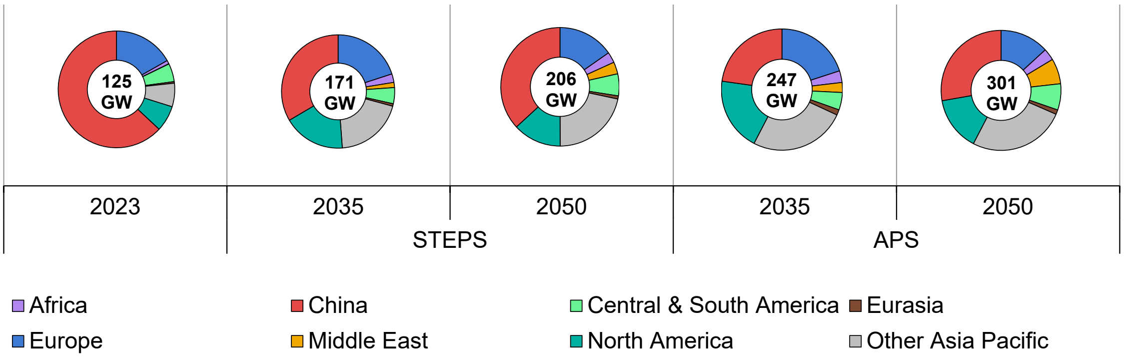
Manufacturing capacity has risen even faster than installations over the past few years or so as companies have sought to sustain and expand their market shares, leading to a low worldwide average utilisation rate, at around 55% (this rate varies little among the major companies). Output has also risen faster than demand, leading to the build-up of inventories, primarily in the European Union and the United States, at levels that are triple and double their respective annual installations. These are expected to be drawn down over the coming years, reducing the need for production in the near term.

Wind turbines

Global demand for wind turbines rises quickly from 125 GW in 2023 to 170 GW in 2035 in STEPS and 247 GW in the APS (Figure 2.4). Advanced economies account for nearly 90% of the growth in global deployment to 2035 in the STEPS and about 70% in the APS, on the back of policy targets and incentives. National and sub-national targets for wind deployment in these economies boost investments, resulting in a peak in annual capacity additions around 2030 in both scenarios. There is a marked shift in the regional breakdown of demand over the longer term. China's share of global wind turbine demand contracts from over 60% in 2023 to just below 40% by 2050 in the STEPS and barely a third in the APS, as deployment elsewhere, particularly in EMDEs, grows even faster. Annual installations in EMDEs increase steadily to 2050, with annual additions increasing five times from 12 GW in 2023 to 60 GW in the STEPS and rising tenfold to 120 GW in the APS. India, which has a target to deploy 140 GW by 2030, accounts for 35% of this demand growth by 2050 in STEPS and nearly 20% in the APS.

Among EMDEs, the Middle East is the second largest market after India, accounting for around 20% of demand growth to 2050 in both scenarios. Wind farm installations in this region are driven partly by low-emissions hydrogen production goals, such as in Oman, which aims to produce 4 million tonnes (Mt) of low-emissions hydrogen a year by 2040. In addition, five countries[6] in the Middle East have targets to reach net zero emissions by 2050 or 2060.

Figure 2.4 Global demand for wind turbines by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2050



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The number displayed in the centre of each pie chart represents the total global demand for wind turbines, including components – nacelles, blades, and towers. The manufacturing demand for any given year is calculated as the average wind turbine installations between that year and the following year.

Global demand for wind turbines is set to double by 2035 in the APS, with EMDEs accounting for a growing share through to 2050.

Demand for wind components is distributed across regions based on the competitiveness of their wind manufacturing industry, the regions' renewable energy targets, and the robustness of their energy supply chains. Other factors such as the presence of synergistic industries, such as mechanical engineering, and access to large ports to allow exports of bulky components, such as blades and tower parts, are also critical.

Heat pumps

Heat pump technology is increasingly common in buildings in major heating markets such as China, North America and Europe, thanks to policies targeting improved energy efficiency and clean heating in buildings. In some countries with mild climates, such as in central and southern China, Japan, the United States and some southern European countries, heat pumps are used to provide both

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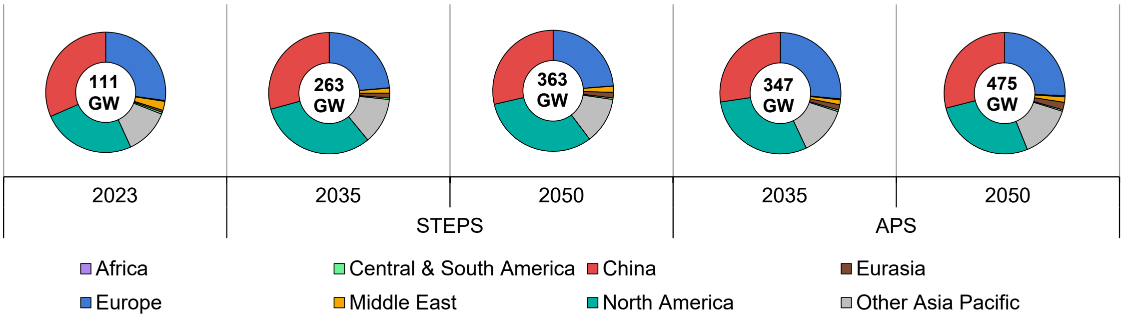
[6] The United Arab Emirates and Oman have set targets to achieve net zero emissions by 2050, while Saudi Arabia, Bahrain and Kuwait have announced a target for 2060 (IEA, 2024).

heating and cooling. Installed capacity of heat pumps worldwide currently amounts to about 1 100 GW – more than 70% of which is in advanced economies, and about one-quarter in China – covering around 10% of global building space heating needs. Demand for new heat pumps reached around 110 GW in 2023 (Figure 2.5).

In the STEPS, existing building energy efficiency policies and financial instruments drive heat pump sales up to about 265 GW in 2035, more than doubling from 2023, and to about 365 GW in 2050. China, North America and Europe account for about 85% of the increase. Other EMDEs remain minor markets, accounting for less than 10% of global sales in both 2035 and 2050. Deployment is even faster in the APS, with sales rising to about 350 GW in 2035 and 475 GW in 2050. In this scenario, heat pumps become the dominant heating technology globally, covering around one-third of space heating needs by 2050. In both scenarios, demand increases most strongly in major heating markets in advanced economies and China.

Figure 2.5 Global demand for heat pumps by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2050



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The numbers in the middle of the pie chart refer to global demand.

Demand for heat pumps increases in all scenarios, primarily in the major heat markets in advanced economies and China, while demand in other EMDEs remains low.

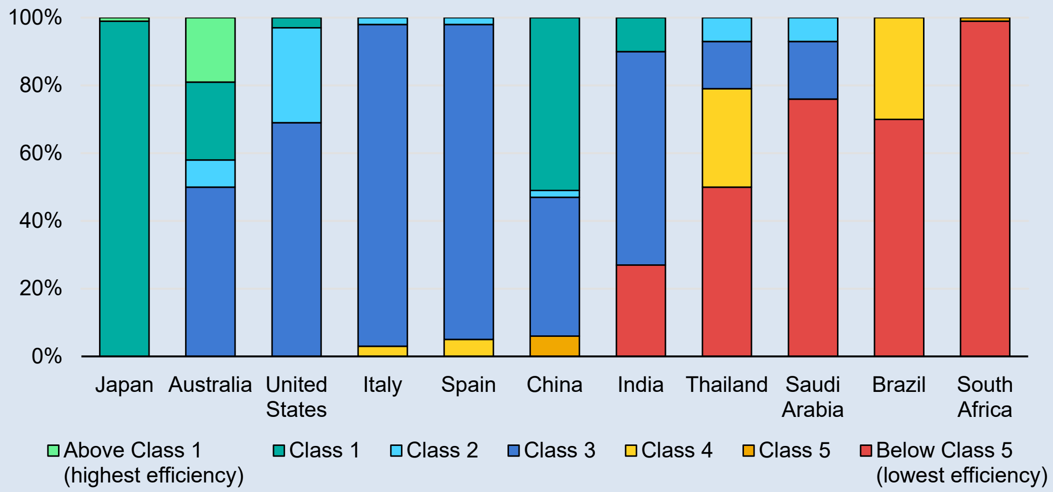
Box 2.2 The impact of standards and labels on heat pump production

Minimum Energy Performance Standards (MEPS) and product labels are cost-effective policy instruments to scale up the penetration of energy-efficient products and drive out less efficient units. More than 90 countries already have MEPS in place for air conditioners – which use the same technology as heat pumps – used in residential buildings, and more than 95 have labelling regulations. Nearly 90% of global space cooling energy consumption in the residential sector is covered by MEPS, up from 67% in 2010 and about 45% in 2000.

The technical specifications required by MEPS and energy labels affect Manufacturing production lines, the choice of components and, consequently, production costs. More efficient units require higher quality components and materials, and more complex designs, requiring more R&D. In China, improving the efficiency of an air conditioner by about 25% on average can raise production costs by 5-10%, while in Japan a 15% improvement typically costs 20-25% more for Japanese manufacturers because the units they currently produce are already more efficient. The introduction of MEPS typically requires 3-10 years of preparation time, including expert consultations, to enable production lines to adapt.

Experience shows that the stringency of MEPS has an enormous impact on the types of air conditioners exported. Chinese manufacturers have different production lines for domestic markets and exports to meet different specifications (Figure 2.6). Manufacturers that are headquartered in countries with ambitious MEPS can decide to locate production in countries with overall lower production costs, not only to cover the local market but also to produce units to be exported to compensate for the additional cost associated with such efficiency measures. For example, imports of Chinese air conditioners in Australia have been dominated by exports from Japanese manufacturers producing in China, where the production cost is about 45% lower than in Japan (see Box 1.4). Similar patterns can also be observed for imports from Thailand and Malaysia to Australia.

Figure 2.6 Selected destinations of air conditioners manufactured in China by energy efficiency class, 2021



IEA. CC BY 4.0.

Note: Energy efficiency classes are based on China standard GB 21455-2019.

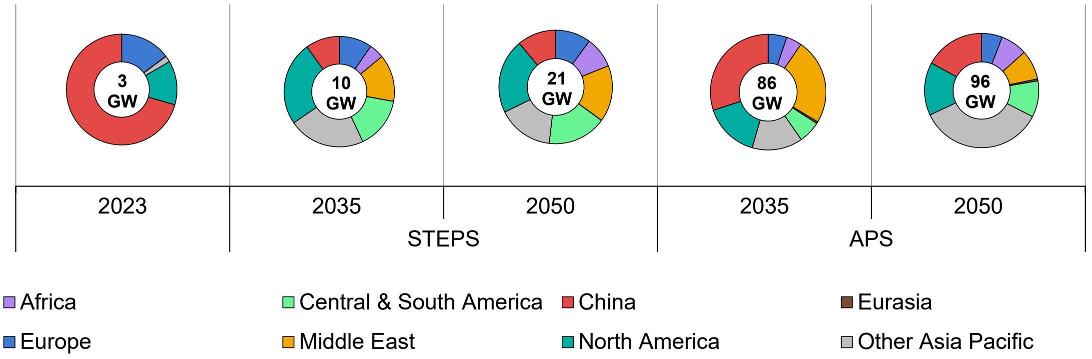
Source: ChinaIOL (2022).

The stringency of current MEPS for heat pumps, as well as regulations on other parameters such as noise and refrigerants, vary enormously across countries (IEA, 2023). These differences, coupled with cultural preferences, have led some heat pump manufacturers to locate their factories close to demand centres. As heat pump markets grow, governments need to set out a medium to long-term regulatory pathway, including more stringent MEPS and support for the harmonisation of standards across regions, to reduce investor uncertainty and lower manufacturing costs.

Electrolysers

Global electrolyser demand is determined by the interplay of demand for low-emissions hydrogen and the ability to produce it cost-efficiently from electrolysis. In the STEPS, global low-emissions hydrogen production from electrolysis jumps from less than 100 kt today (less than 0.1% of total hydrogen production) to 11 Mt in 2035 and close to 40 Mt in 2050 (about 10% and 25% of total hydrogen production respectively). In total, more than 320 GW of electrolyser capacity is installed worldwide by 2050 in the STEPS, with capacity dedicated to synthetic fuels production demand for aviation accounting for almost 120 GW. The EU REFuelEU Aviation initiative is a major driver of this, but in this scenario only one-sixth of this capacity is installed in Europe. Other regions with lower electrolysis production costs, either because of targeted policy financial incentives (such as under the IRA in the United States) or availability of low-cost renewable energy resources (such as in Middle East and Central and South America) attract the bulk of the investment and export the fuels produced to Europe.

Figure 2.7 Global demand for electrolysers by country/region in the Stated Policies and Announced Pledges Scenario, 2023-2050



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The number in the middle of the pie chart refers to global demand.

China's share of global electrolyser demand shrinks from more than 70% in 2023 to around 20% in 2050 in the APS, primarily due to growing demand in EMDEs.

Demand for low-emissions fuels grows much faster in the APS, driving up the demand for electrolysers. Low-emissions hydrogen output grows to around 80 Mt in 2035 and 260 Mt in 2050, by which time almost 80% of it comes from electrolysis. This leads to a demand for electrolysers of more than 1 900 GW over the entire period to 2050, with additions reaching around 85 GW in 2035 and almost 100 GW in 2050 (Figure 2.7). Transport accounts for two-thirds of this demand. Maritime fuels alone require more than 500 GW of electrolysis capacity installed worldwide by 2050 (see Chapter 5). Applications in industry, refining and the power sector account for the rest. China accounts for a quarter of the electrolysers installed by 2050, followed by the United States and the Middle East with 14% each, Central and South America with 10%, India with 9%, and Africa and Europe with 7% each.

Materials

Market size

The overall global markets for steel, aluminium and ammonia are already well-established and orders of magnitude larger than those for clean technologies. In 2023, steel sales were worth USD 1.4 trillion, sales of aluminium around USD 260 billion, and those of ammonia, USD 90 billion.[7] By comparison, the oil market was worth around USD 2.6 trillion in 2023. Near-zero emissions technologies are used to produce a very small share of the supply of these materials, at around 0.1% for steel, 2% for ammonia and virtually zero for aluminium. The manufacturing of clean energy technologies also accounts for a very small share of total demand – 0.8% for steel and 4% for aluminium today. Among those technologies, solar PV modules and wind turbines are the biggest users of aluminium and steel respectively.

The size of the markets for steel, aluminium and ammonia develops very differently in our scenarios according to differences in the strength of policies. In the STEPS, the total market for the three key commodities combined grows by 7% between 2023 and 2035 due mainly to increased demand (Figure 2.8). The rate of growth is much less than that for clean energy technologies, but starts from a much higher base. The size of the market for materials produced via near-zero emissions technologies and that of new energy applications of ammonia grows only incrementally in the STEPS. The rise in production costs owing to the use of

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[7] These market sizes refer to the supply chain stage where these materials are first traded in significant quantities. For steel, this refers to semi-finished steel products, and for aluminium this refers to ingots.

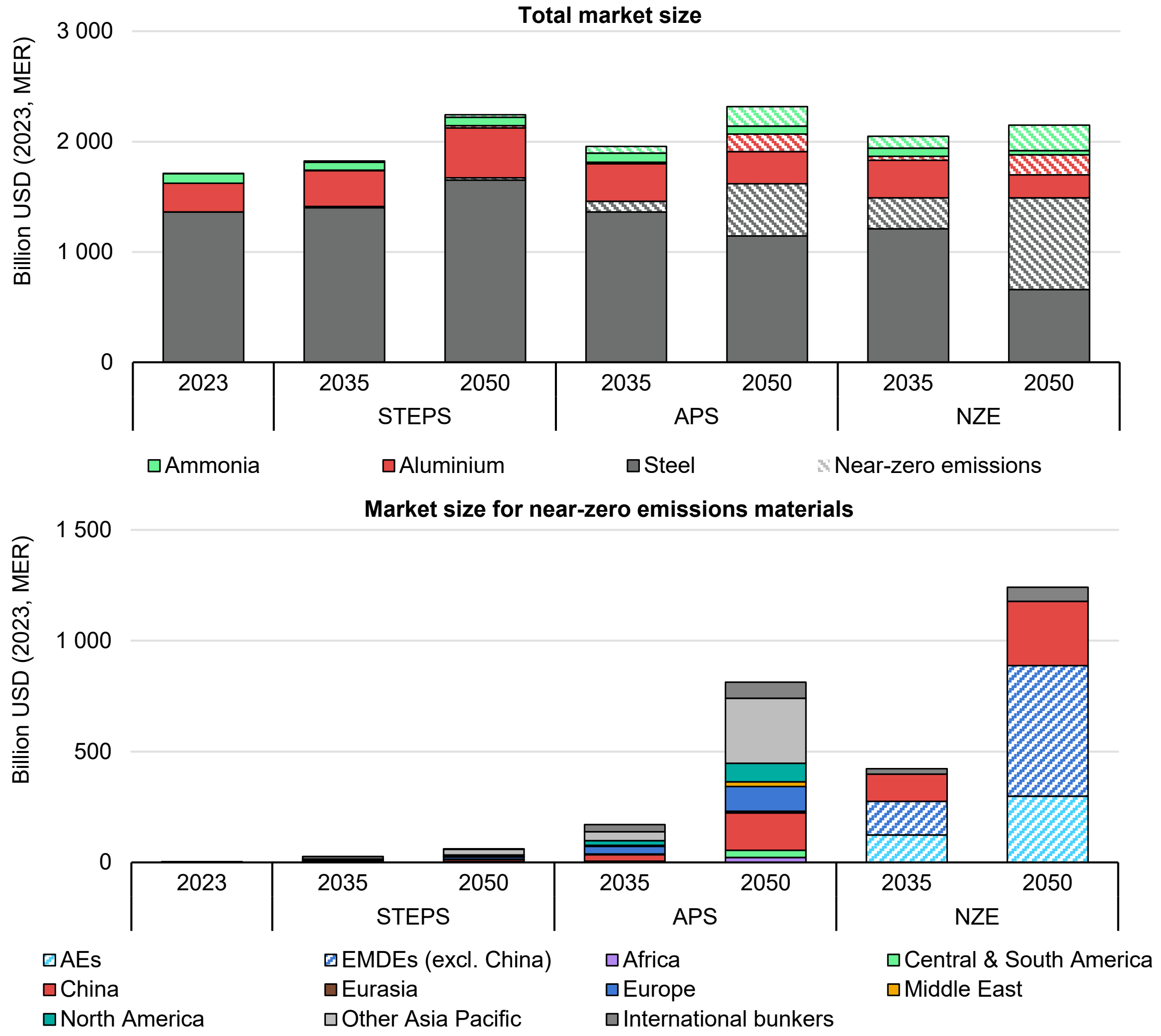
near-zero emissions technologies has a negligible impact on average prices in the STEPS, due to the relatively small quantities produced via these process routes in this scenario.

The overall market for steel, aluminium and ammonia grows more quickly during 2023-2035 in the APS (+14%) and the NZE Scenario (+20%), relative to the STEPS (+7%). Post-2035, growth in the overall market size slows in these scenarios, resulting in final values in 2050 of USD 2.3 trillion in the APS and USD 2.1 trillion in the NZE Scenario, which is very similar to the value reached in the STEPS (USD 2.2 trillion). These differing trajectories are mainly explained by changes in demand and to a lesser extent by changes in prices.

Demand for steel in the APS and NZE Scenario is lower than in the STEPS, as more efficient production and use across a broad suite of applications offsets the effect of greater demand for clean energy technologies like wind turbines. There is upward pressure on aluminium demand in these scenarios due to the increased deployment of clean energy technologies, with materials efficiency strategies – similar to those for steel – offsetting this in the longer term. Ammonia demand is significantly higher in both the APS and NZE Scenarios than in the STEPS, because growth in new energy applications far outweighs improvements in nutrient use efficiency in fertiliser applications.

Average prices for these key materials are projected to be around 5-35% higher by 2035 in the APS and NZE Scenario than in the STEPS, which also contributes to the increased market sizes in these scenarios in the medium term. Higher CO_2 prices for conventional steelmaking technologies, and the higher grades of iron ore and energy costs for certain near-zero emissions processes, mean higher prices are required for steelmakers to recover their costs. Some of this upward pressure on prices is offset by other supply and demand dynamics, in particular for steel. Overall steel demand is lower in these scenarios, which reduces the marginal cost of production, all else being equal, and growing scrap-based production – which is not subject to the same level of increase in production costs as near-zero emissions technologies for producing steel from iron ore – serves to dampen the increases in prices. The price premiums over the STEPS fall slightly to 2050 as a result of these dynamics for steel, and for all materials, as continued cost declines for near-zero emissions technologies relieve the upward pressure on prices.

Figure 2.8 Market size of selected materials by country/region and scenario, 2023-2050



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; Aes = Advanced economies; EMDEs = Emerging markets and developing economies. "International bunkers" refers to the ammonia demand in international shipping. Assumed materials prices as per ETP2024 central assumptions. Price signals for modelling purposes are derived using the evolution of levelized cost of production and demand in each scenario. Scrap-based production is not included under the near-zero emissions heading.

The market for near-zero emissions materials increases significantly in the NZE Scenario, especially in EMDEs.

China and advanced economies are the largest consumers of the three materials today, due to their large processing and manufacturing industries. China sees a slower demand growth in all three scenarios compared to the past two decades, and in some cases, even a gradual decrease in demand, as its economy transitions to less energy-intensive and higher value-added segments of manufacturing. India's steel and aluminium industries are growing fast, as are those of some other developing economies, leading to a significant shift in the materials market towards EMDEs other than China over time, with a share of around 40% by 2050 in all three scenarios, compared with 25% in 2023. In the APS and NZE Scenario, the majority of ammonia production for energy applications is located in EMDEs by 2050, due to their large low-cost renewable energy resources, contributing to the market shift towards those countries.

Projecting the size of the market for materials produced using near-zero emissions technologies is extremely perilous, as it is next to impossible to determine what premium buyers might be willing to pay where they have a choice (there have been very few transactions and off-take agreements to date). Some subsets of customers, notably in the automotive sector, are willing to sign contracts to pay a premium for materials with a lower emissions footprint, though the prices agreed have generally not been revealed. For example, Porsche, Volvo and Mercedes-Benz are among the off-takers for the Stegra (formerly H2 Green Steel) project, which plans to use hydrogen-based near-zero emissions technology to produce steel from iron ore.

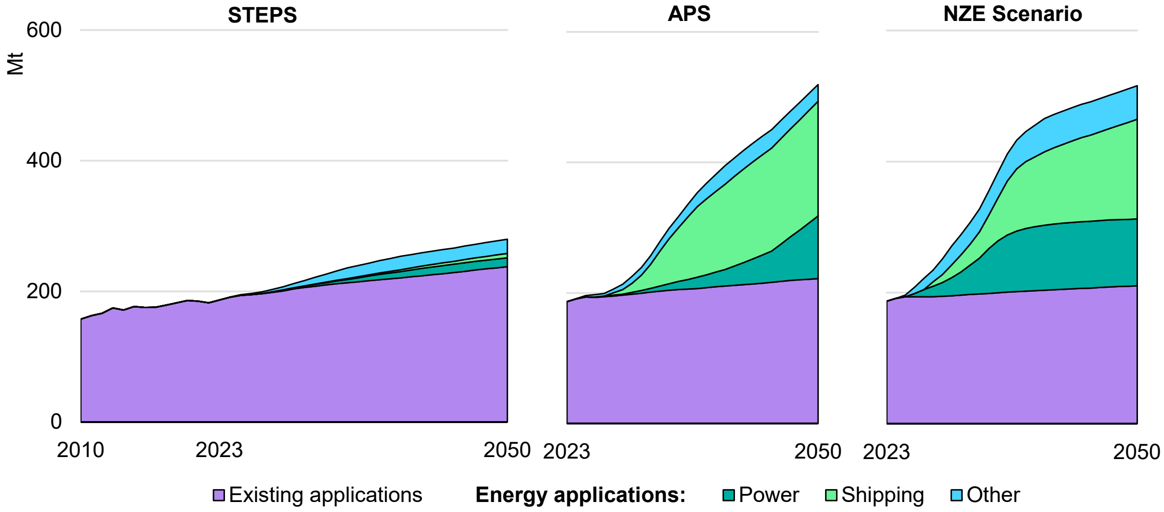
Drivers of demand

The underlying drivers of demand for materials remain broadly unchanged through to 2050 in the STEPS. Steel demand is primarily driven by construction (approximately 50% of current global demand), followed by manufacturing segments, including 15% for transport equipment, 20% for other equipment and 15% for other goods. In China and EMDEs, construction accounts for a larger share. Aluminium demand is also driven strongly by the transport (30%) and construction (20%) sectors, with electrical applications (15%), packaging (15%) and other equipment (10%) also being important demand drivers. Around 70% of global ammonia supply is used in fertilisers, with the share of EMDEs in total ammonia use increasing sharply in line with rising population and agricultural output. Ammonia is starting to be used for energy applications, but remains limited due to limited policy support.

There are some notable differences to the demand drivers in the APS and NZE Scenario. In these scenarios, materials demand is generally lower than in the STEPS due to material efficiency strategies in the transport sector (such as vehicle lightweighting and a modal shift to more public transport, walking or cycling), in buildings (life extensions and modular construction enabling more efficient use and reuse of materials) and in agriculture (higher nutrient use efficiency), and due to higher collection rates for recycling and reduced waste in manufacturing processes. Aluminium is an exception to this, due to its role in making solar PV modules and mountings, as well as in lightweighting vehicles and transmission lines, which all see much higher deployment in the APS and NZE Scenario than in the STEPS. This means that demand for aluminium remains above that in the STEPS until around 2040 in the NZE Scenario and 2045 in the APS. Demand for the intermediate commodities derived from the ores that enter the metal-producing industries (bauxite to produce alumina and iron ore to produce pig iron and direct reduced iron [DRI]) is generally lower in the APS and NZE Scenario than in the STEPS, due to increased recycling and collection of scrap metal off-setting the primary ore inputs, in addition to the overall demand levels being lower.

For ammonia, demand for existing applications is lower in the APS and NZE Scenario compared to the STEPS, as nitrogen fertilisers are used more efficiently and ammonia-based urea is partially substituted with other nitrogen fertilisers that do not require CO_2 in their manufacture. However, these factors are more than outweighed by the emergence of the use of ammonia as a fuel in the shipping and power sectors. These applications grow from virtually nothing today to around 300 Mt by 2050 in both the APS and the NZE Scenario (Figure 2.9).

Figure 2.9 Global demand for ammonia by application and scenario, 2010-2050



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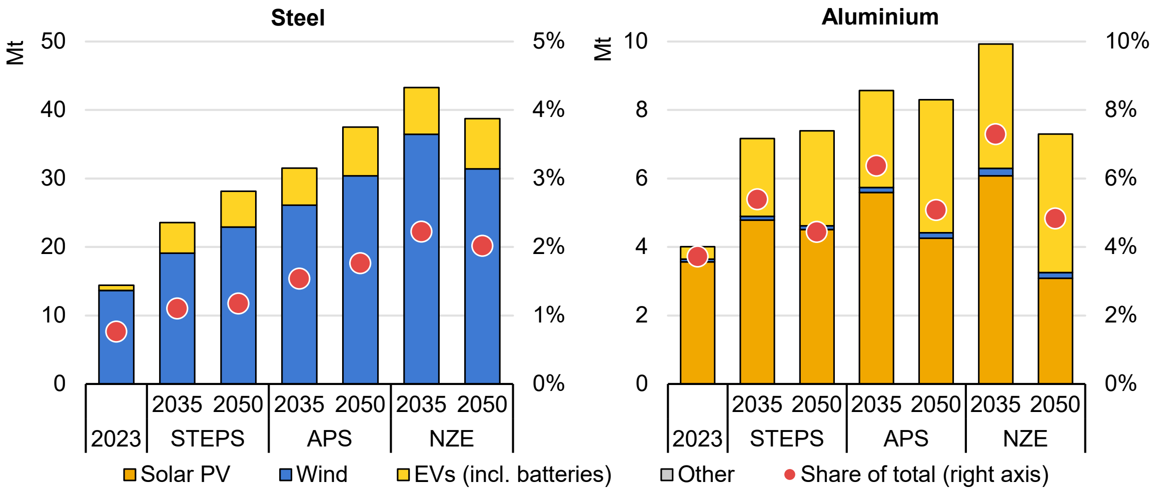
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE Scenario = Net Zero Emissions by 2050 Scenario.

Ammonia demand almost triples by 2050 in the APS and the NZE Scenario, driven by new applications including as a shipping fuel and in power generation.

The main material links between steel and clean technology manufacturing are for wind turbines and EVs, which together with the other clean technology supply chains covered in this report, accounted for an estimated 0.8% of global steel demand in 2023. This share grows to 1.2% by 2050 in the STEPS, 1.8% in the APS and 2.0% in the NZE Scenario, reflecting the differences in the rate of higher deployment of those technologies and overall levels of demand for steel in other uses (Figure 2.10). For aluminium, the main links are with EVs and solar PV – in both cases for structural (as opposed to electrical) aspects of these products. In total, the six clean technologies accounted for 3.7% of global demand in 2023. As with steel, but to a more pronounced degree, the share of global aluminium demand accounted for by these applications increases. It rises to 5.4% by 2035 in the STEPS, to 6.4% in the APS and to 7.3% in the NZE Scenario, though the share of total demand drops after 2035 due to material efficiency and rising demand in other uses.

Figure 2.10 Global demand for steel and aluminium for clean technology manufacturing by scenario, 2023-2050



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Share of total refers to the share of global production, including both primary and secondary production. Other includes electrolysers and heat pumps. Values do not include materials used in installation of the technologies, such as mounting for solar PV.

The share of clean energy technology manufacturing in global steel and aluminium demand grows rapidly, especially in the APS and the NZE Scenario, driven up by faster deployment.

2.3 Manufacturing

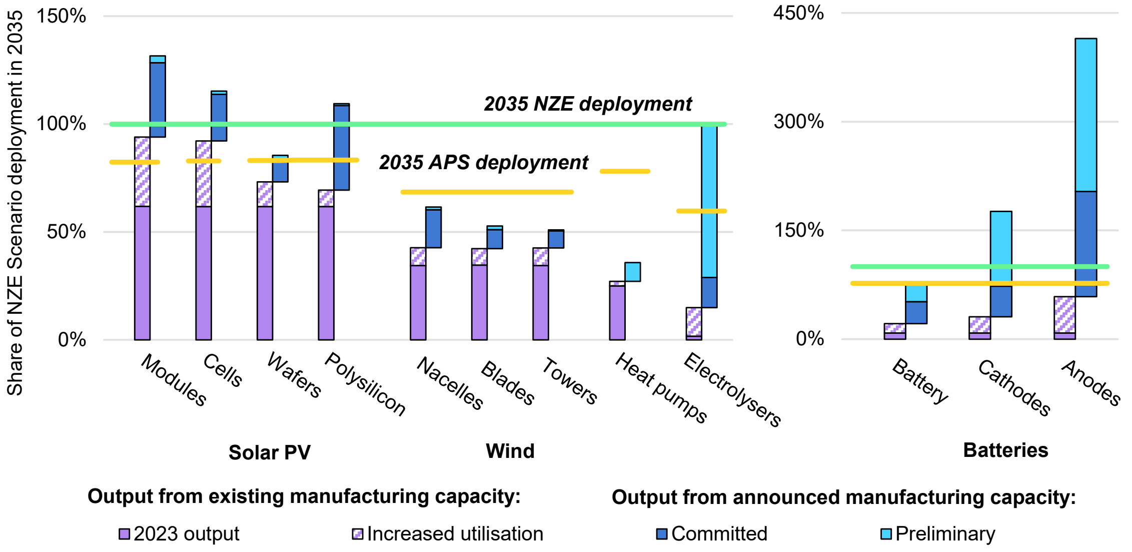
Manufacturing capacity expansion plans

Clean energy technologies

Global clean technology manufacturing capacity grew strongly across several technologies and regions in 2023, driven by robust demand and government incentives to increase diversification of supplies (see Chapter 1). In some cases, output capacity is sufficient to satisfy the APS demand and almost on track for the NZE Scenario: existing solar PV module and cell manufacturing capacity already exceeds that needed to meet the level of deployment projected for 2035 in the APS and is already at over 90% of what is needed in the NZE Scenario (Figure 2.11). In contrast, there are bigger gaps in other cases, including in solar PV supply chains: the current capacity for producing wafers and polysilicon is not sufficient to meet deployment needs in 2035 in the APS and the gap to the

NZE Scenario stands at about 30%. For the other technologies considered in this report, existing manufacturing capacity could deliver around 25% (in the case of batteries and electrolysers) and 60% (in the case of wind) of deployment envisaged in the APS. This compares to meeting between 15% (in the case of electrolysers) and close to 45% (in the case of wind) of the NZE Scenario deployment needs by 2035.

Figure 2.11 Announced annual manufacturing capacity as share of deployment in 2035 by technology and scenario



Notes: APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Battery demand here includes that for all electric vehicle types and stationary storage. Announced manufacturing capacity refers to announcements made by H1 2024 that could come online by 2030.

Existing solar PV module and cell manufacturing capacity can meet deployment needs in 2035 in the APS and is close to NZE Scenario needs, though other technologies fall short.

This outlook changes significantly if all announcements for manufacturing capacity expansion are taken into account. For **solar PV** modules, taking into account only announced capacity expansions that are already committed and that will come online by 2030, capacity would exceed projected demand in 2035 in the NZE Scenario by almost 30% (and by nearly 60% in the APS). This could lead to underutilised or even stranded assets. Module prices fell heavily in 2023, which resulted in cancellations and downward revisions of planned expansions in solar PV manufacturing, especially for PV polysilicon and wafers (see Chapter 1). However, the existing and announced capacity for wafers, in particular, is not anticipated to be on a level to satisfy demand consistent with the NZE Scenario in 2030. However, the new manufacturing sites are likely to produce new-generation components with higher efficiency, as a consequence of growing competition and technology innovation. New capacity could therefore outcompete existing manufacturing capacity, leading to the commercialisation of products that are both cheaper and more efficient, and rendering some existing capacity uncompetitive. Either way, the strong geographical concentration of the entire solar PV manufacturing supply chain is unlikely to change significantly on the basis of announced projects, with China's share of capacity set to fall only marginally by 2030 in both scenarios (Box 2.3).

In the case of **battery** cell manufacturing, capacity expansions are somewhat below that required to meet the projected demand in the NZE Scenario in 2035, even though the share of committed projects in overall announcements is higher than for anodes and cathodes. Battery manufacturing capacity is, however, sufficient to satisfy demand in the APS in 2035. Much of the currently announced battery manufacturing capacity remains concentrated in today's major EV markets – such as China, the United States and the European Union – which are set to have enough domestic capacity to cover all or the vast majority of their needs in 2035 in the APS. Battery manufacturers are focusing on the construction or financing of the numerous projects already announced, rather than focusing on new projects after 2030. Cancellations of some projects have been reported, particularly in Europe, due to uncertainty about future demand and more attractive financial conditions in other regions, such as in North America following the introduction of incentives under the IRA. These cancellations, however, do not jeopardise the availability of sufficient supplies to achieve deployment in line with the NZE Scenario by 2030 (see Chapter 1).

Locating battery manufacturing close to EV manufacturing hubs would reduce exposure to import/export tariffs, as well as insurance costs associated with shipping lithium-ion (Li-ion) batteries. There is an opportunity here for Latin American countries, where few battery manufacturing projects have been announced, and for India, where announced capacity would cover about 25% of its 2035 demand in the STEPS but only about 10% of its demand in the APS. By contrast, global anode and cathode manufacturing capacity is set to exceed deployment needs by a wide margin, though most of the planned capacity additions remain concentrated in China (Box 2.3).

The medium-term prospects are less promising for wind turbines and heat pump manufacturing. In the case of **wind turbines**, the majority of announced expansions are already committed, but the output from these facilities would meet only around half of what is needed in 2035 in the NZE Scenario and 75% in the APS. Based on company announcements, China's manufacturing capacity is set to grow the most, exceeding 2030 APS domestic needs by 60 GW for blades and about 100 GW for nacelles, and by over 20 GW for towers, allowing for higher exports (announced capacity in most other countries and regions falls short of deployment needs). By 2035, China would be able to provide 55% of the blades, about 80% of the nacelles and 35% of the towers needed to close the gap between deployment needs and existing manufacturing capacity in the rest of the world in the APS.

For **heat pumps**, announced capacity additions slowed markedly in 2023. Total capacity taking account of announcements is sufficient to meet only around 35% of global demand for heat pumps in 2035 in the NZE Scenario and about 45% in the APS. However, announcements may not be a reliable indicator of future capacity, as most manufacturers outside of Europe do not usually make public their detailed investment plans. In addition, the lead times for factory expansions, converting a plant from making air conditioners to heat pumps production, or building new factories are relatively short, at 1-3 years, allowing capacity to follow demand trends more easily.

China accounts for 30% of the total manufacturing capacity that could be operational by 2030 for **electrolysers**. Its existing capacity of 15 GW, nearly 60% of the world total, is already sufficient to meet its needs in 2030 and, together with planned additions, about half of global needs in 2035 in the APS. This would allow for a significant volume of exports, though Chinese manufacturers would need to modify their current designs to comply with the standards required in other regions (Hydrogen Insight, 2023), and to respond to doubts about equipment reliability that have arisen from the operational problems seen at the country's largest project to date, at the 260 MW Kuqa facility in northwest China (Hydrogen Insight, 2024).

Box 2.3 Anodes for batteries and wafers for solar PV: blind spots for the diversification of clean energy technology supply chains?

Anodes are an important component in Li-ion batteries, though they make up a small share of total production costs. Anodes are almost exclusively made of graphite, whose properties are key to the performance of the battery, its cycle life (how long the battery can be used) and its safety. The main difficulty in establishing or boosting the production of anodes is access to the expertise and skills needed to produce high-quality graphite. Today, about 90% of graphite anodes are produced in China, which recently introduced export controls. This led to an initial decrease in exports, but they rapidly returned to previous levels and the impact on the industry has been limited so far (GACC, 2024).

The current level of regional concentration, together with the financial risks facing new entrants, makes anode production the single biggest barrier to meeting local content requirements in other countries. China's anode manufacturing capacity already exceeds that required to meet current global demand by at least seven times. Taking account of committed projects, it would exceed global needs in 2030 by a factor of five in the STEPS and three in the NZE Scenario. This has already driven prices down to levels that are too low for new entrants to the market to be competitive, given the large economies of scale enjoyed by existing Chinese producers. In addition, potential new entrants are discouraged by the financial risks associated with Chinese producers temporarily cutting prices to protect their market dominance, as has been the case in the rare earth elements industry (BMI, 2024). Without strong policy support and long-term agreements at higher prices than the current spot price of about USD 2 500 per tonne, there is little prospect of any diversification of graphite anode supply in the near future.

An alternative approach is to develop alternative anode materials, like silicon, which is already used together with graphite to increase its energy density. Competition is less intense in this sector, which would make it easier for new producers outside China to establish themselves, though silicon is already produced at industrial scale by several large Chinese manufacturers (Tycorum, 2023). Although the silicon content in battery anodes is expected to increase over the next years, graphite is still likely to account for the largest share of all anode components.

There are similar barriers to the diversification of wafer manufacturing. China currently holds over 95% of global capacity and, even if all the facilities that have been announced are completed on time and new policies fully implemented, elsewhere, that share is not expected to fall below 90%. In addition to the risks associated with entering such a highly concentrated market, wafer manufacturing requires highly specialised machinery, including diamond wire wafer saws, wafer polishing machines, crucibles and hot-zone materials, which are mainly produced in China. This could limit the ability of investors outside China to acquire the necessary equipment. Wafer manufacturing is also highly energy-intensive, so access to low energy prices is a crucial condition for competing with existing Chinese producers.

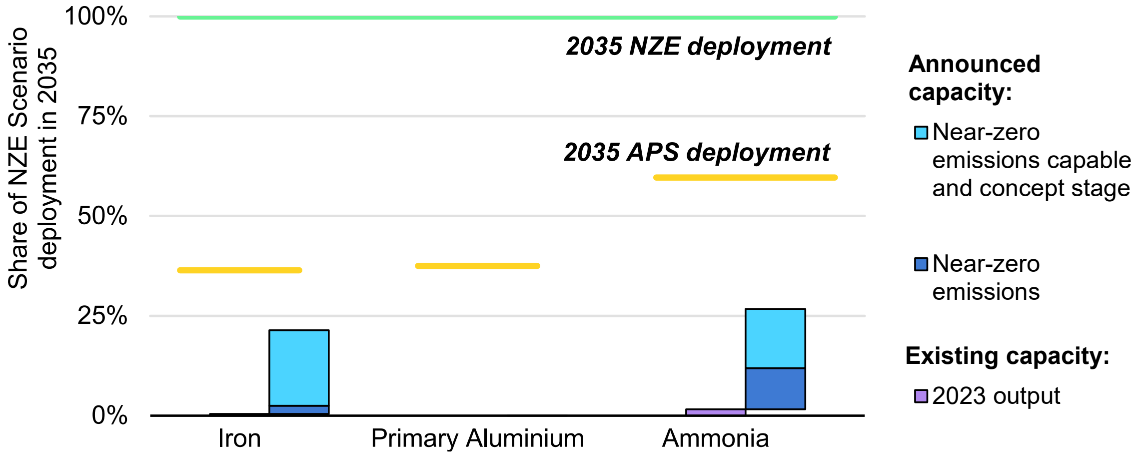
As with battery anodes, the main approach to overcoming these barriers is to develop alternative technologies. They include thin film PV cells which do not need wafers (like CdTe, CIGS or perovskites), which are at various technology readiness levels today. However, thin film PV is generally only appropriate for niche applications such as building-integrated PV that can benefit from their lightness and flexibility, which is why they only account for about 2.5% of solar PV modules produced worldwide today (Fraunhofer ISE, 2024). The prospects of boosting use of thin-film PV are also complicated by its higher cost and use of critical materials that are scarcer than silicon. Another approach is to use other processes for wafer production, like epitaxy, but epitaxial wafers are also more complicated and expensive to produce.

Materials

Today, global steel capacity exceeds production by more than 500 Mt and the problem of excess capacity is expected to persist in the future (OECD, 2024). Current ammonia capacity worldwide is sufficient to meet demand in 2030 in the STEPS, while global aluminium capacity needs to increase to meet growing demand.

In the APS and NZE Scenario, there is a sizeable gap between planned capacity and projected deployment for near-zero emissions technologies to produce iron, primary aluminium and ammonia (Figure 2.12). Among the three materials, plans involving these technologies – using low-emissions hydrogen; carbon capture, utilisation and storage (CCUS) or another technology that results in the majority of emissions being abated from the start of operation – are most advanced for ammonia and steel. For steel, there are an increasing number of projects based on low-emissions hydrogen in DRI furnaces, either immediately on commissioning or after a transition period involving the use of natural gas. There are just two commercial scale CCUS-equipped facilities operating today in the steel sector today, one in Abu Dhabi (though the 0.8 Mt of CO_2 of nameplate capacity represents only a portion of the plant's total emissions) and the other in China (where CO_2 is recovered from a DRI plant and used in downstream processes). The Hybrit demonstration project in Sweden produced its first steel with hydrogen in 2021 (HYBRIT, 2021). If all announced projects came to fruition, of which 55% are in Europe, near-zero emissions technologies for making iron would meet around 60% of the total required in 2035 in the APS and more than 20% in the NZE Scenario. Taking just those projects that have firm plans in place, the share drops to 6% and 2% respectively.

Figure 2.12 Announced annual capacity for near-zero emissions production of iron, primary aluminium and ammonia as share of deployment in 2035 by technology and scenario



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Notes: APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Includes ammonia for existing and energy applications.

The project pipeline for near-zero emissions materials production does not meet the 2035 requirements of either the APS or NZE scenarios, for any materials.

For near-zero emissions aluminium and alumina production, the outlook is less sanguine, despite aluminium smelting based on hydroelectricity already being widely deployed. There are just a handful of demonstration projects under development at the moment, notably the Elysis project in Canada, Arctus & Trimet in Europe, and RUSAL in Russia (all developing inert anodes), an aluminium chloride process through Norsk Hydro (Norway), and mechanical vapour recompression & hydrogen for alumina production in Australia, but significant progress on innovation must take place before they can be commercialised at scale. This suggests that meeting the deployment needs of the APS and NZE Scenario, which reach 5 Mt and 13 Mt of aluminium produced with near-zero emissions technologies in 2035 respectively, is likely to be extremely difficult.

For ammonia, there are already a handful of CCUS-equipped facilities, mainly in China and North America, but only a small number of electrolyser projects with negligible capacity. Based on the pipeline of announced projects, most of which are electrolysis-based projects and explicitly target new energy applications for ammonia demand, about 10% can be considered committed, 35% are in feasibility studies, and the remainder are at concept stage. Those projects combined would meet over 40% of the needs in 2035 in the APS and 25% in the NZE Scenario.

Manufacturing trends by technology and scenario

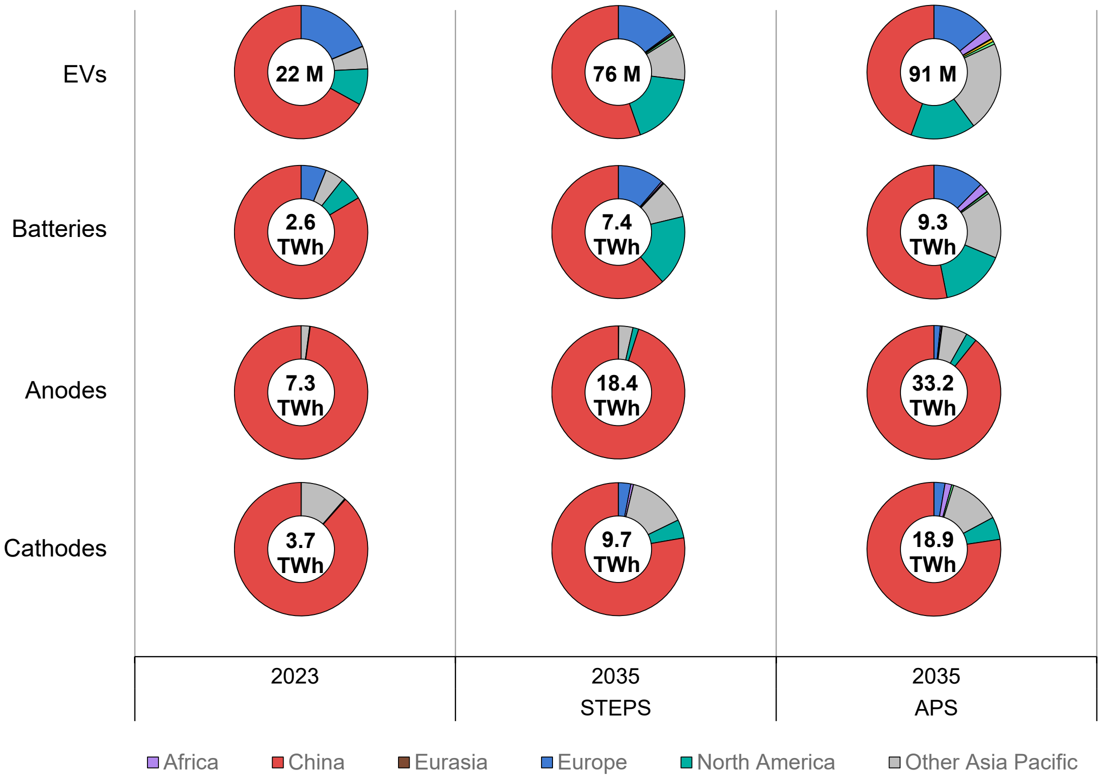
EVs and batteries

Global EV manufacturing capacity stood at more than 22 million units at end-2023, two-thirds of which is in China, 20% in Europe, 10% in North America and most of the rest in Korea and Japan. In the STEPS, global capacity rises more than three-fold to almost 76 million units in 2035 (Figure 2.13), with a large part of the additional manufacturing capacity coming from repurposing conventional car assembly plants. Capacity expands in all currently producing regions, although the combined effects of a large market, policy support and free trade agreements (FTA) mean that capacity grows most in North America, reducing China’s share in global production somewhat (see Chapter 3). Southeast Asia emerges as an increasingly important hub for EV manufacturing, with a 5% share of the EV manufacturing capacity outside China in 2035, building on recent project announcements from companies like BYD, the largest Chinese EV manufacturer (which has announced plans to set up manufacturing facilities in Thailand and Indonesia) as well as local champions like VinFast, which accounts for nearly all EV sales in Viet Nam today. Production capacity in India grows to over 2 million units by 2035, bolstered by the PLI Scheme and tariffs on imported vehicles.

In the APS, global capacity increases to over 90 million units in 2035 in response to growing demand in line with government climate ambitions. Much of the additional capacity over and above that in the STEPS comes from countries in the

Asia Pacific region, including India, Thailand and Indonesia, boosted by their relatively low production costs, growing domestic demand and a supportive policy environment. Production capacity grows quickly to nearly 4 million units in Indonesia, expanding on the country's ambition to produce 600 000 EVs domestically by 2030 (Setkab, 2022). India's aspiration to become a net exporter of clean energy technologies by 2030 translates into an increased production capacity of 6 million units by 2035. Similarly, Brazil's ambition to be a major hub for EV manufacturing under their MOVER plan is reflected in a production capacity of almost half a million units by 2035. Manufacturing capacity in North Africa is set to make significant inroads in the APS by 2035, reaching more than 2 million units. This capacity expansion builds on emerging project announcements in countries such as Morocco and would be sufficient to supply nearly four times the EV demand in the region, thereby enabling it to export to large EV markets nearby, such as in Europe. As a result, China's share of global manufacturing capacity falls by over 20 percentage points between 2023 and 2035 to 45%.

Figure 2.13 Annual manufacturing capacity for EVs, batteries and components by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; M = million units; EV = electric vehicles, specifically passenger cars and pick-up trucks. Batteries includes all EV types and stationary storage.

Global EV and battery production capacity rises in all scenarios, with geographic diversity increasing for EVs and battery cells but remaining concentrated for battery components.

Battery cell manufacturing capacity also becomes more geographically diverse in all scenarios, initially due to major planned investments in North America and Europe, and later in EMDEs, where relatively low production costs make them an attractive destination for new capacity. China's share of global cell manufacturing capacity in 2035 falls to 60% in the STEPS and 50% in the APS, despite their production costs remaining highly competitive. Strong domestic demand growth drives continued rapid growth in capacity in both advanced economies and EMDEs, with many other countries in the Asia Pacific region becoming exporters (see Chapters 3 and 4). North Africa, and in particular Morocco,[8] becomes a large producer of battery materials and cells, which are used to supply domestic EV manufacturers (with production of 1.8 million cars in 2035, about 70% of which are exported, mostly to the United States and Europe) in the APS.

As with EVs and battery cells, both cathode and anode global manufacturing capacity diversifies in all scenarios, though to a much lesser extent than cells. North America, Europe and Asia see the biggest increases in the share of global manufacturing capacity in both the STEPS and APS. For cathode active material, China's share of global capacity drops from 90% in 2023 to around 75% in 2035 in both scenarios. Anode active material manufacturing capacity is even more concentrated in China, which accounts for almost all (98%) capacity today. The Chinese share decreases over time in all scenarios, but it remains between 10% and 20% higher than cathodes for all years in both scenarios.

The diversification of cells, cathode, and anode active materials supply is greater than that of capacity, as the average utilisation rate of Chinese facilities is expected to be lower than in other countries due to excess capacity. Chinese share of global battery cell production decreases from 75% in 2023 to 65% in 2035. In the APS, this falls further to 55% in 2035. Similarly, the Chinese share of cathode production decreases from 80% in 2023 to 70% in 2035 in STEPS, and to 60% in the APS. Anode production also diversifies more than manufacturing capacity only in the APS, with China's share remaining around 90% in STEPS and dropping to 70% in the APS.

Solar PV

The heavy concentration of solar PV production in China is set to decline only mildly as planned projects and supportive policies in other countries stimulate additional investments in manufacturing capacity in the longer term (Figure 2.14). In the STEPS, US capacity in 2035 reaches around 90 GW for modules, 35 GW for cells, 20 GW for wafers and 30 GW for polysilicon, while in the APS it reaches

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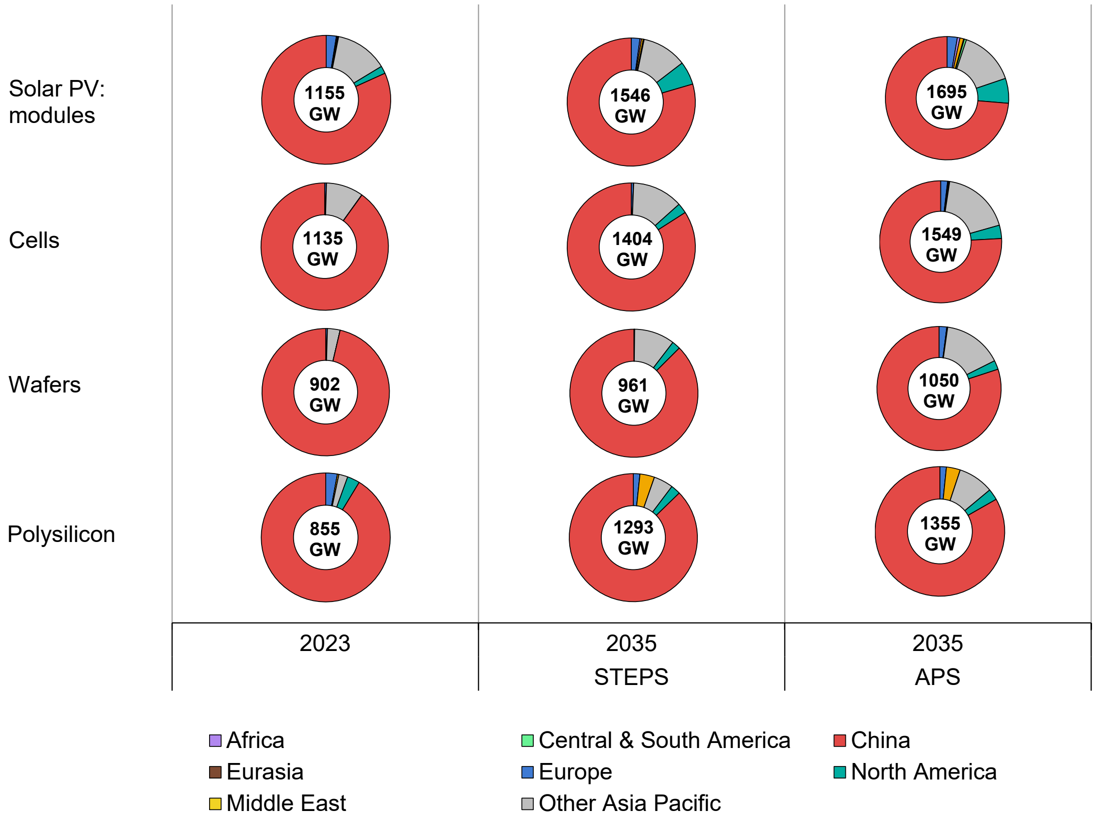
[8] Morocco has the world's largest reserves of phosphate and an established car manufacturing sector. It also has free trade agreements with both the European Union and the United States. Investments of more than USD 15 billion for lithium phosphate cathodes and battery production have already been announced (Bloomberg, 2023).

slightly over 100 GW for modules, and around 50 GW, 25 GW and 40 GW for cells, wafers and polysilicon respectively. Indian capacity reaches about 80 GW for modules, 70 GW for cells and 50 GW for wafers and 35 GW for polysilicon in the STEPS, and around 120 GW, 105 GW, 90 GW and 80 GW respectively in the APS. In both countries, growth in domestic capacity is more easily achieved for the downstream components of modules and cells, which are more easily accessible (as evidenced by the greater number of countries with manufacturing facilities). In the European Union, the APS reflects faster growth in capacity stimulated by the NZIA, with the target to meet 40% of demand from domestic production assumed to be met. In both scenarios, Southeast Asia remains an important supplier of PV components, becoming even more so upstream and taking a larger share of global output.

Figure 2.14 Annual manufacturing capacity for solar PV components by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

Strong regional concentration of global solar PV production in China is set to decline only modestly as planned projects elsewhere come to fruition.

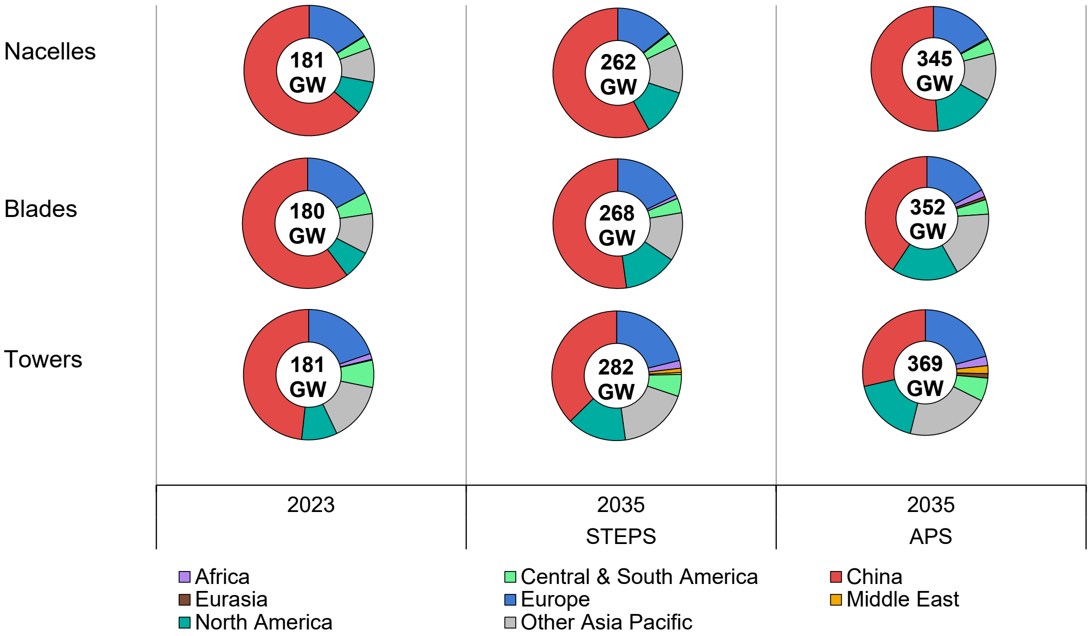
In addition to domestic deployment, the differences in the rates of capacity expansion between regions to 2035 in both scenarios are driven largely by the current state of capacity expansion plans and government policies. In the longer term, differences in cost fundamentals are likely to become increasingly important. Variable operating costs make up about 80% of the Levelized cost of production (LCOP) of solar PV modules, including all the components – predominantly for material inputs (around 50%) and energy (30%) (see Chapter 1). The prices of materials vary much less across regions than those of energy, so the latter is a more important determinant of the location of new solar PV supply chain investments – especially in polysilicon and wafer production, which are the most energy-intensive. This gives a strong competitive edge to regions with low energy prices, including China, India, Southeast Asia and the Middle East. For modules and cells, the use of aluminium and silver, respectively, are important considerations, so innovations that substitute or use less of them (such as frameless modules) can offer a significant cost advantage. In the case of cell and wafer manufacturing, capital expenditures account for a proportionally larger share of the LCOP, favouring China and the advanced economies due to their easier access to cheap capital.

Factors other than cost also influence the location of new manufacturing operations, including the existence of manufacturing capacity in other parts of the supply chain and access to infrastructure (see Chapter 1). A large domestic market, resulting either from pre-existing comparative advantages or policy support, is also an important factor for downstream manufacturing development, particularly for regions with low costs like Africa and especially over the longer term (see Chapter 4).

Wind turbines

Global manufacturing capacity of nacelles, blades, and towers for wind turbines amounted to 180 GW at end-2023, with production totalling about 125 GW over that year. Most of this capacity is China (60%) and Europe (15%), which roughly matches where the finished turbines are installed (Figure 2.15).

Figure 2.15 Annual manufacturing capacity for wind turbine components by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; Capacities between components may differ from each other, whereas the demand is the same across components.

Blade and tower manufacturing is set to become more geographically diverse, although China continues to account for the lion's share.

In the STEPS, committed projects, of which 90% are in China, fall 5% to 10% short to supply the 195 GW peak in demand in 2030 depending on the component. In the APS, the gap widens, even though preliminary plans are assumed to be realised, with a shortfall of 70 GW to 80 GW in 2030, equal to 25% of global demand. In the APS, it is likely not going to be possible to use all available and announced manufacturing capacity to meet global demand due to regional supply or demand mismatches, high shipping costs or tariffs and local content requirements, so even more capacity would need to be added.

In the STEPS, capacity is only expanded where turbines are already produced today and where production costs are favourable. This is the case in the United States thanks to financial support from the IRA, as well as in Mexico and Türkiye, where blade manufacturing is expanded due to increasing demand in neighbouring regions and relatively low production costs. The shortfall in available and announced manufacturing capacity in the APS provides an opportunity to scale up manufacturing, including in countries and regions that do not produce wind components today, such as in North Africa and Southeast Asia. In the APS, they start producing to meet regional demand, benefiting from low labour costs and relatively good access to port infrastructure that can (or will be able to) handle bulky components. This leads to a more diversified blade manufacturing landscape by 2035, with the share of China in global output dropping from 65%

today to 30% in the APS (compared with 40% in the STEPS). For nacelles, which are easier to transport, China remains the dominant manufacturer.

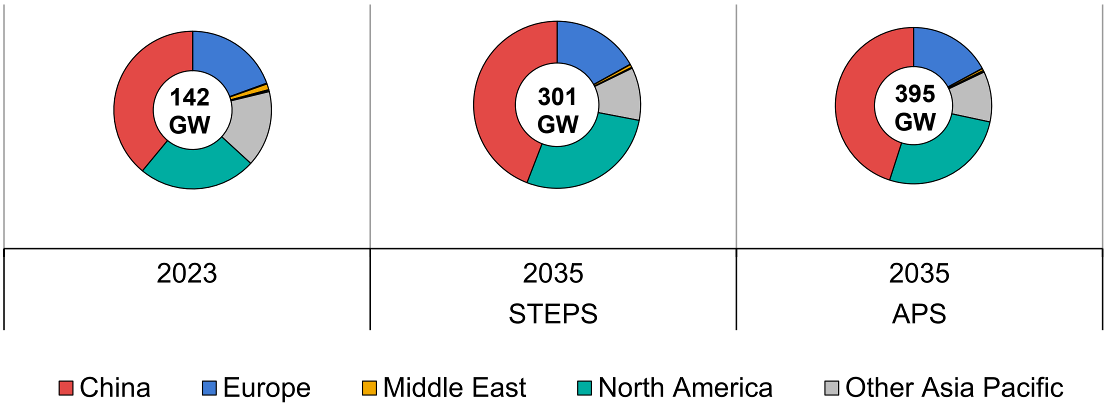
As for solar PV, the location of future manufacturing facilities for wind energy components depends on several factors other than cost, especially access to transportation infrastructure and the distance involved in shipping the turbines to the wind farm. Turbines, especially for offshore projects, are extremely heavy and bulky, so are difficult and costly to transport. This favours local production, even where overall production costs may be significantly higher than in some other regions. Domestic content requirements also drive investment in some countries, such as Brazil and the United States.

Heat pumps

In addition to the basic cost of production, the location of heat pump manufacturing is largely determined by the availability of skilled labour, infrastructure, the reliability of power supply and proximity to both demand centres and suppliers of components and materials. China has a clear competitive advantage with respect to all these factors, which is why it remains the largest manufacturer globally. Yet the rapid growth in demand outside China – alongside supportive government policies and the need to meet local design and installation standards – could favour domestic production, especially in Europe and North America.

In the STEPS, domestic production of heat pumps increases in most regions, but there is no significant change in the geographic concentration of supply. China maintains its leading role in manufacturing, more than doubling existing manufacturing capacity and boosting its share in the global total from about 40% in 2023 to about 45% by 2035. (Figure 2.16)

Figure 2.16 Annual manufacturing capacity for heat pumps by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

Domestic production of heat pumps increases in most regions in all scenarios, but there is no significant change in the geographic concentration of supply.

In the STEPS, the United States remains the second largest producing country, thanks to generous financial support to manufacturers under the IRA, though capacity does not fully keep pace with domestic demand. Being the lowest-cost producer among North American countries, Mexico's heat pump production nearly triples by 2035, with the country exporting its surplus primarily to the United States. In the European Union, the realisation of announced projects would be enough to satisfy domestic demand until 2030.

The overall market dynamics in the APS are similar to in the STEPS, with China remaining the leading manufacturer, followed by the United States and the European Union.[9] Ambitious industrial policy plans nonetheless strengthen domestic production in some countries. In addition, countries with strong manufacturing capacity for air conditioners in Southeast Asia significantly increase their production of reversible heat pumps, approaching 10 GW by 2050, even though its share in the global total remains small, at around 2%. In the European Union, the NZIA aim of meeting 40% of domestic demand with domestic production has already been achieved for heat pumps, but announced manufacturing expansions, if implemented in full, would be enough to cover almost all the region's demand in 2030. However, imports – mainly from China, where production costs remain highly competitive – increase sharply thereafter, as demand increases rapidly.

Box 2.4 Heat pumps: an industry of differentiated markets and specialisation

How people heat their homes is influenced not only by climate, but also by cultural preferences, traditional building design, occupancy patterns and, in some cases, the availability/planning of thermal networks. As a result, it is possible to identify certain patterns in heating systems that are more common in different regions (Figure 2.17). In the United States, for example, over 80% of homes have central heating systems, the vast majority of which use ducted systems (ducts distributing heated or cooled air to rooms). In some European countries, such as the United Kingdom and Germany as well as in northern Italy, hydronic distribution systems (pipes distributing hot water to a heat terminal such as radiators or underfloor pipes) are the most common choice. In Japan and central-southern

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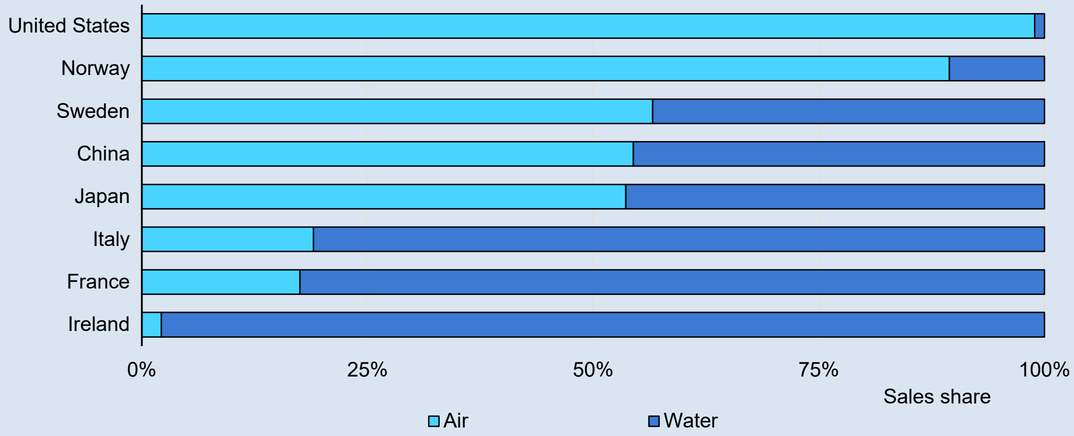
[9] An important consideration in the APS relates to more stringent energy efficiency policies that affect not just the efficiency but also the type of unit sold in each market. For example, the US market is currently dominated by large, centralised units used in ducted systems (Box 2.4). These units remain dominant in that scenario, but more efficient reversible air-to-air units nonetheless gain market share. The manufacturing of these units is more competitive, as they use similar technology as for air conditioners. As a result, a larger number of such units are imported from Mexico than in the STEPS. For similar reasons, a larger share of heat pumps is manufactured in Southeast Asia.

China, most homes use multiple units for space heating, such as reversible air conditioners installed in different rooms. In northern China, Eastern Europe and Russia, district heating networks are the most common source of heating, and therefore most households rely on hydronic distribution systems.

Figure 2.17 Share of heat pump sales by technology in selected countries, 2023



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Notes: Air and water refer to how the heat is distributed throughout the building. This includes water heaters and excludes large geothermal units. Sales share is in capacity terms.

Source: IEA analysis based on data from national associations.

Beyond the investments needed to adapt existing buildings to a different heating distribution system, it can also be hard to change preferences in new buildings. Cultural preferences and architectural heritage influence the type of heat pumps that are bought and manufactured in different places, as well as those that are traded internationally. As a result, heat pumps are not a widely traded commodity (only about 25% of global production was traded in 2023) compared with other mass-produced clean energy technologies such as solar PV modules or batteries.

The fact that equipment is adapted to local conditions gives local heating equipment manufacturers a competitive advantage, as they are already familiar with local preferences and standards. In Japan, for example, a specific type of heat pump water heater was developed only to serve the local market with features not common elsewhere (Heat Pump and Thermal Storage Center of Japan, 2024). This differentiation of heat pump markets also stimulates manufacturers to tailor their business strategies to particular markets. Those that can compete with local producers elsewhere on cost and quality can have dedicated specialised production lines for exports. For example, it is estimated that Chinese heat pump manufacturers exported 8.5 GW of heat pumps to the European Union in 2023 despite different consumer preferences and specifications in the two markets.

Electrolysers

Global electrolyser manufacturing capacity amounted to about 25 GW at the end of 2023, with almost 60% concentrated in China and one-fifth in Europe. This capacity is currently underutilised, as only 2.5 GW was produced in 2023.[10] Of all the installed water electrolyser capacity of 1.4 GW by 2023, less than 15% was traded internationally (IEA, 2024b). Based on announced projects for electrolyser manufacturing, more than 165 GW could be operational by 2030, but only about 15% of the new capacity is committed. One-third of the total planned capacity that could be operated by 2030 is in China.

Current manufacturing capacity is almost enough to cover global demand in 2035 in the STEPS, with the committed projects taking capacity well beyond this scenario. In the APS, manufacturing capacity increases fivefold compared with today, reaching about 125 GW by 2035 (Figure 2.18). China remains the leading manufacturer, producing more than half of the world's electrolysers in 2035; the share of the advanced economies increases only slightly thereafter. Nevertheless, China's share of global manufacturing capacity declines from today's 60% to around 45% by 2035 in the APS, as several EMDEs enter the market to cover increased domestic demand. By 2035, Europe and the Middle East will each contribute 15% of global manufacturing capacity, the United States 11%, and India 7%. With increasing demand for electrolysers in India and Middle East, driven by the potential to produce low-emissions hydrogen to supply domestic demand and to export, manufacturing facilities are developed in these regions from 2030 onwards. Manufacturing capacity in Latin America reaches 1 GW after 2030, reflecting current plans to kick-start the industry.[11] The share of advanced economies in global manufacturing capacity goes down by almost ten percentage points by 2035 in the APS. Europe and the United States account for 15% and 10% of global capacity in 2035 respectively, driven by increased demand for low-emissions hydrogen to decarbonise industry and transport.

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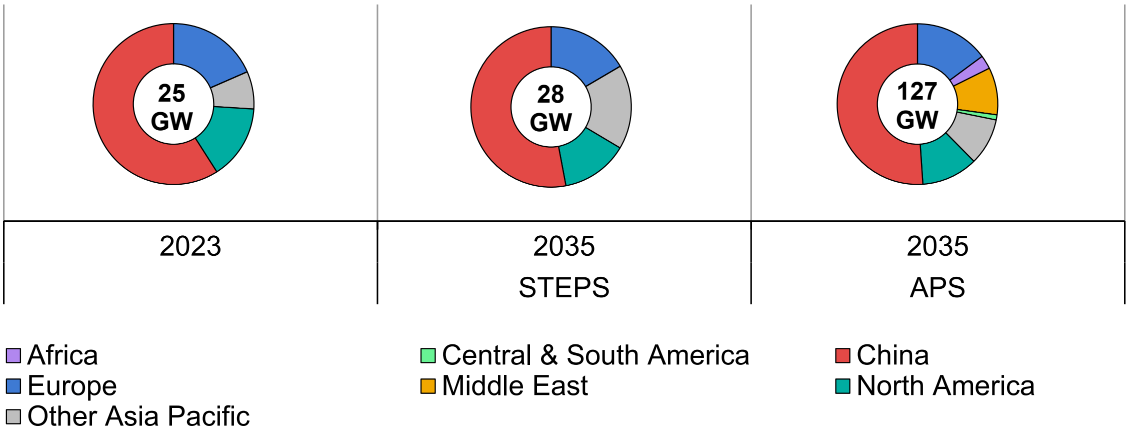
[10] This estimate includes manufacturing of electrolysers for the chlor-alkali industry, which has been traditionally the core market for electrolysers, as well as water electrolysers manufactured for dedicated production of hydrogen, which is now the largest market for electrolysers.

[11] In Chile, CORFO's call for electrolyser manufacturers to establish facilities in the country has received interest from several companies: expressions of interest for six plants, each with a capacity of 0.5-1 GW, have been submitted.

Figure 2.18 Annual manufacturing capacity for electrolysers by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

China dominates electrolyser manufacturing today, with 60% of global capacity, a share that remains high in both scenarios to 2035.

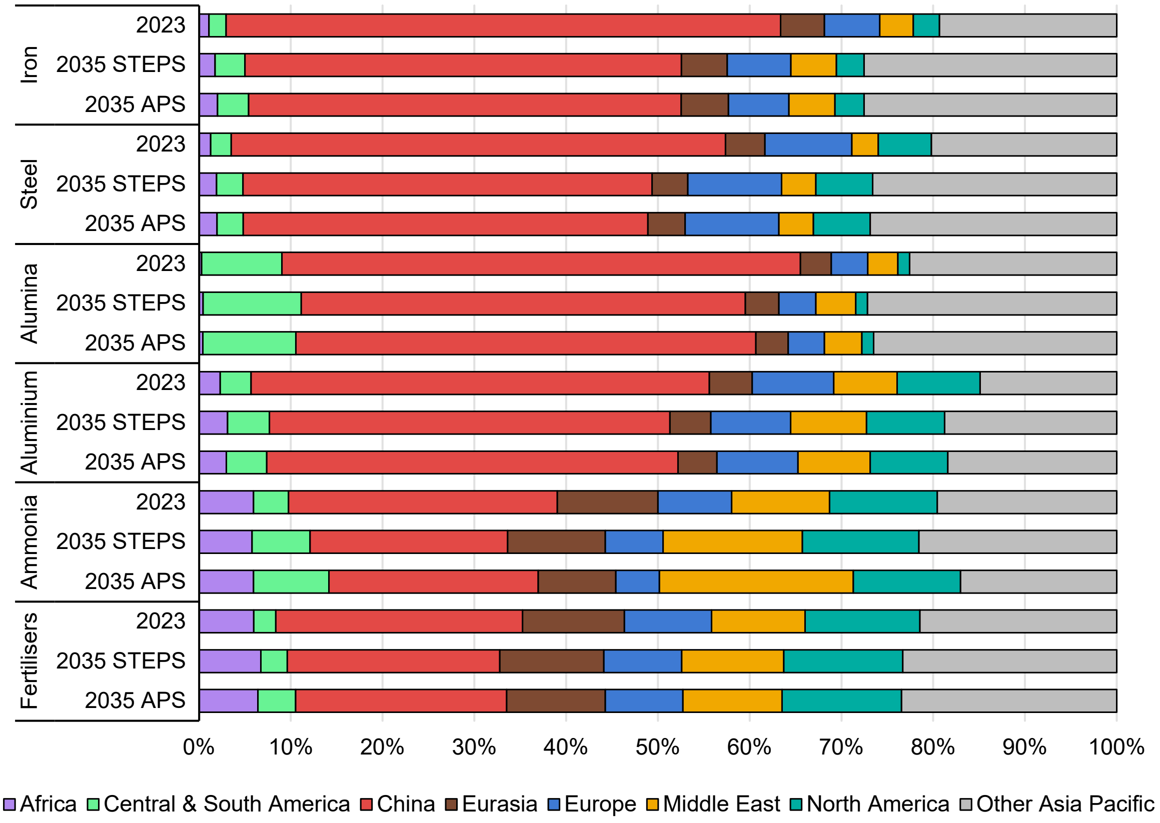
Manufacturing costs in 2035 are projected to be 35% lower in China than in the United States or the European Union in the APS, due to the lower cost of labour, energy and construction. The economies of scale from mass-manufacturing should continue to drive down costs. China remains the lowest-cost producer in both the STEPS and APS, though cost is not the only driver of manufacturing capacity deployment and opportunities for electrolyser manufacturing emerge in other regions, particularly in the APS.

Materials

Historically, the production of materials was concentrated in advanced economies, but China has emerged as the leading producer since the early 2000s. The majority of China's production is for domestic use in construction and manufacturing, but a significant share of finished products is exported. China is today by far the world's biggest producer of steel and aluminium, with 54% and 50%, respectively, of global production in 2023. While still the largest single producer, China is less dominant in ammonia and fertiliser production, accounting for 29% and 27% of global production, respectively, largely because this is already enough to fulfil domestic demand.

China's dominance is set to decline as production in other EMDEs increases and as China's economy restructures, pivoting away from energy-intensive manufacturing. Production limits imposed by the government on steel and primary aluminium in China, to reduce energy consumption, improve air quality and address surplus capacity, also contribute to this shift. In the STEPS, China's proportion of global production drops slightly to around 45% for steel and aluminium, and 25% for fertilisers in 2035 (Figure 2.19). The decline is similar in the APS. In both scenarios, the decline either remains similar or gets faster after 2035 as other EMDEs ramp up the construction of infrastructure needed to facilitate the large-scale manufacturing of those materials. By 2035, the share of production in other EMDEs reaches 35% for steel, 35% for aluminium, and 55% for ammonia (up from 23%, 27% and 50% today) in the APS. The regional distribution of production in the two scenarios is generally similar, with some important differences, including the bigger role of Africa and Latin America in iron and ammonia production in the APS thanks to low-cost renewables providing a competitive advantage for near-zero emissions production technologies, which play a much bigger role globally than in the STEPS. Conventional iron production also increases in other EMDEs outside of China.

Figure 2.19 Production of key materials by country/region in 2023, and in the Stated Policies and Announced Pledges Scenarios, 2035



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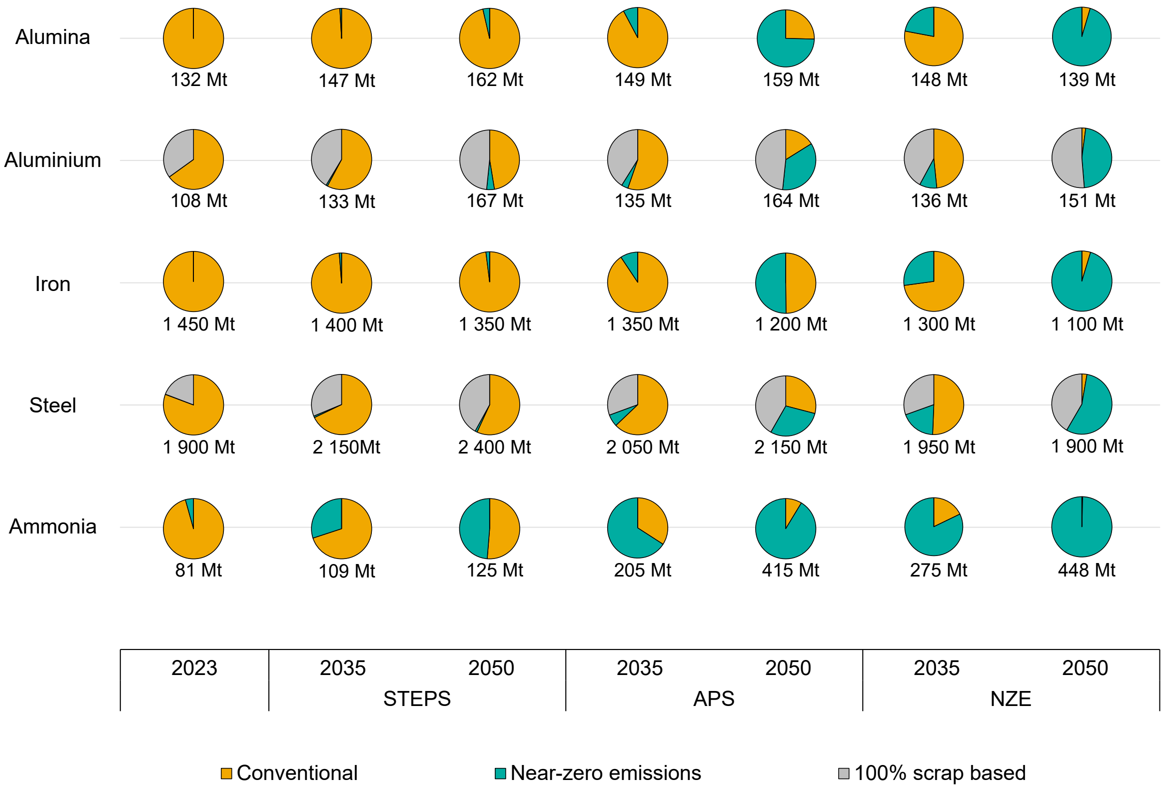
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Includes ammonia for fuel applications.

Materials production is today concentrated in China, but its lead is set to narrow as its economy restructures, domestic demand plateaus and production in other EMDEs grows.

Near-zero emissions technologies

The deployment of near-zero emissions technologies for making materials is concentrated in a few locations initially, as there are only a few projects planned. In the APS, only 10% of iron is produced this way in 2035, rising to 50% in 2050, with the same figures for primary aluminium being 6% (2035) and 70% (2050), 8% (2035) and 75% (2050) for alumina, and for ammonia, 65% (2035) and 90% (2050) (Figure 2.20). These technologies generally rely more on electricity as the main energy input, either directly or indirectly for producing electrolytic hydrogen. These technologies include hydrogen DRI (H_2-DRI), inert anodes and mechanical vapour recompression for aluminium and alumina respectively, and production based on electrolysis for ammonia and fertilisers.

Figure 2.20 Global materials production with near-zero emissions and conventional technologies by scenario, 2023-2035



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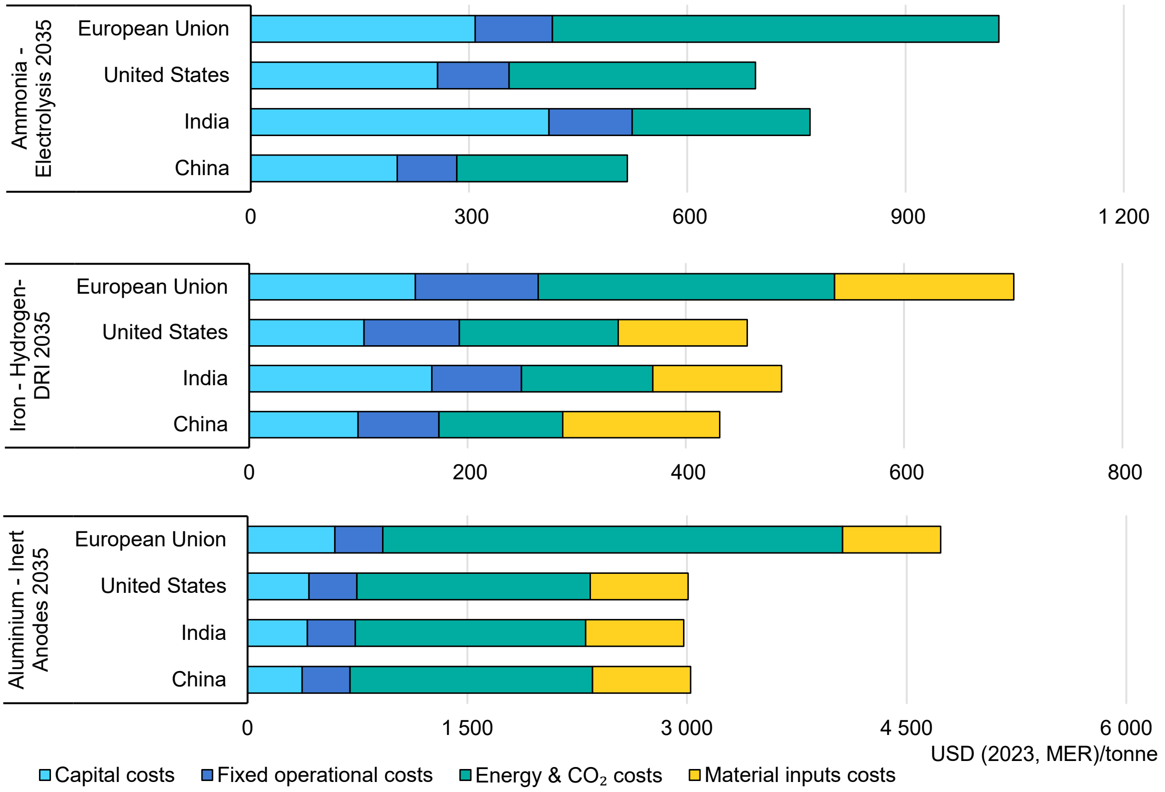
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. The figures for ammonia exclude the portion destined for urea production with fossil CO_2 as a feedstock. The figures for alumina include only metallurgical alumina. Values for iron and steel are rounded to the nearest 50 Mt.

Demand for and production of materials produced using near-zero emissions technologies expands quickly in the APS and the NZE Scenario.

Regions with abundant low-cost renewable energy resources, such as Latin America and the Middle East, enjoy low costs for producing materials using near-zero emissions technologies. Costs are generally high in the European Union, due mainly to high energy and CO_2 prices (Figure 2.21). These technologies are slightly more capital-intensive than conventional technologies, favouring regions with lower capital and construction costs. There are also transport cost savings from locating production close to growing demand centres, many of which also have abundant low-cost renewables.

Figure 2.21 Indicative levelized cost of production for selected near-zero emissions materials production routes by country/region in the Announced Pledges Scenario, 2035



Notes: DRI = direct reduced iron. Grid electricity prices used for electricity consumption (outside of that for hydrogen production through electrolysis).

Near-zero emissions technologies generally rely more on electricity as the energy input, favouring regions with low-cost renewables.

The growing deployment of near-zero emissions technologies has an important impact on the siting of new materials production facilities. These technologies do not drastically change the process for making alumina or aluminium (at least in comparison to iron or ammonia), and so do not change the factors that affect the choice of location. For aluminium, primary production has always been co-located near low-cost electricity generation, such as hydropower in Canada or Norway, coal in China and gas in the Middle East. Processes using inert anodes or CCUS generally have the same energy requirements and so the siting factors remain similar to those for conventional processes. For alumina, near-zero emissions technologies such as hydrogen calcination or mechanical vapour recompression for process heating increase overall electricity demand, so may favour locating new facilities in regions of low-cost renewable energy.

By contrast, both CCUS-equipped fossil-based and electrolytic hydrogen-based routes for the production of ammonia and iron can differ markedly from conventional routes, both with respect to the process equipment and the main fuels used, and so change the siting of new production. CCUS-equipped technologies require access to CO_2 transport and storage infrastructure and electrolytic hydrogen benefits from access to low-cost, low-emissions electricity, both favouring production in locations like the Middle East, Latin America and Africa. Outside of China, other EMDEs see an increase in the global share of ammonia and iron production in the APS relative to the STEPS. These opportunities are explored in Chapter 4.

There are few policies currently on the books that would help overcome the cost premiums associated with using these technologies, which is why their penetration is so limited in the STEPS. The one exception is the United States, where the IRA already provides sufficient incentives to make steel and ammonia using CCUS and hydrogen. Otherwise, production of these materials using near-zero emissions technologies is limited to a handful of projects that have already reached FID or are under construction.

In most large materials-producing regions in the APS and worldwide in the NZE Scenario, there is a gradual shift to near-zero emissions technologies in response to stronger climate policy action. Deployment by 2035 is limited in all scenarios because of the long lead times of these technologies: in many cases, they have not yet been demonstrated at commercial scale.[12]

Deployment of these technologies occurs on a much larger scale in the APS and especially the NZE Scenario in the longer term. In the APS, 50% of iron, 70% of primary aluminium and 90% of ammonia globally are produced using these technologies in 2050, rising to 95%, 95% and 99% respectively in the NZE Scenario. The small remaining portions of conventional primary production in the NZE Scenario are unabated blast furnaces and smelters that are constructed (mainly in EMDEs) during the late 2020s and that are still in their first investment cycle.

Scrap-based production – a commercially available technology that can produce steel and aluminium with substantially lower emissions than primary production

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[12] See the IEA's Clean Energy Technology Guide for a current snapshot of the technology readiness level and development milestones for each of these technologies.

today – increases in line with scrap availability. Scrap-based production makes an important contribution to emissions reductions in both scenarios, but limits on the availability of scrap mean these production processes cannot fully negate the need for deployment of near-zero emissions technologies for primary production. The scrap share of metallic inputs for steel rises from 32% in 2023 to 40% in 2035 and 50% in 2050 in both the APS and the NZE Scenario. For aluminium, significant progress on reducing pre-consumer scrap (produced during manufacturing of finished products) limits the increase in the overall scrap share. Despite this, the percentage of scrap-based production in the APS and the NZE Scenario climbs from 35% in 2023 to 40% in 2035 and 50% in 2050. For both steel and aluminium, the most significant increases of scrap-based production are in EMDEs, as the development of these economies results in increases in scrap availability.

The gradual shift away from urea as a fertiliser in the APS and NZE Scenario towards alternatives like ammonium nitrate and ammonium sulphate facilitates faster deployment of near-zero emissions technologies. This shift away from fertilisers containing carbon partly reduces the need to capture CO_2 from the fossil fuel emissions streams in a conventional ammonia plant, allowing faster penetration of the production of ammonia via electrolysis.

Investment

The growing deployment of clean energy technologies calls for large investments in manufacturing plants, both for making intermediate and final products and for the materials on which they depend. Global investment needs are higher in the APS than in the STEPS, and higher still in the NZE Scenario, reflecting the faster rate of deployment for all six technologies and near-zero emissions materials covered in this report. Over the period 2024-50, aggregate investment in manufacturing of the six clean energy technologies considered and production of the three near-zero emissions materials averages USD 85 billion per year (in 2023 prices) in the STEPS, USD 170 billion/year in the APS and USD 205 billion/year in the NZE Scenario (Figure 2.22).[13]

Crucially, the average annual amount of investment that would be needed over 2024-50, even in the NZE Scenario, is less than the investment of about USD 235 billion that was made in 2023. This is explained partly by the sheer size of the existing project pipeline, for solar PV and battery manufacturing in particular, for which major investments were made over the last few years. It is also due to the fact that the need to boost manufacturing capacity and, therefore, investment tends to be higher in the early stages of the transition as demand for the

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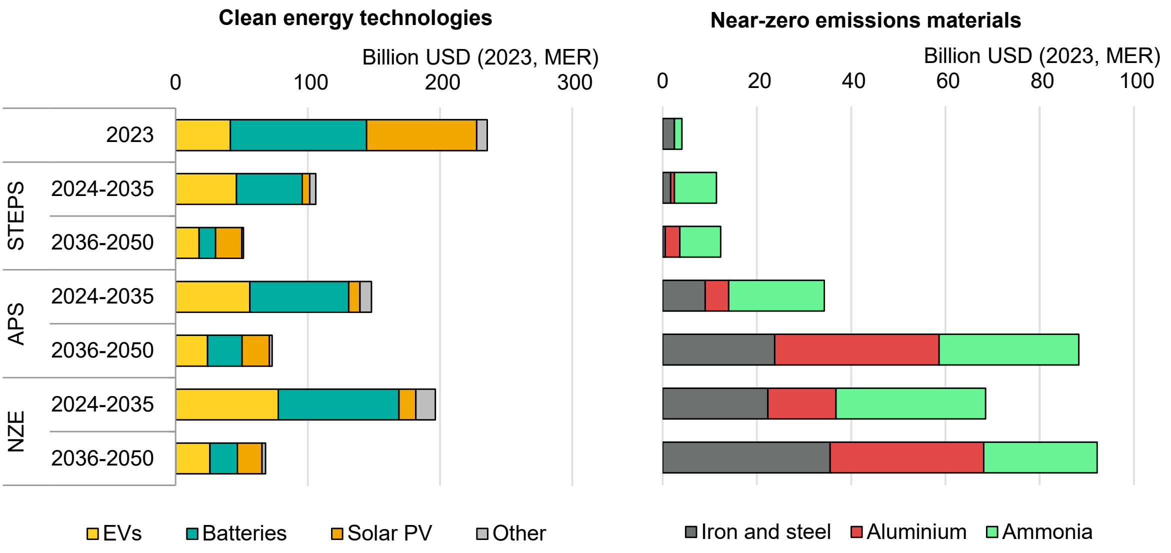
[13] Our projections of investment needs do not take account of any over-capacity that might emerge as a result of competition between companies or miscalculations of expected demand, nor the investments that might be needed to repurpose old plants or build new ones due to technological changes that would make the old plants obsolete during the projection period.

technologies is accelerating, and falls as demand growth starts to slow. In all three scenarios, average annual investment is lower in 2036-50 than in 2024-35. For example, in the NZE Scenario, the energy system is completely decarbonised by 2050, so demand for clean technologies is solely to replace obsolete clean energy products and underlying increases in energy-related services, rather than conventional fossil-based technologies. The need to build new manufacturing capacity is, therefore, much less than in the near term, when the focus is mainly on replacing existing capacity. Declining investment needs are also due to falling unit costs through a combination of economies of scale, technological advances and incremental improvements in operational performance.

Figure 2.22 Average annual investment in manufacturing of key clean energy technologies and near-zero emissions materials production by scenario, 2023-2050



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Investment in 2023 is actual investment spending while the projections relate to overnight investments. Clean technologies include components, see the Annex for more details. EV = electric vehicles, specifically passenger cars and pick-up trucks. "Batteries" includes all EV types and stationary storage.

The average annual amount of investment needed over 2024-50 in all scenarios is well below the investment of USD 235 billion that was made in 2023.

Cumulative investments to 2050 in the six key clean energy technologies analysed are one-and-a-half to seven times larger than for the three near-zero emissions materials depending on the scenario, driving investment trends. Among the key clean energy technologies (Figure 2.23), **EVs and batteries** account for the largest share of total manufacturing investment needs today and in all three scenarios. Investment is concentrated in the period to 2035, as a large share (between 75% and 85% depending on the scenario) of the global required capacity to 2050 must already be installed by then, reflecting surging demand and targets around the world to phase-out conventional passenger cars within that period. Therefore, investments over the period 2024-35 reach USD 95-170 billion depending on the scenario, compared to 2023 levels of about USD 145 billion.

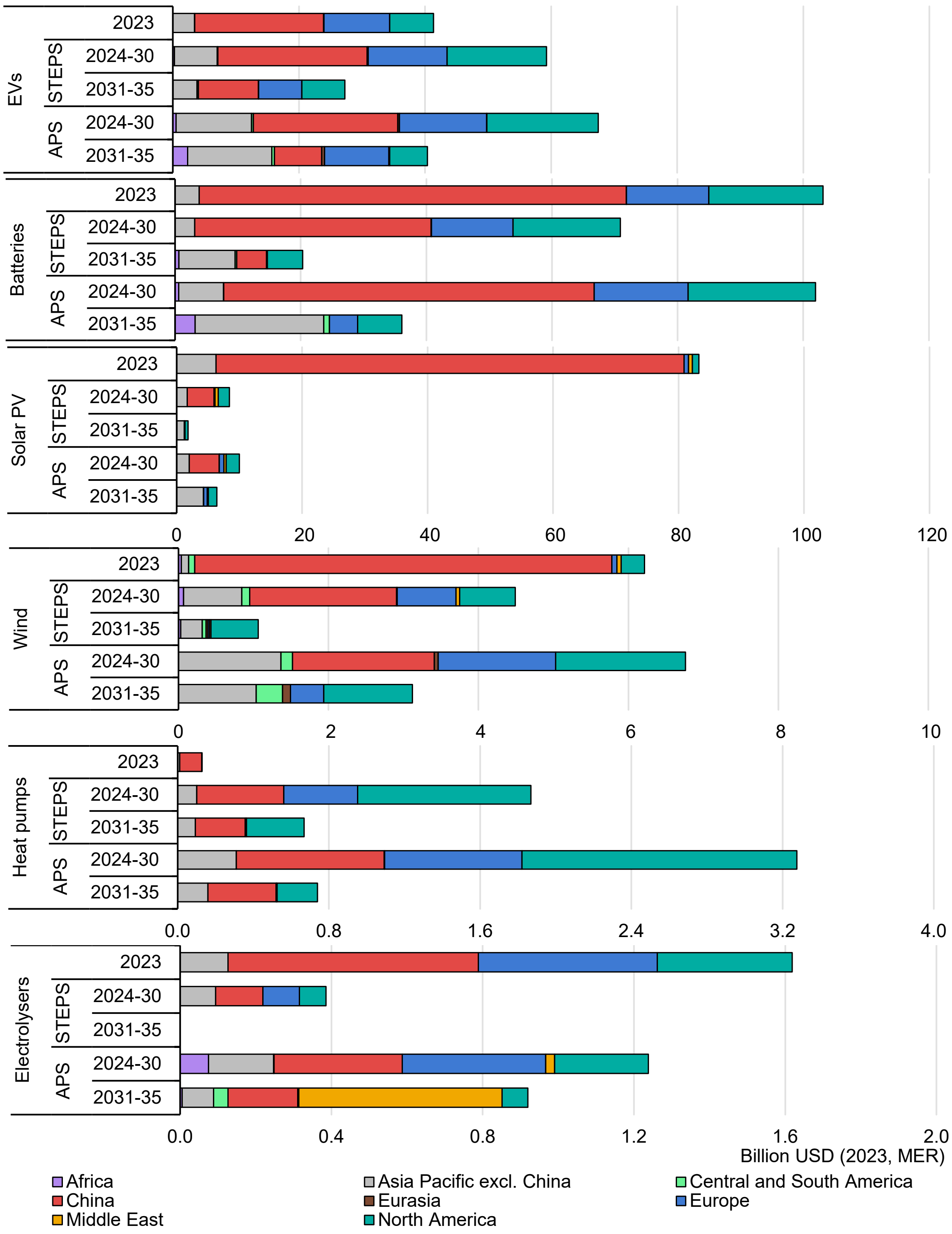
In the STEPS, nearly 40% of the investments in **EV** manufacturing capacity are projected to occur in China, which is projected to hold nearly 60% of the global capacity until 2035. In the APS, higher global electric car demand results in higher manufacturing capacity requirements, pushing up investment needs in return. Average annual investments over 2024-35 reach USD 55 billion – over 20% more than in the STEPS and about 35% more than the 2023 level. In both the APS and NZE Scenario, EV production outside China ramps up quickly, reducing China's overall share in global manufacturing capacity. As a result, about one-sixth of global investments are estimated to be made in other EMDEs over that period in the APS, and one-third in the NZE Scenario.

The race to establish **battery** production in North America and Europe and the planned expansion of the battery industry in China drive up investment, especially over the period to 2030 in both the STEPS and APS. This leaves the world with a more diversified battery supply chain, but also with significant levels of excess manufacturing capacity, reducing the need for investment later on. By contrast, investment continues to grow in EMDEs outside China.

For the **solar PV** supply chain, 2023 saw the biggest-ever increase in manufacturing capacity in both absolute and relative terms, with almost 500 GW of nominal capacity added globally for modules, 560 GW for cells and 350 GW for wafers and nearly 400 GW for polysilicon. This boosted installed capacity by 60-100% depending on the supply chain segment and involved an astonishing USD 85 billion of investment. Given that current capacity is more than sufficient to meet a significant share of the deployment, even in the NZE Scenario, average annual investment is set to fall in the next few years, from over USD 80 billion in 2023 to around USD 10 billion over 2024-30 and even lower over 2031-2035, especially in the STEPS, due to lower demand compared to APS. The bulk of investment is needed in China, the United States, India and the European Union.

Investment in **wind turbine** manufacturing peaks between 2024 and 2030 in line with the growth in demand in both the STEPS and APS, and then declines in all scenarios in the period between 2031 and 2035. In the STEPS, investment averages USD 4.5 billion per year over 2024-30. Around 45% of this investment is in China, and North America, Europe and other Asia Pacific countries each account for roughly 15%. In the APS, the share of the latter three regions, as well as North Africa and Latin America, is much higher, pushing down the share of investment in China relative to the STEPS. Global annual investment in the APS averages USD 7 billion over 2024-30. In the NZE Scenario, it averages USD 11 billion.

Figure 2.23 Average annual investments in manufacturing of key clean technologies by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investment includes components, apart from for electrolysers and heat pumps. Investment in 2023 is actual investment spending while the projections relate to overnight investments. EV = electric vehicles. Batteries include all EV types and stationary storage.

Manufacturing investment is highest in the EV supply chain, with investments in all technologies peaking by 2030.

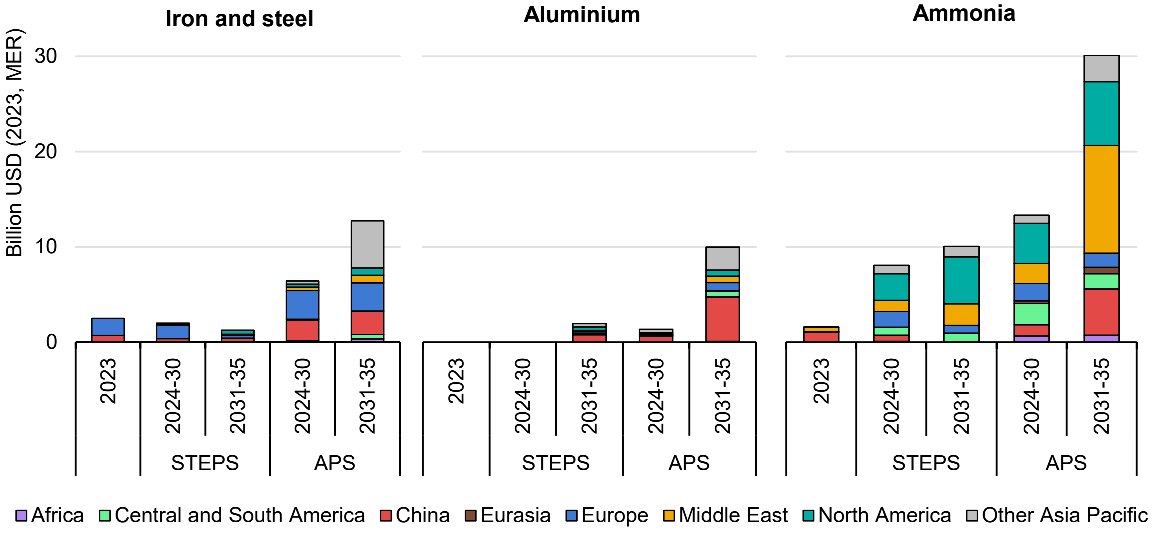
Investment in **heat pump** manufacturing also peaks in the period 2024-2030. Compared to 2023, investments increase significantly over this period, following the growth in demand. Annual investments in the period 2024-2030 reach about USD 2 billion in the STEPS, more than USD 3 billion in the APS and about USD 4.5 billion in the NZE Scenario – up from about USD 0.25 billion in 2023. Investment is concentrated in the major markets, with the fastest growth occurring in North America. China continues to expand capacity during that period to cover domestic needs and growing exports, accounting for about 25% of global heat pump investment in the STEPS and 40% in the APS. Global investment falls after 2035 and remains lower than in 2023 in all scenarios through to 2050.

Investment in making **electrolysers** also peaks well before 2035 in all three scenarios, but at a much higher levels in the APS and the NZE Scenario than in the STEPS. Less than USD 400 million needs to be invested cumulatively in new facilities up to 2050 in the STEPS given the relatively low demand and current over-capacity, all of it before 2030. In the APS, 60 GW of cumulative manufacturing capacity is built over 2024-30 – 55% of all new capacity built up to 2050. In total, the 110 GW of cumulative capacity added globally by 2050 requires on average USD 40 million per year of investment. The bulk of that investment is in regions hosting the majority of today's capacity, namely North America (30%), China (18.5%) and Europe (18%), with India attracting around 10% (most investment there is in the second half of the projection period).

In contrast to clean technology manufacturing, global investment in near-zero emissions production of steel, aluminium and ammonia is currently very low and needs to increase significantly. In the period between 2036-50, average annual investment in near-zero emissions production of these materials doubles and reaches USD 12 billion in STEPS, while it increases tenfold in the APS and NZE Scenario (Figure 2.22).

Among the three materials, the medium-term investment needs grow most for ammonia. Demand for ammonia is still increasing, and innovative technologies are entering the market faster than in the steel or aluminium sector. In the STEPS, investment in near-zero emissions steel and aluminium production increases slowly, while investment in ammonia production averages USD 2.2 billion annually between 2024-2030, driven partly by projects supplying energy applications (Figure 2.24). In the APS, investments in near-zero emissions production ramp up quickly, reaching on average USD 12 billion, USD 10 billion and USD 30 billion for steel, aluminium and ammonia, respectively, in 2031-35. Near-zero emissions technologies can be more capital-intensive than conventional production routes and, in some cases, require a completely new facility rather than refitting existing facilities and equipment. The regional breakdown of materials investment needs broadly reflects the distribution of manufacturing capacity additions.

Figure 2.24 Average annual investment in near-zero emissions production of key materials by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2035



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

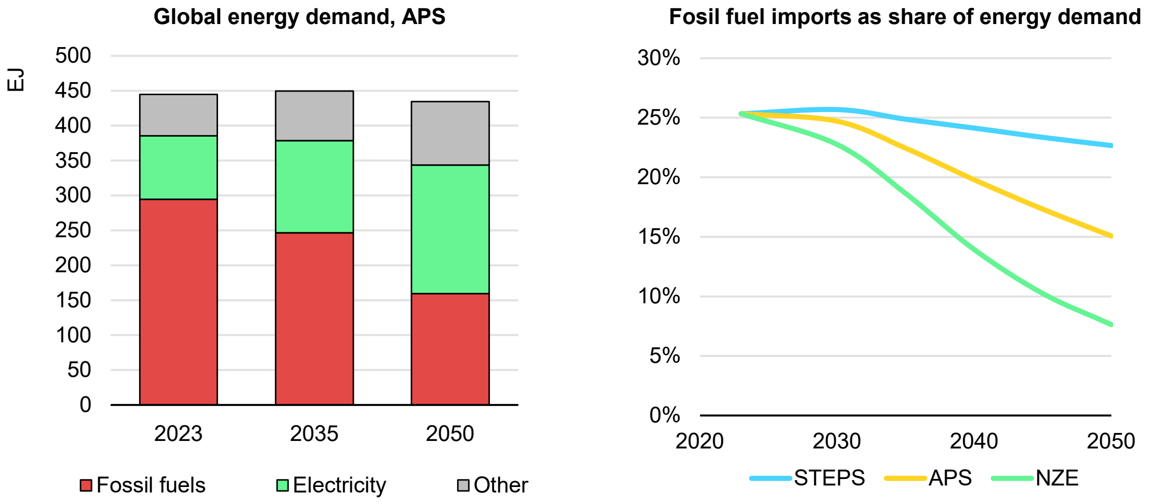
Global investment in near-zero emissions materials production is currently very low, but ramps up quickly after 2030 in the APS.

2.4 Inter-regional trade

Energy security is a key consideration for policy makers when designing strategies to meet climate goals and has a direct impact on trade flows. While disruptions in fuel supply can lead to negative economic impacts in the very short term, any disruption in the supply of clean technologies or materials has a less immediate impact. Such disruptions would not interfere in the actual operations of a country's energy system, but rather in its transformation. Supply shortages of clean energy technologies or materials can translate into higher prices for such commodities, with knock-on impacts on their uptake and on the costs of goods they are used to produce or transform, such as renewable energy. A high level of diversification in the supply of energy, technologies and materials can help moderate such negative impacts (see Chapter 6) but would have a direct impact on trade flows.

As clean energy transitions advance and become more ambitious, reliance on fuel imports gradually declines. The share of electricity in the global energy mix increases from 20% in 2023 to over 40% in 2050 in the APS, of which nearly 80% is generated by domestic renewable sources like solar, wind and hydropower. For regions and countries dependent on imported fossil fuels for much of their energy supply today, such as the European Union and Japan, the shift away from reliance on imported energy occurs more quickly than the global average. Nonetheless, significant trade in fossil fuels will continue in the coming decade in parallel to the scale-up of clean technology trade, each with its own risks and characteristics (Figure 2.25).

Figure 2.25 Global energy demand by fuel type in the Announced Pledges Scenario and share of demand provided by fossil fuel imports by scenario, 2023-2050



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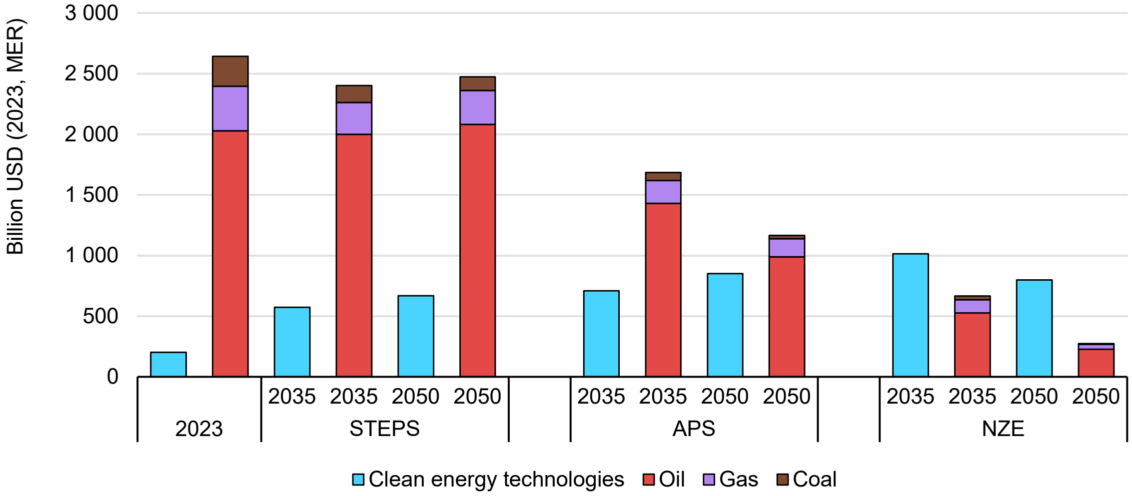
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. "Other" includes bioenergy and hydrogen-based fuels.

More ambitious climate goals lead to lower shares of total energy demand relying on fossil fuel imports, and therefore lower potential risks to supply.

Clean energy technologies

Trade in the six key clean energy technologies between the countries and regions modelled in this *ETP* was worth USD 200 billion in 2023, accounting for around 1% of the global traded value of all goods (compared to around 10% for fossil fuels). The projected growth in demand for clean energy technologies is more evenly distributed than the projected increases in manufacturing capacity over the medium term in both the STEPS and APS, resulting in growing inter-regional trade. The total traded value of the selected clean energy technologies nearly triples between 2023 and 2035 in the STEPS, reaching USD 575 billion or around 50% more than the value of global trade in natural gas today. The value of trade in clean energy technology over this period is higher in the APS, at over USD 700 billion, and even higher in the NZE Scenario at over USD 1 trillion, as global demand soars and manufacturing remains concentrated in a relatively small number of countries (Figure 2.26). The value of clean technology trade continues to grow through to 2050 in the STEPS and APS; in the APS, it is around 70% times higher than the value of crude oil trade by then. In contrast, in the NZE Scenario, the value of trade in clean energy technologies declines between 2035 and 2050, as the scenario is designed with inclusivity as a guiding principle, meaning that more supply is co-located with demand (particularly in EMDEs), thereby limiting the role of trade.

Figure 2.26 Inter-regional trade value of fossil fuels and key clean energy technologies by scenario, 2023-2050



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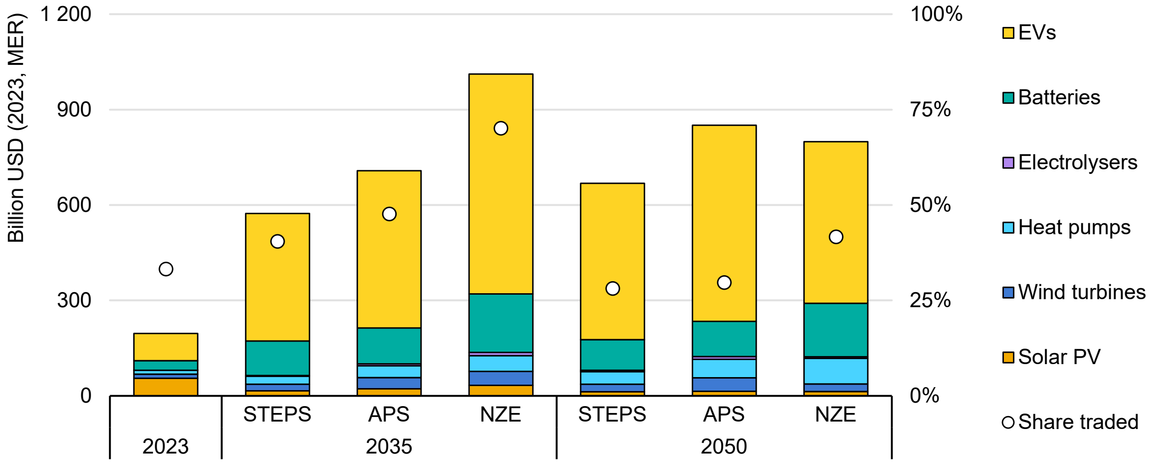
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Clean energy technologies include EVs (including batteries), solar PV, wind turbines, heat pumps and electrolysers (including components). Trade is between the countries and regions modelled in this *ETP* (see Annex for details). Oil trade is in gross terms, i.e. the sum of crude and products exports.

The geographical mismatch in demand and manufacturing capacities means inter-regional trade in clean energy technologies is set to grow, though the pace differs by scenario.

EVs remain the main driver of inter-regional trade of clean energy technologies in all scenarios. From USD 85 billion in 2023, EV trade soars to USD 400 billion in the STEPS by 2035 and thereafter increases slowly to about USD 500 billion in 2050 (Figure 2.27). By comparison, inter-regional car trade in 2023 amounted to USD 360 billion. The most important trade routes involve China, which accounts for 60% of exports, the US-Mexico-Canada Agreement countries, and Japan and Korea. In the STEPS, Europe and the United States are by far the largest importers of EVs in 2035, each accounting for a share of about 30% of global trade. Battery trade in that scenario triples over the same period to USD 75 billion, dominated by flows from China to Europe and Southeast Asian exporters to North America. This projected increase in trade underscores the importance of developing agreed international standards for Li-ion battery shipping.

Figure 2.27 Inter-regional trade value for key clean energy technologies by type and scenario, 2023-2050



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Share traded refers to the share of global production. EV = electric vehicles, specifically passenger cars and pick-up trucks. “Batteries” includes all EV types and stationary storage.

EVs remain the main driver of inter-regional trade of clean energy technologies in value terms in all scenarios.

Solar PV modules are an already highly traded commodity, with inter-regional trade accounting for 45% of global solar PV module demand in 2023. Trade levels in 2023 are not expected to persist in the years to come, since today’s trade levels are inflated by rapid inventory build-up (Figure 2.28). Only in the NZE Scenario trade volumes in 2035 approach 2023 levels again. The simultaneous expansion of manufacturing capacities for solar PV modules, led by the United States and India, further reduces the need for imports. There are fewer committed and preliminary announced projects for other steps of the manufacturing supply chain, so trade in cells, wafers and polysilicon expands. However, since the added value of these goods is lower, it is not sufficient to counterbalance the drop in PV module trade. China remains at the centre of the solar PV supply chain, supplying two-thirds of wafer exports and one-third of cells by 2035 in the STEPS. Southeast Asia becomes the main exporter of cells (40% of global exports), which are exported mainly to the United States and used to make solar PV modules.

Box 2.5 Modelling of trade flows between countries and of investments in manufacturing facilities

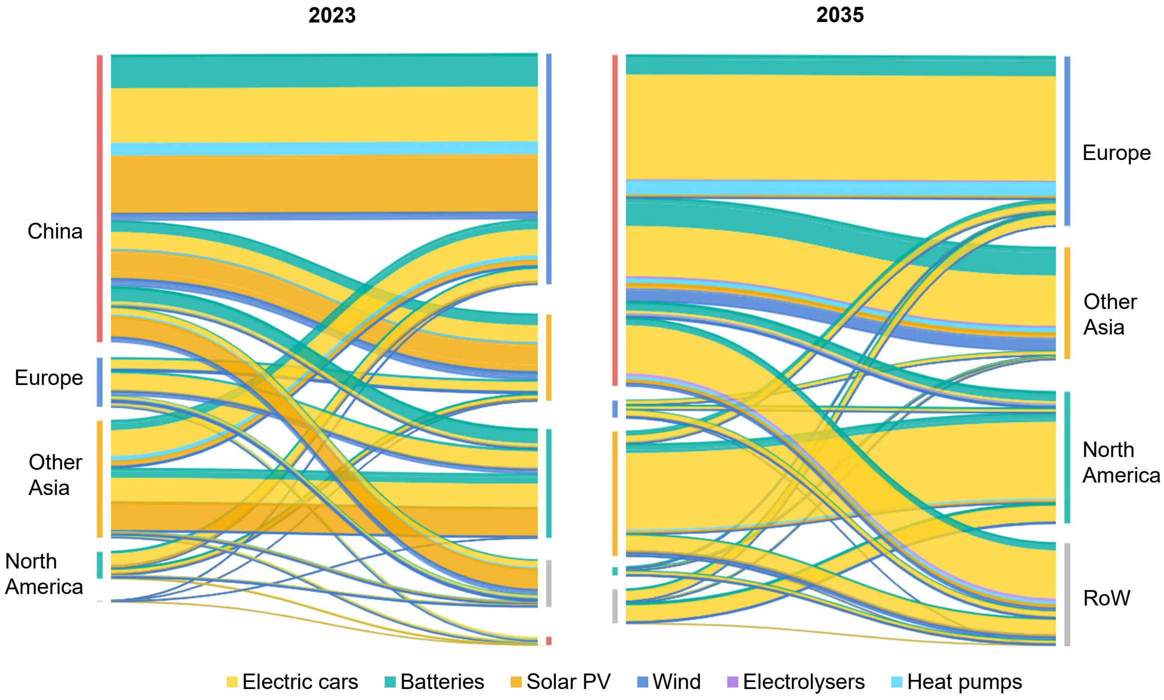
The IEA MaT Model projects trade flows between countries or regions reflecting the differences in manufacturing cost, policies, availability of skilled workforce, tariffs and transport costs, and access to trade infrastructures such as ports. The trade flows are defined only as a function of the country of destination and production. For example, if a Western OEM produces cars in China to serve the EU market, this is counted as a Chinese export to Europe. In contrast, if a Chinese OEMs produces cars in Europe registered locally, this is accounted as domestic production. The regional allocation of investment follows the same approach, i.e. projected investments relate to the location of the manufacturing facilities, rather than the headquarters of the investing company.

Trade in wind turbine nacelles and blades increases by 60% by 2035 in the STEPS. Unlike EVs, these technologies are not widely traded today, but the rapid increase in global demand and geographical concentration of wind manufacturing capacity in China, Europe, India and Latin America means that trade expands, despite shipping costs accounting for up to 15% of the cost of nacelles and blades. China is the largest exporter, and the United States the largest importer, mostly importing blades from Mexico.

Trade in heat pumps is small for now, representing just one-fifth of global production in 2023. In the STEPS, trade grows significantly, doubling by 2035 driven by export flows from China to most other countries. By 2050, total trade value reaches USD 40 billion, with the biggest flows from China to Europe and North America.

In the APS, total inter-regional trade of the six key clean energy technologies to 2035 is only about a quarter higher than the STEPS, because as demand grows, advanced economies are able to successfully develop domestic production to meet a share of their rising demand. In this scenario, announced committed projects are not sufficient to meet the faster growth in demand for wind components and heat pumps, resulting in significantly higher inter-regional trade values compared to the STEPS. On the contrary, trade in solar PV components is very similar in STEPS and APS, as more announced projects come online outside of China. The EU NZIA boosts production in the European Union and leads to a drop in its imports from China, especially in terms of electric cars and solar PV modules.

Figure 2.28 Trade flows for key clean energy technologies between countries/regions in 2023 and in the Announced Pledges Scenario, 2035



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Notes: RoW = Rest of World. Expressed in monetary value. Batteries includes all electric vehicle types and stationary storage. See the Annex for a break down per supply chain.

EVs and batteries continue to dominate trade flows between all major countries and regions to 2035 in the APS, while trade in solar PV falls sharply.

Inter-regional trade changes far less over 2035-50 than during the period to 2035. In the APS, trade for most clean energy technologies increases by 20% between 2035 and 2050. China remains the largest exporter of clean energy technology at that time, with exports just short of USD 400 billion, while the largest importers are the United States, with imports totalling USD 210 billion, and the European Union, importing USD 100 billion of clean energy technologies.

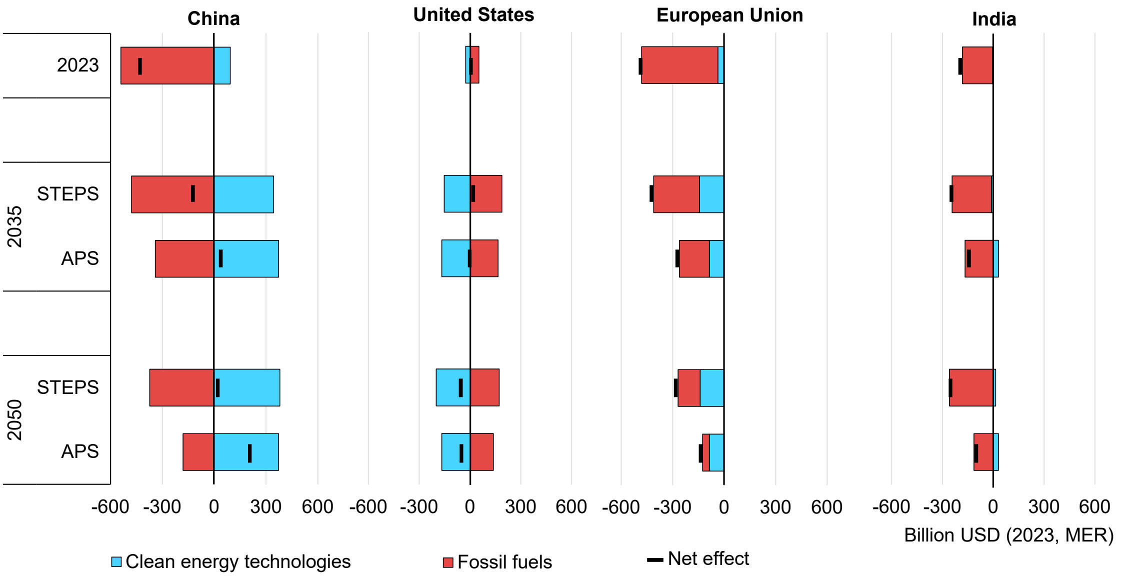
Expanding international trade is a vital consideration for accelerating the energy transition and getting on track for net zero emissions. For example, at the global level, around three-quarters of demand for wind turbines could be met with domestic manufacturing capacity (based on committed project announcements) in 2030 in the STEPS, but outside China, only around half of that demand could be met without trade. For solar PV modules, a technology for which there is ample manufacturing capacity, excluding China only 60% of demand can be supplied using domestic manufacturing. In the APS, even considering all announced manufacturing projects, the shares are even lower – in the absence of trade, less than half of solar PV demand outside China could be met.

Trade is also a means of lowering the cost of the energy transition. As with other goods, clean technology trade is a way for countries to play to their strengths while collaborating with partners internationally, including on innovation, thereby lowering prices and, as such, the overall economic costs of the transition, and increasing resilience through increased diversity of supply. Attempting to meet demand entirely with domestic production would also push up the need for investment in clean energy technology manufacturing capacity, and risk creating inefficiencies in the event of the emergence of surplus capacity, which could be otherwise be used to serve export markets.

The energy transition also promises to lower fossil fuel import bills for importing countries, with clean energy technology exports helping to further improve net trade balances for some of those countries. The net impact varies across countries and time, and according to the pace of the transition. For example, the value of EU net imports of clean energy technologies rises from just USD 35 billion in 2023 to USD 140 billion in 2035 in the STEPS – a value similar to the value of the European Union's car exports today – with one-third of these imports coming from China. At the same time, fossil fuel imports decline from around USD 440 billion in 2023 to USD 300 billion in 2035, meaning that the value of the required import of clean energy technologies fully offsets the gains from lowering the fossil fuel import bill (Figure 2.29). In the APS, thanks to a more rapid deployment of clean energy technologies, the EU fossil fuel import bill falls by another nearly USD 100 billion over the same period, improving the net effect between those two types of commodities by USD 180 billion over the same period of time to USD 260 billion. Despite the increase in clean technology import bills, the end result in both scenarios is that the European Union is more resilient to the economic impacts of supply chain disruptions, which tend to be more disruptive for the economy in the case of fossil fuels imports.

The picture is different in the United States, largely because it is an exporter of fossil fuels. In the STEPS, clean energy technology imports grow to USD 150 billion in 2035, originating mainly from Mexico, as well as countries that the United States has trade agreements with. However, this is offset by an increase in fossil fuel exports, resulting in a small positive net effect. In the APS in 2035, clean energy imports are slightly higher, at USD 165 billion, resulting in the value of net trade in clean technology and fossil fuels being in equilibrium. In China, the value of fossil fuel imports was more than five times higher than its clean energy technology exports in 2023. In the STEPS, those exports reach USD 340 billion in 2035, equal to 70% of the cost of net fossil fuel imports. Total trade in clean technologies and fossil fuels balances just before 2050. In the APS, this is already achieved by the mid-2030s, i.e. more than 15 years earlier than in the STEPS, thanks to more ambitious climate policies that cut fossil fuel demand and import needs. In this scenario, the value of China's exports of clean energy technologies far exceeds the net import bill for fossil fuels in 2050.

Figure 2.29 Net trade in key clean energy technologies and fossil fuels by selected country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2050



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Note: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

China's net trade in clean technologies and fossil fuels reach equilibrium just after 2035 in the APS, thanks to increased policy ambition to cut fossil fuel demand and import needs.

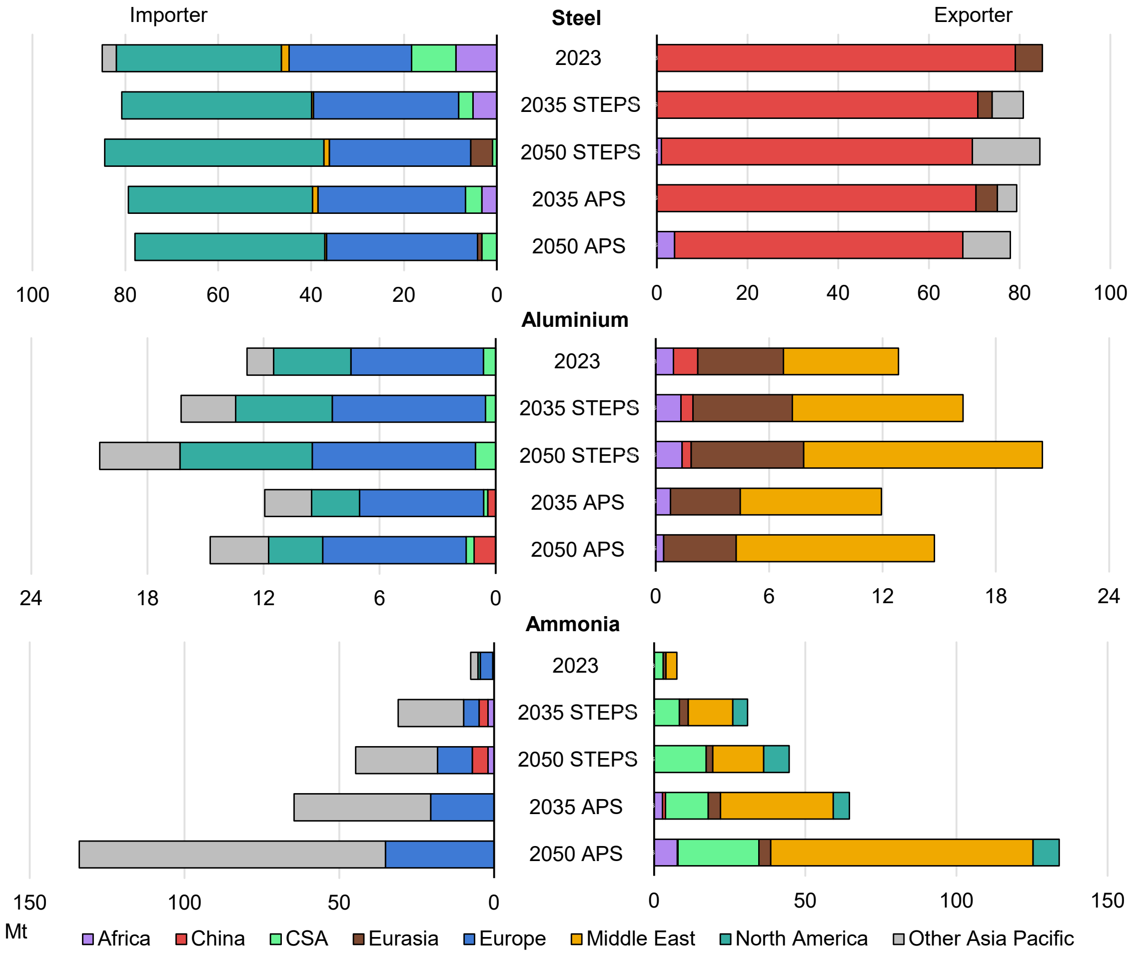
India remains a major importer of fossil fuels throughout the projection period, especially in the STEPS, due to its heavy dependence on imports of oil and gas. In the APS, the country becomes a net exporter of clean technologies by 2035. Its net fossil fuel imports are cut by 30% relative to the STEPS in 2035, reducing the net trade bill for fossil fuels from USD 230 billion to USD 160 billion.

The potential savings associated with faster deployment of clean energy technologies would be larger if tariffs were lower. Today, tariffs on renewable energy systems and components are several times those applied to fossil fuels on average, in both advanced economies and EMDEs. As a global average, it is estimated that around 5% of the cost of a traded solar PV module goes towards paying for tariffs. Added to this are the impacts of NTMs, often deriving from regulations, which can affect costs and, ultimately, trade.

Materials

Inter-regional trade increases in the STEPS and APS for ammonia, and in the STEPS alone for aluminium (Figure 2.30). In the case of steel, trade dips from 85 Mt in 2023 to about 81 Mt in 2035, recovering to current levels in 2050 in the STEPS; it falls slightly more rapidly to 79 Mt in 2035 and then plateaus through to 2050 in the APS. China's net exports decline the most in absolute terms, while other countries in the Asia Pacific region go from being net importers to net exporters by 2050 in both scenarios, as their industrialisation advances and they move down the supply chain (see Chapter 4).

Figure 2.30 Net trade volumes for key materials by country/region in the Stated Policies and Announced Pledges Scenarios, 2023-2050



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Notes: CSA = Central and South America; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Only net trade at the regional level is considered in this figure. Internal trade within selected regions is excluded. Trade in steel includes semi-finished production and trade in aluminium includes both ingots (HS7601) and semi-finished products (HS7603-9).

Inter-regional trade increases in the STEPS and APS for ammonia, and in the STEPS for aluminium, but falls slightly in both scenarios for steel.

Aluminium trade between regions increases significantly in the STEPS as production of aluminium continues to increase (more so than steel), with European and North American net imports increasing by 23% and 71% in the STEPS by 2050. China remains a net exporter of aluminium, driven by semi-finished products, though its net exports drop by 50% over the same period, while the country continues to import unwrought aluminium ingots. Most of China's semi-finished production continues to be used domestically in further manufacturing of finished goods. The Middle East's exports of aluminium also grow significantly in both the STEPS and APS, as low-cost renewable electricity production in the region confers a significant competitive advantage for new facilities. In the APS, overall inter-regional trade remains relatively flat. Increased demand for aluminium in clean energy applications is balanced with greater post-consumer scrap availability from rising collection and recycling rates.

For ammonia, trade grows much more in the APS than in the STEPS, as its use as an energy carrier expands. In the APS, it grows nearly eightfold between 2023 and 2035 and by a factor of almost eighteen between 2023 and 2050, compared with increases of 300% and 500%, respectively, in the STEPS. As the price of ammonia is highly dependent on the cost of energy, trade largely reflects regional differences in energy prices. Access to cheap natural gas remains a key competitive advantage for the main producing regions, notably the Middle East, in all scenarios, especially for ammonia production from natural gas with CCUS (a near-zero emissions production technology). In some regions, low-cost renewables for electrolysis are a competitive option for the production of synthetic ammonia. The Middle East sees the biggest increase in exports in the APS for this reason, followed by Latin America.

The growing use of ammonia as a fuel is partially driven by synergies with ammonia trade for use as fertiliser or other industrial uses, as traded ammonia can be used for both. This does not have to come at the expense of food security, though greater infrastructure and activity around the trade of ammonia as an export commodity could help facilitate and normalise ammonia trade for other uses.

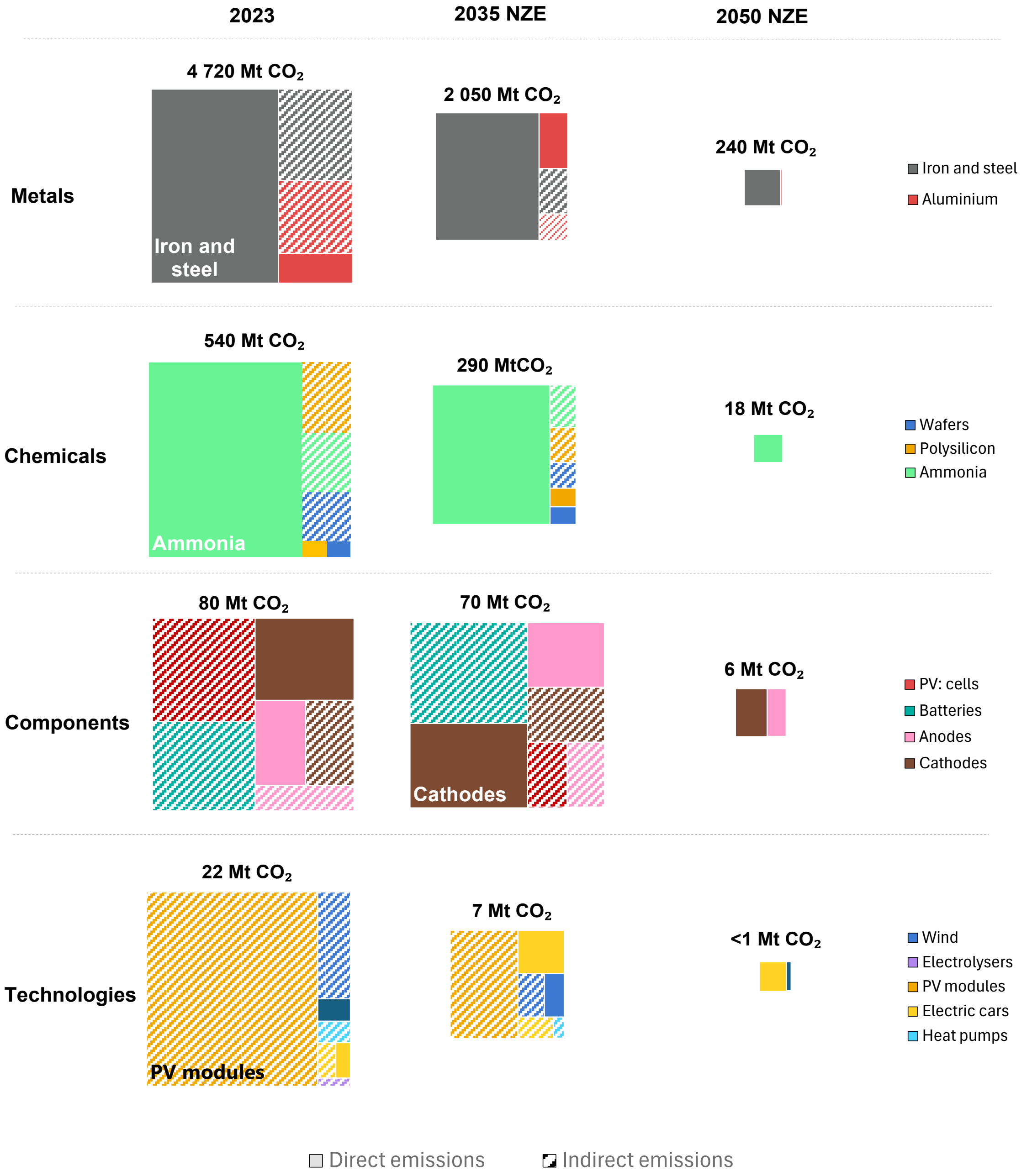
2.5 CO_2 emissions

Clean energy technologies are, by definition, capable of providing services without directly emitting a significant amount of CO_2, but their supply chains may do so, depending on the type of energy used in the production processes and transportation. The earlier steps of clean energy technology supply chains, particularly materials production, are today generally more emissions-intensive than later ones, mainly because the temperature of thermal processing is higher, and because practical low-emissions alternatives to fossil fuels, including electricity, are not yet available.

Steel, aluminium and ammonia production together account for around 40% of all direct CO_2 emissions in industry worldwide. Today, about 70% of CO_2 emissions from materials and chemicals production are related to the combustion or other direct use of fossil fuels, compared with just 25% for technology and component manufacturing (Figure 2.31). Aluminium production is an exceptionally electricity-intensive industry, so electricity needs from smelters are in many cases supplied by dedicated power generation facilities using cheap local energy resources. Getting to net zero will require these emissions to be eliminated or balanced by emissions removal in other sectors. In the NZE Scenario, indirect CO_2 emissions from the generation of the electricity used in manufacturing plummet as the power sector decarbonises. For example, while indirect emissions from component manufacturing in 2023 accounted for two-thirds of total CO_2 emissions, that share shrinks to zero before 2050 in the NZE Scenario.

Emissions related to transportation contribute further to the emissions for materials and products. As far as shipment of energy-related manufactured goods is concerned, the emissions intensity of container ships used to transport most clean energy technologies, is currently nearly four times higher than that of bulk carriers used to transport materials. This is mainly because container ships travel faster, and because bulk carriers are around 40% larger than the average container ship, contributing to a better energy efficiency per tonne-km (see Chapter 5). Along with the decarbonisation of the shipping sector, emission intensities plunge by 2035 and almost reach zero by 2050 in the APS, on the assumption that the International Maritime Organization goal to reach net zero GHG emissions close to 2050 (IMO, 2023) is achieved.

Figure 2.31 Global CO_2 emissions along manufacturing supply chains in the Net Zero Emissions by 2050 Scenario, 2023-2050



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Notes: NZE = Net Zero Emissions by 2050 Scenario. “Batteries” includes all EV types and stationary storage. Metals in this graph include the iron and steel and aluminium sectors. Chemicals in this graph include the production of ammonia and relevant components for the clean energy technologies in scope – wafers and polysilicon. Indirect emissions are from the generation of the electricity and district heat consumed in manufacturing processes, and are calculated based on the average emissions intensity from the electricity grid and district heating networks. This can be inaccurate in sectors using captive or dedicated power supplies like the aluminium industry.

Materials production accounts for most of the CO_2 emissions related to the manufacturing of clean energy technologies.

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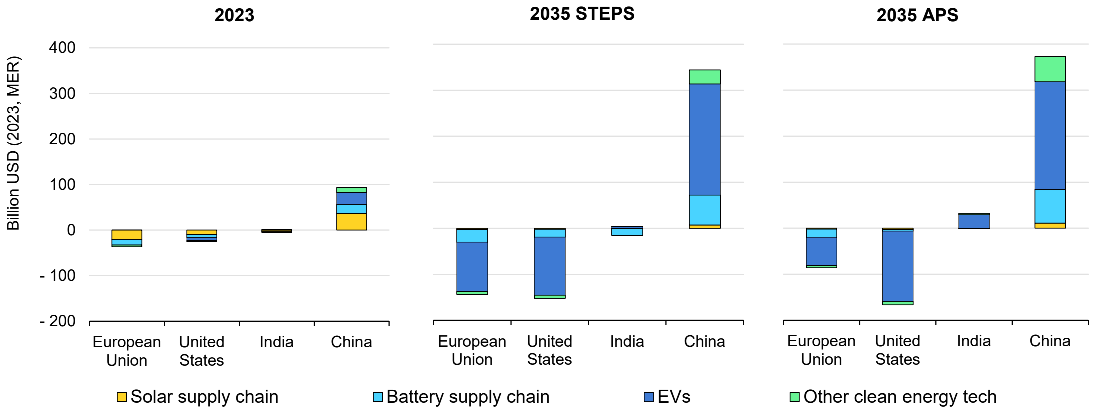
Chapter 3: Outlook in major markets

Highlights

- In the United States, the Inflation Reduction Act and the Bipartisan Infrastructure Law are mobilising unprecedented levels of government financial support for the deployment and manufacturing of clean energy technologies and unlocking further investment. In the Stated Policies Scenario (STEPS), US demand for solar PV modules and polysilicon is met almost entirely from domestic production by 2035, but demand for solar PV cells and wafers still relies on imports. In the Announced Pledges Scenario (APS), Mexico builds on existing car manufacturing strengths to become a hub for electric vehicle (EV) manufacturing, accounting for 35% of US imports by 2035. In the STEPS, the investment needed in clean energy technology manufacturing and near-zero emissions materials to 2030 is USD 250 billion (at 2023 prices), and almost USD 300 billion in the APS.
- In the European Union, the Net-Zero Industry Act (NZIA) benchmark of 40% of EU deployment being met by EU manufacturing is most readily achievable for heat pumps, if there is sufficient demand, and for wind turbines. The current pipeline of projects to produce batteries is largely sufficient to reach NZIA targets, but will require a reduction in production costs and growth in the domestic EV market to make the EV supply chain competitive. EV imports from China are roughly 50% lower in 2035 in the APS than in STEPS as a result. The competitiveness of EU materials production facilities has been hit by the surge in energy costs since 2021, and need to keep modernising to remain at the forefront of developments in near-zero emissions processes. Investment of USD 10 billion in such projects have already been committed, accounting for almost 50% worldwide, and another USD 10 billion has been announced.
- China will remain the global powerhouse for clean technology manufacturing but realising its full potential depends on a range of factors. Around 60% of all EVs sold worldwide in 2035 in the STEPS are manufactured in China. For solar PV modules, existing and announced capacity would be largely sufficient to serve global demand in 2030 in the APS, but in this scenario, other countries also invest in manufacturing capacity, meeting about 35% of global demand. China remains the largest material producer in 2035 in the APS, though its global share of production declines slightly.
- India's Production Linked Incentive scheme incentivises vertical integration across supply chains, a key source of China's competitive edge today. In the STEPS, this leads India's production of solar PV modules to grow by a factor of nine to 2030, and production of battery cells to grow from being a nascent industry in 2023 to over 50 GWh in 2030 – a level close to that in the European Union in 2023.

This chapter takes a detailed look at the prospects for clean energy manufacturing and trade in the United States, the European Union, China and India. These markets accounted for almost 90% of the total value of clean technologies produced in 2023 (see Chapter 1), and together, they produced over 85% of the solar PV modules that were sold in 2023, over 90% of EVs and 90% of wind turbines. Their clean technology manufacturing industries have been built on existing manufacturing strengths for other technologies – they contributed a combined 68% of global manufacturing value added in 2023 – and large domestic markets. They also account for over two-thirds of global demand for steel and aluminium, and more than half of that for ammonia. In the three scenarios presented in this report, energy-related trade balances shift markedly over time and a new international energy economy takes shape. The four markets considered in this chapter all stand to reap large macroeconomic benefits from export revenues and cheaper imports as the energy transition advances, including through trade. China's net clean energy trade balance improves enormously in both the STEPS and APS, thanks mainly to exports of EVs and batteries, demonstrating the value to China of supporting more rapid transitions to clean transport globally (Figure 3.1). The European Union and the United States become net importers of most technologies in the STEPS and the APS. This is not necessarily a reflection of a lack of competitiveness in domestic manufacturing, but rather of a combination of factors, including the need to build up cost-effective and diverse clean technology supply chains that take account of the opportunities offered by trade. Indian manufacturing capacity expands briskly to meet domestic demand, with the country becoming a net exporter of EVs, solar PV modules, and wind turbines by 2035 in the APS thanks to its competitive production costs.

Figure 3.1 Net trade balances for key clean energy technologies by market and scenario, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; EV = electric vehicle. "Other clean energy technology" includes wind turbine components, heat pumps and electrolysers. A negative figure indicates imports.

Net trade balances for clean technologies improve for several major markets in the APS compared with the STEPS, as domestic manufacturing outpaces demand.

3.1 United States

Manufacturing is considered a strategic sector in the United States. In recent years, several major pieces of legislation have been put in place to boost clean energy technology manufacturing, with the aim of both stimulating economic growth and job creation, and supporting energy security and climate goals. The Inflation Reduction Act (IRA) and the Bipartisan Infrastructure Law (BIL) have mobilised unprecedented levels of government financial support to drive up deployment and investment in manufacturing of those technologies, as well as the decarbonisation of materials production (Table 3.1).

In the STEPS, the IRA helps to mobilise private investments in clean energy technology manufacturing capacity worth USD 230 billion (at 2023 prices) between 2023 and 2030. In the APS, thanks to faster technology deployment, cumulative investments reach more than USD 260 billion. At the time of writing, significant investments in building new or expanding existing manufacturing facilities with IRA or BIL support have been announced (Figure 3.2), of which nearly 80% is for EVs and for the battery supply chain (Clean Investment Monitor, 2024). Most of these investments are in parts of the country with below-average incomes (Figure 3.3).

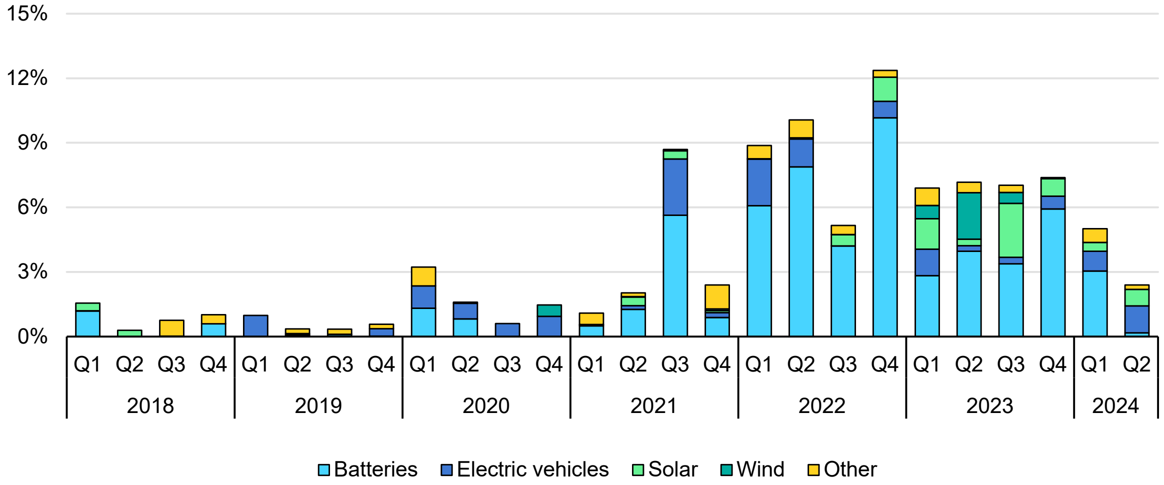
Table 3.1 Selected US industrial and trade policies relevant to clean energy technology and materials manufacturing

Policy (enactment year)	Description
Inflation Reduction Act (IRA) – Production tax credits (PTC) (2022)	Tax credits include the 45X Advanced Manufacturing Production Credit for the domestic production and sale of solar, wind and certain battery components and critical minerals, and the 30D Clean Vehicle Tax Credit for the purchase of EVs that meet certain domestic content requirements. Some PTCs can reduce the cost of producing materials with lower associated emissions, including the 45Q Carbon Oxide Sequestration Credit and the 45V Hydrogen Production Tax Credit.
Inflation Reduction Act – Investment tax credits (ITC) (2022)	The 48C Advanced Energy Project Credit was originally established by the American Recovery and Reinvestment Act of 2009, with additional funding under the IRA. It can provide between 6% and 30% of the qualifying investment, subject to certain requirements, for clean energy manufacturing, industrial decarbonisation and critical materials projects. The Domestic Manufacturing Auto Conversion Grants programme provides support for the conversion of automotive manufacturing plants to EV facilities.
Bipartisan Infrastructure Law (BIL) (2021)	Provides funding for domestic production of advanced batteries and battery materials, and substantial funding for the Hydrogen Hubs Program to promote regional hubs for low-emissions hydrogen production and use, which could potentially be available for materials production. It also provides funding to modernise and expand the electricity transmission network, increase the integration of renewable energy sources and improve grid reliability.
USMCA free trade agreement (2020)	The United States-Mexico-Canada Agreement (USMCA) replaced the North American Free Trade Agreement. It imposes more stringent rules of origin for automobiles, requiring 75% of a vehicle's components (including for EVs) to be manufactured in North America to qualify for tariff-free status. Trade in steel, aluminium and fertilisers remains tariff-free, except from some imports from Mexico under the Section 232 Steel and Aluminium Proclamations.

Policy (enactment year)	Description
Other free trade agreements	Those relevant to the supply of critical materials include agreements with: Korea (KORUS, entry into force in 2012), Australia (AUSFTA, 2005), Chile (USCFTA, 2004) and Morocco (USMFTA, 2006). A critical minerals agreement with Japan (2023) enables certain Japanese products to qualify for the IRA EV tax credit.
Section 301 tariffs on imports from China (2018, expanded in 2024)	The scope and rates of tariffs increased in 2024 to 25% ad valorem on steel, aluminium, other critical minerals and batteries, 50% on solar cells and modules, and 100% on EVs. For wafers and polysilicon, an increase of the tariffs to 25% has been proposed.
Section 232 tariffs on Steel and Aluminium (2018)	Global tariffs of 25% on steel imports and 10% on aluminium imports were imposed in the Trade Expansion Act of 1962. Canada, Mexico and Australia are now exempt, and these tariffs have been replaced with a quota system for Argentina, Brazil, Korea, the European Union, Japan and the United Kingdom, allowing a certain amount of steel to enter without tariffs, while maintaining tariffs above that threshold.

Sources: Bureau of Industry and Security (2024); Executive Office of the President of the United States (2024); The White House (2024); US DOE, (2024a); and US Trade Representative, (2019).

Figure 3.2 Share of announced investments in clean technology manufacturing in the United States by quarter, Q1 2018-Q2 2024



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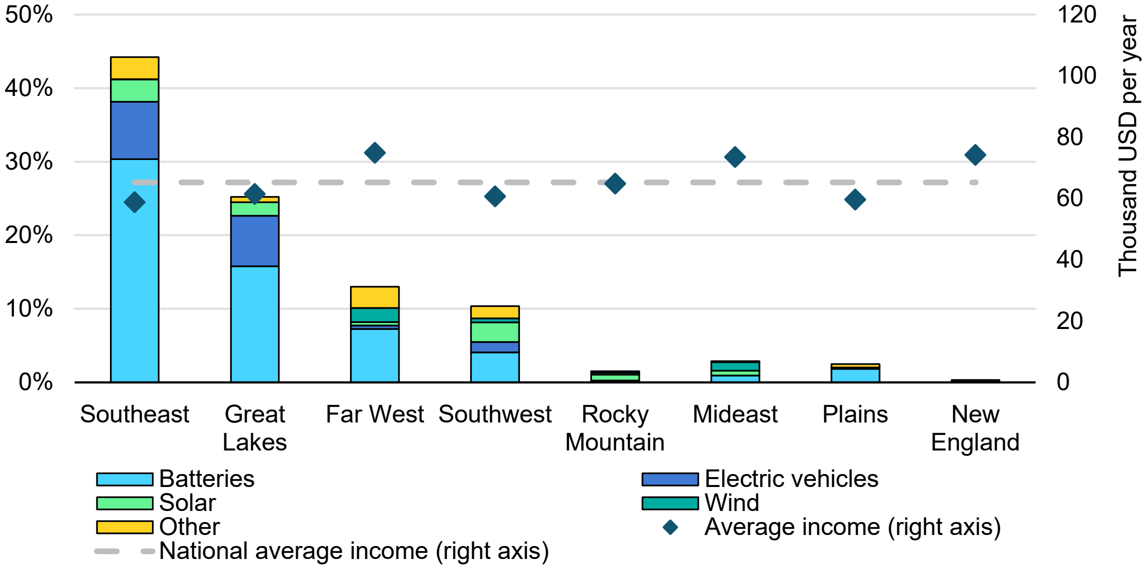
Note: Other includes charging stations, critical minerals, and electrolysers.
Source: Clean Investment Monitor (2024).

Announcements in clean energy technologies peaked after the introduction of the IRA but 2024 is showing a slowdown.

Since 2022 investment announcements have skyrocketed on the back on the IRA. However, in the first half of 2024, announcements were down 50% compared to the same period the previous year. Given that the period between announcement and full-scale production is usually at least 2-3 years, any new announcement is likely to receive less in IRA-backed incentives, since the scheme is set to end by the early 2030s.

Figure 3.3 Share of announced investments in clean technology manufacturing in the United States and per capita income by region



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Notes: Other includes charging stations, critical minerals, and electrolysers. Income refers to 2023. Regional groups refer to Bureau of Economic Analysis groupings.

Source: Clean Investment Monitor (2024); and Bureau of Labor Statistics (2023).

The vast majority of manufacturing investments with IRA support are for EVs and their supply chain, with regions with below-average incomes receiving the most.

EVs and batteries

Current market and policy support

Strong policy support, notably financial support through the IRA, is driving a wave of investment in EV and battery supply chains in the United States. In 2021, the year before the IRA was adopted, roughly 700 000 electric cars were produced (equivalent to 6% of car production in the United States), 70% of them by Tesla. Production rose to around 1.2 million in 2023 and is set to grow further in the next few years as new plants come onstream. Battery production is also soaring, from about 50 GWh in 2021 to over 70 GWh in 2023, with manufacturing capacity that reached nearly 150 GWh at the end of 2023. Domestic production of battery components, which was almost non-existent before the BIL and the IRA, has also started to take off (Automotive Dive, 2023; Energy News, 2024; Anovion, 2023).

The main form of financial support for EVs in the IRA is a tax credit for purchasers, which amounts to up to USD 7 500 per vehicle (USD 4 000 for used EVs priced at less than USD 25 000). Half of the credit is granted if at least 50% of the critical mineral value used to make the battery has been extracted or processed in the United States or in a country with which the United States has a free trade agreement (the share increases steadily to 80% by 2027). The other half is granted if at least 60% of the battery by value is manufactured or assembled in North America (increasing steadily to 100% by 2029).

The IRA also provides 180evelizal support for battery cell production, amounting to USD 35/kWh. Another USD 10/kWh is available if the battery cells are assembled into packs in the United States. In addition, grants equal to 30% of the cost of investment in battery and battery components manufacturing capacity are provided, which has had a huge impact on the costs of battery manufacturing. Without the support, battery cell production costs would be about 40% higher in the United States than in China; with the IRA, the cost of production is nearly 10% lower. Costs when accounting for the IRA are also about 40% lower than in Europe, which is why several carmakers there have recently announced their intention to shift manufacturing operations to the United States.

The introduction of financial support such as the Advanced manufacturing Production Credit 45X (which gradually decreases from 2030 and finishes by the end of 2032), has led to the announcement of plans for new battery manufacturing capacity in the United States and Canada. In the United States, planned battery cell manufacturing capacity for 2030 has grown by 80% from 700 GWh to over 1 250 GWh since the IRA was adopted in 2022. About 65% of currently planned capacity is already committed. In Canada, planned capacity for 2030 grew more than four times, from less than 50 GWh to 200 GWh today, also thanks to the eligibility of batteries produced in Canada for IRA financial support. Half of the committed battery manufacturing capacity in the United States will be delivered by joint ventures between an EV and a battery manufacturer.[1]

More plans to expand EV manufacturing are likely to emerge in line with commitments made by original equipment manufacturers (OEMs) operating in the United States to switch to EV technology and away from ICE vehicles. Overall car manufacturing capacity in the United States, including conventional vehicles, was estimated at around 15 million units in 2023, of which Tesla accounts for almost 1 million (all of which are EVs). Various existing assembly plants already produce both EVs and ICE models, or plan to do so in the future. Electric car manufacturing capacity could expand quickly as existing conventional car production facilities can generally be repurposed. It is therefore unlikely that car manufacturing capacity would be a limiting factor for domestic EV production. Foreign OEMs are also seeking to take advantage of the financial support from IRA by building plants in the country; for example, the Vietnamese OEM, VinFast, announced in 2022 the construction of an EV and battery factory with a capacity of 150 000 units (Reuters, 2022b). Similar announcements have been made by incumbent OEMs such as Toyota (Reuters, 2023d) and Stellantis (Reuters, 2023e).

Under the USMCA, US customers purchasing EVs produced in Mexico are eligible for financial support from the IRA, boosting the prospects for Mexican exports to the US market and reducing the cost of EVs sold there. Mexico already exports over 2.5 million cars annually to the United States (US ITC, 2023). In 2023, nearly

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[1] For example, LG-GM (Reuters, 2022); LG-Honda (Honda, 2022); LG-Hyundai (Reuters, 2023); Samsung-GM (Reuters, 2023a); Samsung-Stellantis (BNEF, 2022); Panasonic-Tesla (Panasonic, 2022); LG-Toyota (Reuters, 2023b); SKI-Ford (Reuters, 2023c) and SKI-Hyundai (Reuters, 2022a).

all of the 45 000 electric cars (90%) imported from Mexico were manufactured by US-headquartered OEMs. US carmakers own roughly 25% of the 5 million unit car manufacturing capacity in Mexico. Tesla has announced that it plans to build a new gigafactory in Mexico with a capacity of 2 million units, starting production in 2027 (Reuters, 2023f; Marklines, 2023). Audi has also announced the construction of an EV plant in Mexico, at a cost of USD 1 billion (Reuters, 2024).

Manufacturing and trade prospects

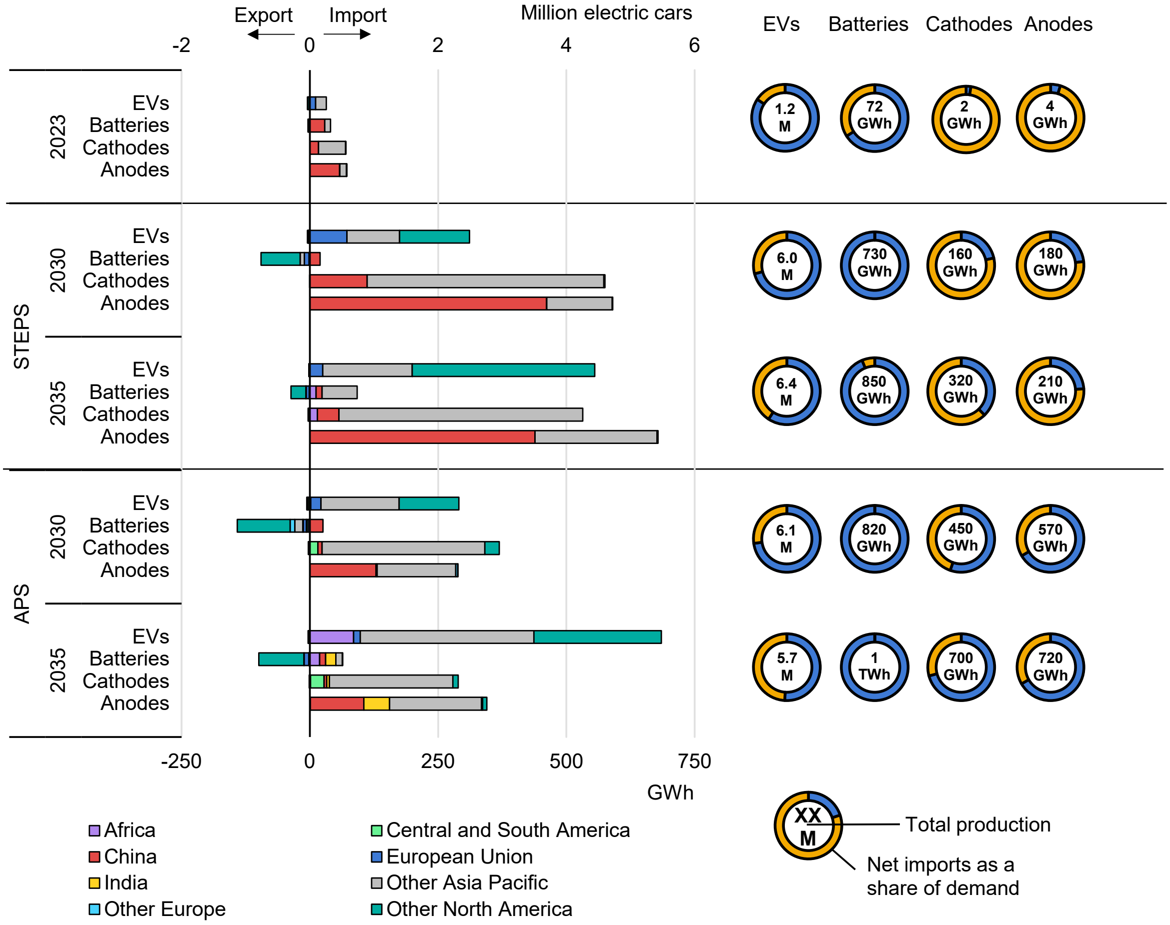
The IRA makes the United States a particularly attractive country for EV and battery manufacturing, such that most of the growth in demand over the coming decade is set to be met by domestic production. At present, the country is broadly self-sufficient in EVs, but is a net importer of batteries and, to a larger degree, cathode and anode active materials. EV manufacturing capacity reached 1.8 million units at end-2023, compared with production in 2023 of nearly 1.2 million and total sales of 1.4 million.

In the **STEPS**, which takes account of announced projects for which investments have been committed, production of EVs increases more than fourfold to 2035 to nearly 6.5 million units. The growth in output nonetheless lags behind that in demand, which reaches almost 11 million or 70% of all cars sold in 2035. This means that imports would rise from about 450 000 vehicles in 2023 to around 4.5 million, equivalent to about 40% of total US demand, in 2035 (Figure 3.4). Most of these imports are from Mexico (around 2.8 million), Korea (800 000), Japan (over 500 000) and Europe (around 200 000). The high level of imports from Mexico reflects the continued involvement of US OEMs in the country and its eligibility for financial support from IRA. The ramp-up in EV manufacturing capacity in Mexico also serves its growing domestic market.

The growth in EV production in the STEPS slows from 2032 onwards, based on the assumption that financial support under IRA is not rolled over. However, the large investments made by then make the US EV and battery industry sufficiently developed to bring down costs of production, gain competitiveness, and maintain stable production levels. In the STEPS in 2035, the United States produces about the same number of electric cars as in 2032 even as demand grows by more than 10% over the period, and about 850 GWh of batteries, of which over 5% are exported to Mexico. Integration of the US-Mexico supply chain is mutually beneficial, combining strong battery production in the United States and Mexico's expertise in the automotive sector and lower EV production costs. Consequently, Mexico supports rapidly growing US EV demand, while benefiting from the development of a high value added industry, in spite of currently lacking a battery industry and committed manufacturing capacity.

Confirmed battery cell manufacturing projects are sufficient to exceed demand to 2030, making the United States a net exporter in 2030. However, these projects are not large enough to satisfy demand in 2035, with net imports meeting just over 5% of demand that year. For cathodes, 40% of total US demand in 2035 is satisfied by domestic production and about 45% by imports from Korea in the STEPS; imports from China remain low at only 5% of demand. The remainder is imported from Indonesia, Japan and North Africa, in particular Morocco. For anodes, domestic production in 2035 would only meet a quarter of demand, with imports serving the rest, primarily from China (50% of US demand), Korea (15%) and Southeast Asian countries (10%). US imports of anodes from China continue despite tariffs, as there is as not yet enough manufacturing capacity committed outside of China to cater for demand (see Box 2.3).

Figure 3.4 US market and import-export balance for EVs, batteries and selected components in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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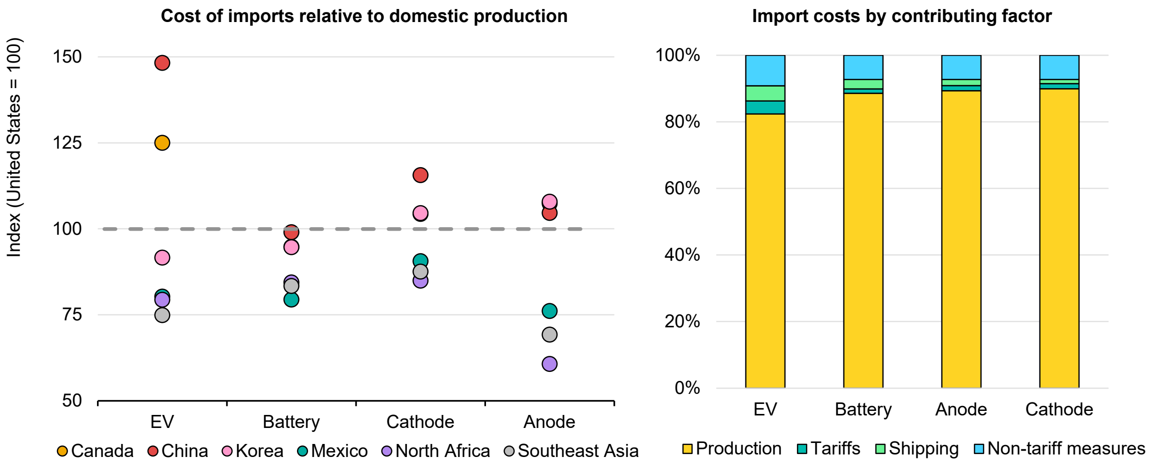
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; M = million; EVs = electric vehicles, specifically passenger cars and pick-up trucks. Battery demand, production, and trade include all EV types and stationary storage. It is assumed that all countries and regions produce the global average chemistry share for both batteries and components. Cathode and anode refer to active materials. Demand for components is determined by the production of the subsequent component. EV data is reported in million units (top axis), while battery cell, cathode and anode active materials are in GWh (bottom axis). Import and export refer to net trade flows between the United States and each of the regions displayed, while net imports as a share of demand refers to the net imports to the United States accounting for all regions as a share of domestic demand.

Most of the growth in US demand for electric cars and battery cells in the coming decade is set to be met by domestic production, in large part due to IRA incentives.

The outlook for manufacturing EVs in the **APS** diverges somewhat from that in the STEPS after 2030. EV production in the APS is slightly lower than that in the STEPS, at about 5.7 million units in 2035. As manufacturing investment in other countries ramps up, less production takes place in the United States and more takes place in other countries. As production costs in other countries are often lower (Figure 3.5), imports take a larger share of the US market for new EVs in the APS relative to the STEPS. This leads to more diversified imports, with Mexico, Southeast Asia, Morocco, Korea and Japan emerging as the main suppliers in 2035. Production costs make up the larger share of the total cost of importing EVs and components into the United States, while tariffs and non-tariff measures (NTMs) contribute only about 15% on average to the overall costs. One important exception is for EVs made in China, which are not imported due to very high tariffs.

Figure 3.5 Total production cost of EVs and batteries in the United States compared with imports and US import costs by contributing factor in the Announced Pledges Scenario, 2035



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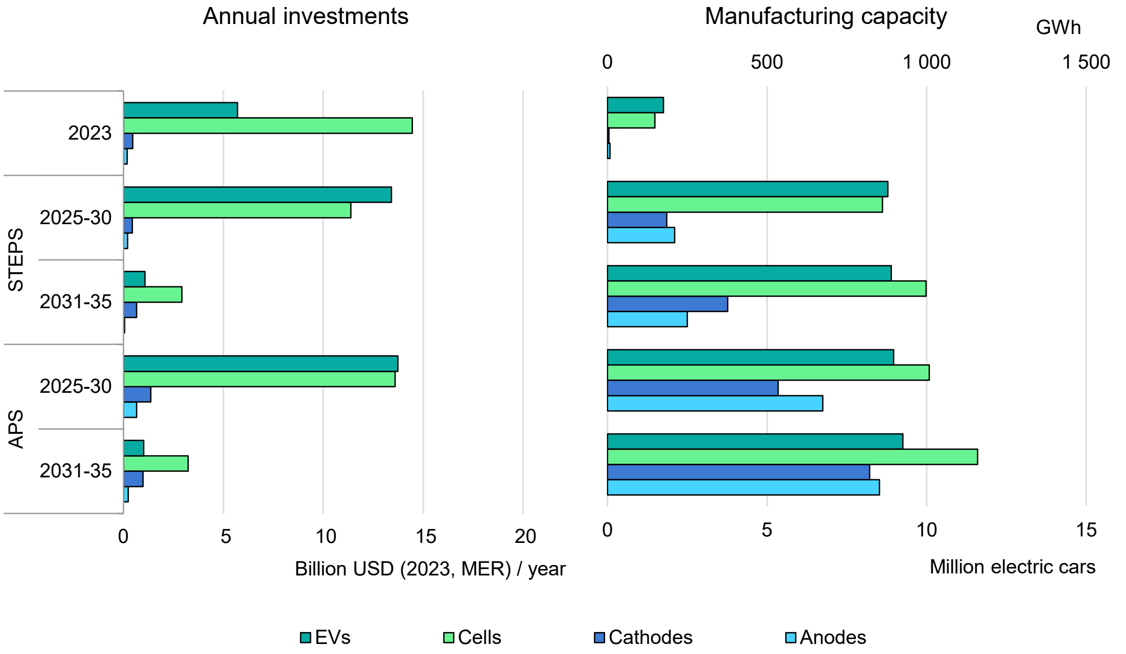
Notes: EVs = Electric Vehicles (electric passenger cars exclusively). The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in the United States (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

Major EV suppliers to the United States achieve total import costs that are on average more than 20% cheaper than locally produced EVs by 2035 in the APS.

Battery production follows a similar trend to EV production to 2030 in the APS, reaching over 800 GWh, and then grows to 1 TWh in 2035 because the somewhat lower demand from domestic production of electric cars is compensated by greater demand for commercial vehicles such as electric trucks. The construction of committed and otherwise announced manufacturing capacity for cathode and anode active material in the United States boosts domestic production and significantly cuts into imports from China. As soon as 2030, about half of cathode demand is met by domestic production, with most of the rest coming from Korea, and to a lesser extent from Indonesia and South America. In the same year, anode production reaches almost 600 GWh, covering two-thirds of domestic demand. The shortfall is satisfied through imports mainly from Korea (just over 15%) and China (just over 10%). Cathode and anode active material production increases slightly to 2035, satisfying almost 70% of demand (compared with less than 5% today). The self-sufficiency of the EV supply chain will, however, also depend on how diversified the US critical mineral supply chain is and where those minerals are refined (IEA, 2024).

Figure 3.6 US EV and battery manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. EVs = Electric Vehicles (electric passenger cars exclusively). Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

US EV and battery manufacturing investment needs average around USD 25 billion per year over 2025-30 in the STEPS, and an extra USD 4 billion per year in the APS.

Total investment needs in the EV and battery manufacturing sectors vary between the two scenarios. They amount to an average of around USD 25 billion/year over 2025-30 in the STEPS – about 20% more than in 2023 (Figure 3.6). In the APS, investment is around USD 4 billion higher compared with STEPS, averaging almost USD 30 billion/year. This investment facilitates the construction of a manufacturing capacity of nearly 9 million electric cars in both scenarios, compared with less than 1.8 million units in 2023. Battery manufacturing capacity reaches between 850 GWh and slightly above 1 TWh in 2035 in the STEPS and APS respectively, up from 150 GWh in 2023. The capacities for cathode and anode production vary widely between the two scenarios in 2035, from around

200 GWh in the STEPS to 550-700 GWh in the APS. The average utilisation rate for this capacity is high in both scenarios, at about 80% for batteries and battery components, and around 70% for EVs.

Box 3.1 Impact of new US import tariffs on Chinese EVs

In May 2024, the US administration decided to impose new tariffs on Chinese-origin goods including EVs, lithium-ion (Li-ion) batteries, critical minerals used in battery cell manufacturing (including cobalt and manganese ores and concentrates) and other EV-related components such as permanent magnets for electric machines and natural graphite for battery anodes. This move was a response to alleged Chinese trade and non-market practices. The United States and Canada are currently the only countries to have introduced such high tariffs on imports of Chinese EVs, though the European Union recently introduced special duties on some of them.

Table 3.2 Tariffs on imports of Chinese-origin EV-related goods

Product	Current tariff rate	New tariff rate	Effective date
EVs	27.5%	102.5%	2024-09-27
Li-ion batteries (EVs)	7.5%	25%	2024-09-27
Li-ion batteries (not EVs)	7.5%	25%	2026-01-01
Li-ion battery components	7.5%	25%	2024-09-27
Natural graphite	0%	25%	2026-01-01
Permanent magnets	0%	25%	2026-01-01

Note: The 100% tariff on EVs under Section 301 comes on top of the standard 2.5% tariff on car imports.

Source: The White House (2024).

The increase in EV tariffs is designed to pre-empt any future increase in imports from China. Historically, US consumers have purchased few, if any, Chinese EVs, which tend to be cheaper than American models. Today, exports of Chinese EVs to the United States are negligible. The US market for new EVs is characterised by wealthy consumers, * who are generally less price-sensitive than consumers in other countries. In addition, the United States has a less mature EV market than in China or Europe, and the US market is skewed towards high-end vehicles. The average price of an electric sport utility vehicle (SUV) sold in 2022 in the United States was USD 63 000, compared with USD 35 000 in China. In such a market driven by wealthier early adopters, the competitive advantage of Chinese-made vehicles has had185evelie to no impact on sales in the United States so far. As EV markets mature and a wider range of consumers seek to acquire electric cars, however, upfront affordability is becoming increasingly important. While the analysis of how uptake may have progressed without these tariffs is out of the scope of this analysis, it is likely that without them imports of more affordable models from China would have increased to serve growing demand from mass-market consumers.

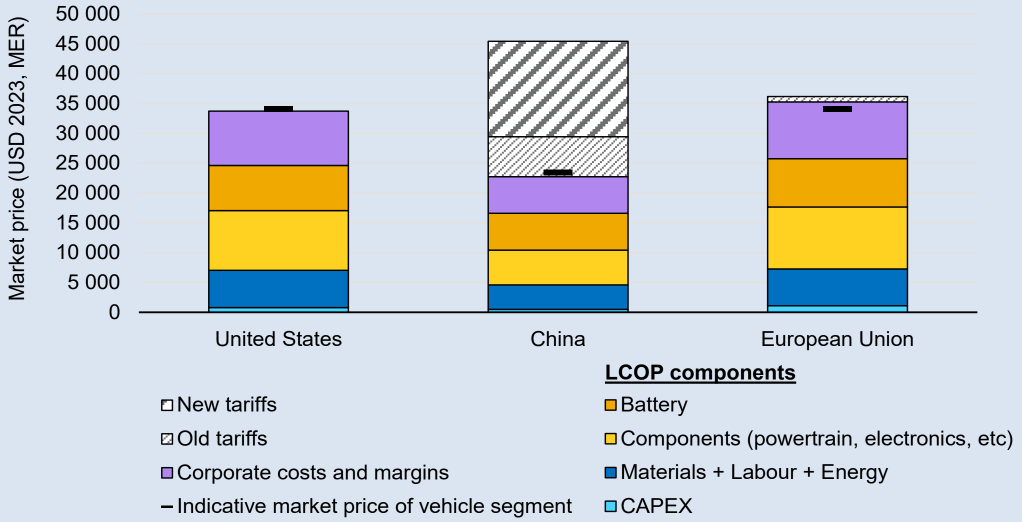
On the other hand, it is reasonable to assume that the increase in tariffs will only have a limited impact on EV manufacturing in the United States in the near term.

Domestic production capacity stood at around 1.8 million electric cars in 2023, exceeding the 1.4 million units sold that year. On top of that, parts of the sizeable domestic ICE car manufacturing capacity could be repurposed. Existing trade partners, including Mexico, Korea, Japan and European countries, also have additional manufacturing capacity that could supply the US market.

Overall, the assumed impact of increasing tariffs on EV availability in the United States is mixed. While there is clearly enough EV production capacity domestically or with preferred trading partners to meet US demand, questions remain about the affordability of the EVs produced relative to the cheaper models made in China. Ultimately, this price premium will depend on whether OEMs outside China successfully roll out cheaper models, adjust their margins for existing offerings, and absorb the impact of tariffs on components originating from China or higher cost components sourced elsewhere.

Tariffs on batteries and battery components might have a larger impact on segments further up the EV manufacturing supply chain, encouraging more domestic production or other source of imports. Nevertheless, the impact on consumer prices to 2030 could be limited, as Korea is planning sufficient cathodes manufacturing capacity to supply the US market. Sourcing anode materials from outside China is expected to be harder, but the impact on the cost of battery cells will be limited, as anodes constitute only a small share of the total production cost.

Figure 3.7 **Cost breakdown of domestically produced and imported EVs in the United States**



Notes: CAPEX = capital expenditures. Price refers to the domestic market. Electric compact SUV is the vehicle segment considered in the chart.

Sources: ICCT (2022), (2021); UBS (2017) used for components, labour and materials costs. Corporate cost and margins are estimated trying to match indicative market prices. Battery manufacturing cost comes from IEA modelling and assumes 2023 global average chemistry (40% LFP and 60% nickel-based chemistries). OEMs plants database from Marklines (2024) used to derive CAPEX in the United States. Vehicle indicative market price values derived from EV Volumes (2024).

* The average household income for an EV buyer is USD 140 000 per year, against USD 115 000 per year for new car buyer.

Solar PV

Current market and policy support

The IRA has completely changed the landscape for solar PV manufacturing in the United States. The Act provides tax credits to investment in solar PV manufacturing capacity and for plant operation, covering all segments of the supply chain. The investment tax credit (Advanced Energy Project Credit 48C) runs to 2030 and amounts to 30% of the total investment in the facility. The production tax credit (Advanced Manufacturing Production Credit 45X) runs to 2032 and amounts to USD 0.07/Watt for PV modules, USD 0.04/Watt for PV cells, USD 12/m^2 of wafers and USD 3/kg of solar grade polysilicon. The two credits are mutually exclusive and cannot be combined.

The government has adopted several other measures to support and protect the development of domestic industry, including an increase in tariffs under Section 301 from 25% to 50% on imports of cells and modules coming from China (PV Magazine, 2024a), implemented in September 2024. In addition, the government announced its intention to expand tariffs to also cover polysilicon and wafers with a 50% tariff rate, and the US International Trade Commission (USTR) is now taking public comments on this (Reuters, 2024a).[2] The USTR has also made a preliminary decision on imposing countervailing duties on modules and cells imported from Cambodia, Malaysia, Thailand and Viet Nam (US Trade Representative, 2024) – many of which are produced by Chinese-headquartered companies. There is also a patchwork of federal, state and local policies and regulations that seek to promote solar PV deployment, including state solar carve-out programmes, fixed prices for renewable energy generation, and rebates, which indirectly support local manufacturing.

The recent strengthening of policy support has increased the attractiveness of investing in the US solar PV industry, with several firms announcing major investments and shifting production from other regions, including Europe. As a result, US manufacturing capacity is set to reach 45 GW for modules, 8 GW for cells, 6 GW for wafers and 33 GW for polysilicon at the end of 2024 – increases of several orders of magnitude compared with just 4 years earlier, when module manufacturing capacity was at 5.6 GW, polysilicon at 18 GW and cells and wafers at just a few hundred MW. The increase in module manufacturing capacity alone over the course of 2024 is expected to amount to 26 GW – an increase of more

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[2] The preexisting Uyghur Forced Labor Prevention Act (UFLPA), effective since June 2022, presumes that all goods produced, either wholly or in part, in Xinjiang are made with forced labour, and therefore cannot gain entry into the US market. Although this is not related to anti-dumping policies, it indirectly affects the PV imports from China, as an important part of the Chinese polysilicon production is made in the province of Xinjiang.

than 100%. Announced expansions alone would lead capacity in 2030 to reach 75 GW, 28 GW, 15 GW and 33 GW, respectively.

Recent capacity additions have, however, struggled to keep pace with rising demand and the United States currently remains dependent on imports, with production of modules relying almost entirely on imported components. Domestic production of modules was equal to just one-eighth of US demand in 2023, with the country being the world's second-largest importer (just behind the European Union). About three-quarters of US module imports come from Southeast Asia, essentially Viet Nam, Thailand and Malaysia, where significant manufacturing capabilities have been built over the last few years. The rest come from India, Mexico and Korea. By contrast, domestic manufacturing of polysilicon far exceeds the country's needs, due to its historical importance and focus on the semiconductor industry, meaning surplus is exported.

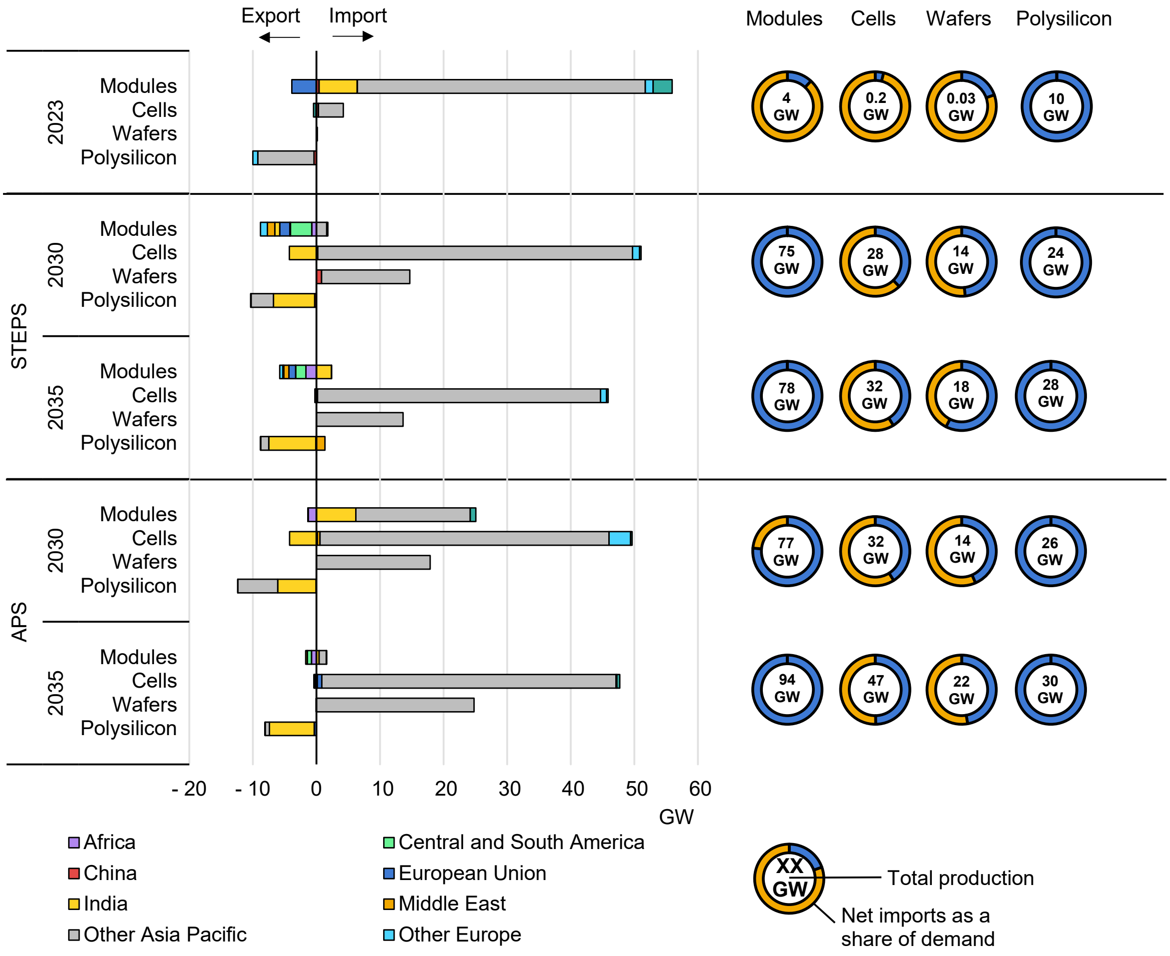
Manufacturing and trade prospects

The prospects for the solar PV industry in the United States diverge markedly across the two scenarios presented here, with faster growth in production projected in the APS, particularly for modules, due to faster domestic demand growth. In both scenarios, US production costs are generally low, thanks mainly to IRA financial support, which eliminates the cost advantage of some other regions that would otherwise be able to supply some components and modules at significantly lower prices. As the PV modules are commodity-like products with fairly standardised characteristics, price is the key driver in capturing market share in all markets. The US market remains mostly isolated from Chinese exports, due to existing tariffs and NTMs applied to solar PV made in China and by some Chinese companies elsewhere.

In the **STEPS**, the United States becomes self-sufficient in modules before 2030 on the assumption that committed investments are forthcoming, with manufacturing capacity reaching more than 85 GW in 2035 (Figure 3.10). Despite the end of IRA subsidies in 2032, the process of building up facilities in operation at that time and associated know-how stimulates continued growth in capacity. Module demand reaches about 75 GW in 2035, of which slightly less than 5 GW are net exports.

Cell production also expands significantly, despite starting from a very low base, but not fast enough to meet all the needs of the module manufacturing sector. In 2035, domestic cells are able to meet less than half of domestic demand, with the rest being met by imports from Southeast Asia and, to a lesser degree, India (high tariffs deter imports from China). Similarly, but to a more pronounced degree, the expansion of wafer production capacity is insufficient to meet domestic demand, with the shortfall being met by Southeast Asian imports. By contrast, production of polysilicon – currently the strongest segment in the US solar PV supply chain – continues to outpace domestic needs, with exports (mainly to India and Southeast Asia) reaching 10 GW, or around 30% of total output, in 2035 – slightly lower than in 2030.

Figure 3.8 US market and import-export balance for solar PV modules and components in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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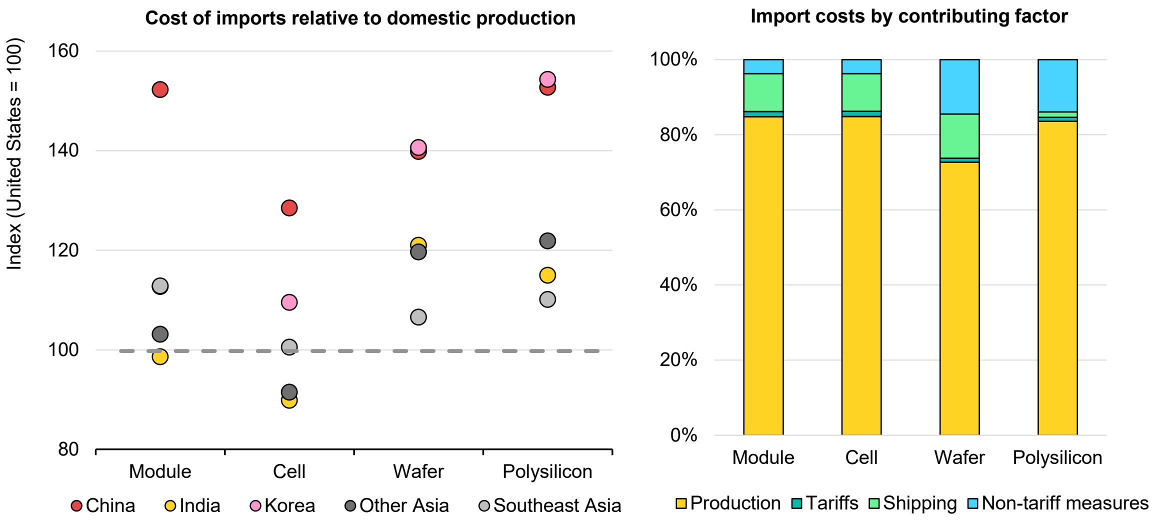
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Demand for components that are not the final product are determined by the production of the subsequent component. Import and export refer to net trade flows between the United States and each of the regions displayed, while net imports as a share of demand refers to the net imports to the United States accounting for all regions as a share of domestic demand.

Solar PV manufacturing grows slightly faster in the APS, but stronger growth in domestic demand means the United States relies more on imports of modules and components.

In the **APS**, solar PV manufacturing capacities generally grow slightly faster than in the STEPS, but stronger growth in domestic demand driven by more rigorous demand-side policies means that the United States relies more on imported modules and components (with the exception of polysilicon). Rising production reflects the recent spate of announcements of new planned projects. Module production reaches almost 95 GW in 2035 – around 20% more than in the STEPS and matches the level of domestic demand, resulting in exports of around 2 GW (mostly to Africa and the Other Asia Pacific region), and about the same amount of imports (2 GW). Cell production also rises faster than in the STEPS, but, at less than 50 GW in 2035, remains well below domestic demand of around 95 GW, with the shortfall being met by imports from Asia Pacific and Southeast Asian countries, where production costs (which account for the bulk of total import costs) are generally lower (Figure 3.9). Wafer production also fails to keep pace with demand, with slightly over half of the nearly 50 GW of domestic needs coming from imports, mainly from Southeast Asian countries. Polysilicon output continues to expand, with nearly 30% of the 30 GW of output in 2035 exported, mainly to India.

Figure 3.9 Total production cost of solar PV in the United States compared with imports and US import costs by contributing factor in the Announced Pledges Scenario, 2035



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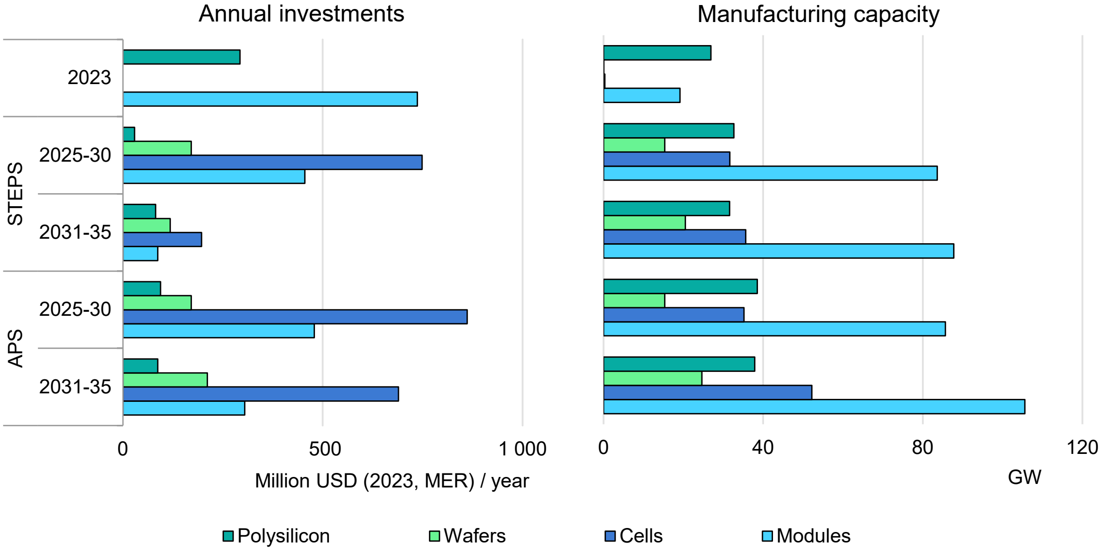
Notes: The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in the United States (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

In the APS, solar PV cells in the United States are mostly imported from Asia, where production costs are generally lower.

With the faster growth in solar PV manufacturing capacity in the APS, investment in the sector is roughly 45% higher over 2025-35 compared to in the STEPS. The largest share in both scenarios is for building cell factories, reflecting the more capital-intensive nature of manufacturing cells. Annual capital needs for the sector as a whole average almost USD 1.5 billion/year, compared with almost USD 1 billion/year in the STEPS (Figure 3.10).

Figure 3.10 US solar PV manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

With the faster growth in solar PV manufacturing capacity in the APS, investment in the sector is roughly 50% higher over 2025-35 compared to the STEPS.

Wind turbines

Current market and policy support

US demand for wind turbines is currently met by a mixture of domestic and imported components. There is a well-established nacelle and tower manufacturing industry, which supplied over 90% of the nacelles and about 80% of the towers installed across the country in 2023. In contrast, a large share of the wind turbine blades that are installed are imported, with domestic content of only around 10% in 2023 (Lawrence Berkeley National Laboratory, 2024). The bulk of imported blades come from Mexico and Europe. TPI Composites, a US company that operates five facilities in Mexico, is the main supplier of these blades to the United States. Recently, there has been a noticeable decline in blade imports from other countries, while imports from Mexico have remained stable or even increased (US ITC, 2024), pointing to a shift towards more regionalised production strategies to exploit efficiencies in supply chains between the United States and Mexico. Tower imports are about the same level of nacelle imports, with most of them coming from Europe. Tower imports have been declining since 2020, which reflects in part import duties: the Department of Commerce put in place antidumping duties of over 70% on wind towers from Spain in 2021 (ITA, 2021) and 20-60% on those from China, India and Viet Nam (ITA, 2012; 2020; 2021a).

The IRA provides 192evelizt for domestic wind manufacturing in two ways. Wind turbine component manufacturers can apply for a tax credit, known as the advanced manufacturing production credits, while wind project developers can apply for an increase of their tax credit of 10% if they meet domestic content requirement thresholds (IRS, 2023). To qualify, onshore projects installed before 2025 must source at least 40% of all equipment domestically (20% for offshore projects). This rises to 55% after 2026 (2027 for offshore projects). In addition, 100% of steel and iron construction materials must be manufactured domestically.

Manufacturing and trade prospects

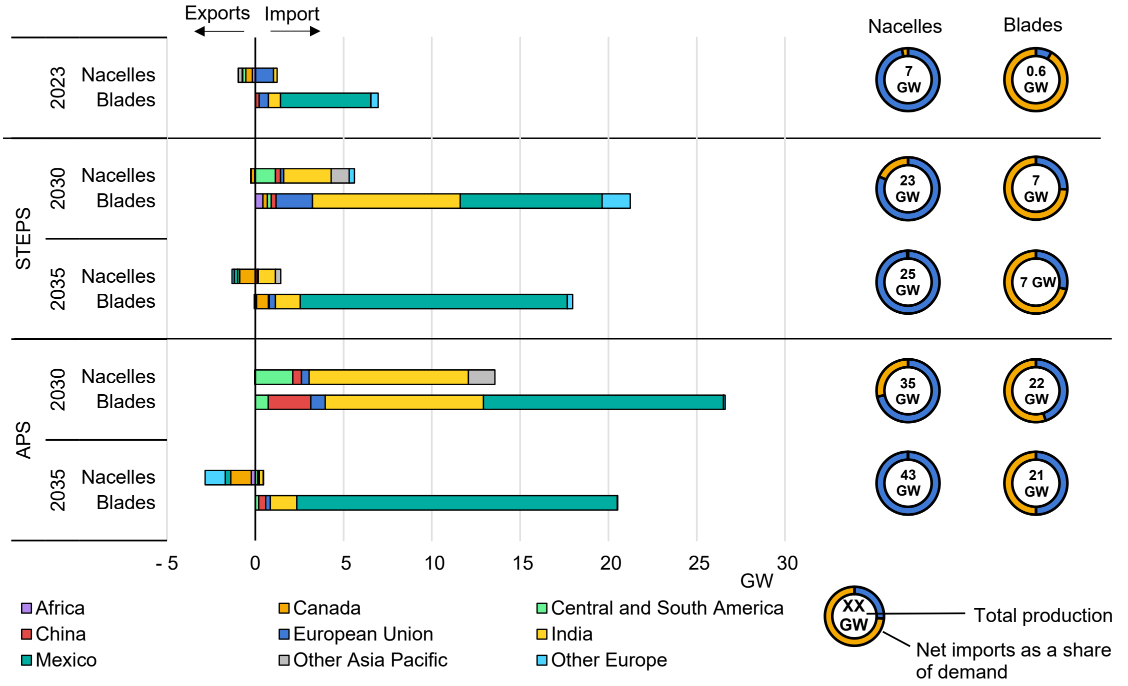
Wind energy generation capacity installed in the United States today is almost entirely onshore, but this is set to change as offshore wind projects attract growing interest, and the government is targeting installed capacity of 30 GW of offshore wind by 2030 (The White House, 2023). In the STEPS, offshore capacity additions increase from virtually zero in 2023 to over 3 GW in 2030, and nearly double that in the APS, whereas onshore added capacities rise from 6.5 GW in 2023 to over 20 GW in STEPS and nearly 40 GW in APS.

At present, there are several planned additions to manufacturing capacity of the main wind power components – nacelles, towers and blades. At the end of 2023, the total capacity of committed and preliminary projects amounted to 4 GW for nacelles, nearly 5 GW for blades and 6.5 GW for towers. These additions would, if completed, lead to a total manufacturing capacity of about 9 GW for blades and nearly 20 GW for nacelles and towers, with a gap of 25 GW for blades and 15 GW for nacelles and towers to satisfy demand in the STEPS. The lack of announcements in this sector partly reflects concerns about future demand, production costs and lengthening queues to connect new installations to the grid. However, domestic content requirements in the IRA and other incentives will likely push domestic production capacity beyond what is currently announced.

In the **STEPS**, despite a projected increase in local manufacturing capacity, the United States continues to import wind energy components to satisfy increasing demand, underpinned by increasingly stringent policy targets. Manufacturing of nacelles increases to 27 GW in 2030 – 12 GW, or 80% up on 2023. Utilisation rates increase as well, from 50% in 2023 to 85% in 2030, but then starts to fall back slightly to around 80% in 2035 while both domestic demand and imports from other regions decline (Figure 3.11). The production of blades also rises, but does not keep pace with demand, driving up imports from Mexico and India. The share of domestic production in the total supply of nacelles to the US market drops from over 90% in 2023 to 80% in 2030, while that of blades increases from 8% to 25%.

In the **APS**, nacelle and blade production grows even faster, to around 45 GW and 20 GW respectively in 2035. This reflects faster domestic demand growth as a result of stronger policies (installations are around 75% higher in 2035 than in the STEPS), as well as higher import costs as other countries exploit more of their own capacity to meet their stronger domestic targets. The share of total demand that is met by domestic producers in 2030 falls to 70% for nacelles but rises to 45% for blades.

Figure 3.11 US market and import-export balance for wind turbine nacelles and blades in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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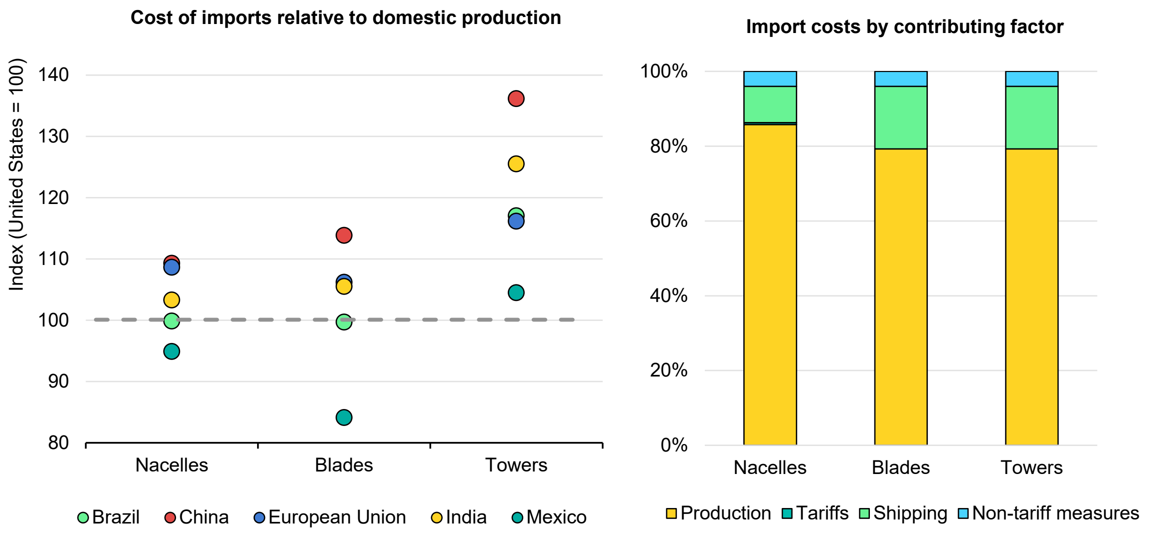
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Towers are not included. Import and export refer to net trade flows between the United States and each of the regions displayed, while net imports as a share of demand refers to the net imports to the United States accounting for all regions as a share of domestic demand.

US production of nacelles and blades rises strongly in the STEPS and APS, but is surpassed by demand, meaning imports are still required, mostly from India and Mexico.

India emerges as one of the main suppliers of nacelles and blades in both scenarios, reflecting its increasing manufacturing capabilities and relatively low supply costs, including shipping, tariffs and NTMs (Figure 3.12). The share of the European Union (which accounts for 15% of global production today) in serving US demand declines over time, as its capacity is used increasingly to meet domestic demand, limiting its ability to export components to the United States. For all wind components, production accounts on average for over 80% of the cost of US imports, with shipping making up most of the rest. Blades and towers have higher shipping costs than nacelles, their relative contribution being roughly twice that of nacelles.

Figure 3.12 Total production cost of wind turbine nacelles and blades in the United States compared with imports and US import costs by contributing factor in the Announced Pledges Scenario, 2035



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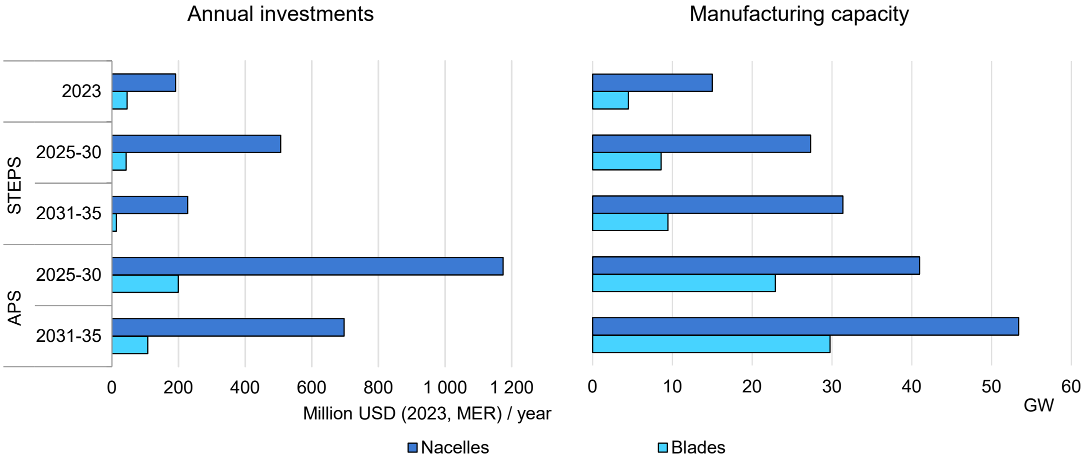
Notes: The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in the United States (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

Shipping wind turbine components is costly, making Mexico and Brazil the most attractive sources for US imports.

Mexico is also projected to play a crucial role in supplementing US manufacturing capacity in the longer term, in particular for blades, for which it already has capacity. It accounts for 60% of US blade imports in 2035 in the STEPS and nearly half in the APS. Large amounts of capacity are added in Mexico in both scenarios, with total capacity increasing from around 7 GW in 2023 to around 20 GW in 2035 in the STEPS and nearly 30 GW in the APS, far exceeding its own domestic demand of 1 GW and 1.5 GW, respectively. Cross-border production strategies will be vital to meeting US demand for wind components and avoiding over—reliance on a single distant international supplier; there are a number of other countries, such as Brazil, which can build on an existing manufacturing base (see Chapter 4).

The much bigger increase in nacelle and blade manufacturing capacity in the APS compared to the STEPS calls for significantly more investment, mainly for nacelles. Investments in nacelles capacity exceed USD 1.1 billion/year on average to 2030, falling to USD 700 million over 2031-35 in the APS as domestic installations slow (Figure 3.13).

Figure 3.13 US wind turbine component manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

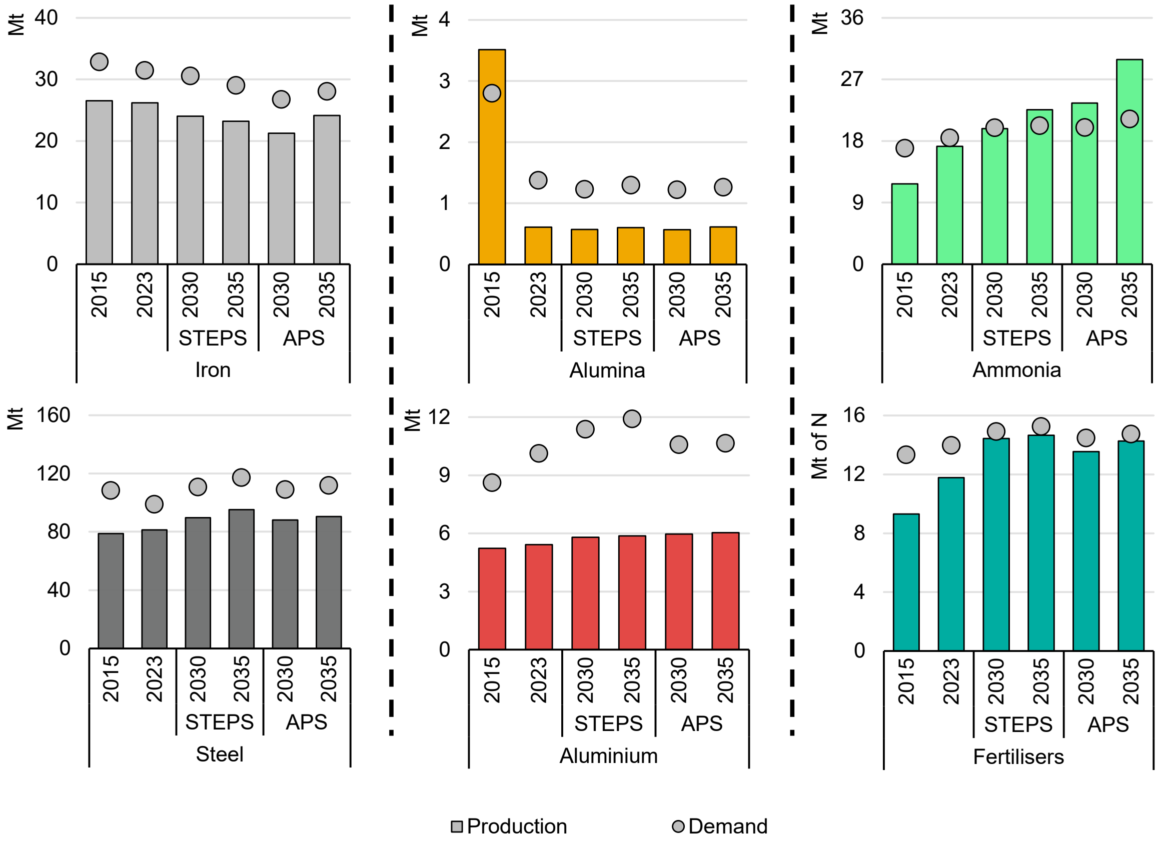
In the APS, investment in nacelle manufacturing capacity exceeds USD 1.1 billion per year on average to 2030, falling to USD 700 million over 2031-35.

Materials

The United States is the world’s third-largest consumer of steel and nitrogenous fertilisers after China and India, and the second-largest consumer of aluminium after China. Demand for aluminium and nitrogen fertilisers grew by 40% and 9% respectively over the 10 years to 2023, while demand for steel decreased slightly. Value added in the iron and steel, non-ferrous metals and primary chemicals and fertilisers sectors fell by 4%, 3% and 4%, respectively, over the same period (Oxford Economics Limited, 2024), while the total share of manufacturing in GDP fell from around 12% to 11%, with a shift towards other economic activities, notably services and a booming information technology sector. The United States is also a significant importer of steel (mainly from Canada, Mexico, Korea and Brazil), aluminium (from Canada) and ammonia (from Canada and Trinidad and Tobago) (CEPII, 2024). In July 2024, new measures on trade in steel and aluminium were introduced by the government in conjunction with Mexico, to improve transparency and prevent tariff evasion (Biden & Manuel López Obrador, 2024; Biden, 2024).

The outlook for US manufacturing of the main materials relevant to manufacturing and trade in clean energy technologies differs only marginally between the STEPS and APS, mainly because the energy sector is but one end user. Ammonia is an exception to this trend: ammonia production in the APS is 7 Mt higher than in the STEPS by 2035, driven by higher global demand for new applications in shipping, power and as a hydrogen carrier. Aluminium production is also slightly higher in the APS than In the STEPS, due to increased demand for domestic clean technology manufacturing, particularly for solar PV. Aluminium production is nonetheless broadly flat through to 2035, as modest increases in total US demand are met mainly by imports.

Figure 3.14 Demand for and production of key materials and intermediate commodities in the United States, historically and in the Stated Policies and Announced Pledges Scenarios, 2015-2035



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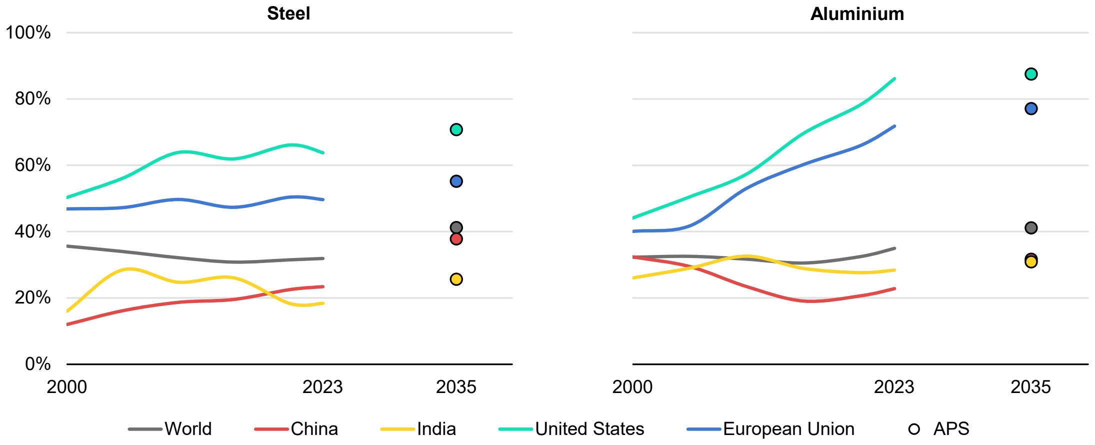
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Mt of N = million tonnes of nitrogen. Ammonia demand does not include international bunkers. The figures for alumina include only metallurgical alumina.

Incentives provided under the IRA boost US materials production in both the STEPS and the APS.

Continued growth in the use of scrap metal continues to help constrain US demand for alumina and iron used in the production of primary steel and aluminium in both scenarios. The share of scrap in steel production in the country rose from little more than half at the start of the century to well over 60% in 2023 and is projected to rise to over 70% by 2035 in the APS (Figure 3.15). The use of scrap in unwrought aluminium production has also risen sharply in recent years to about 85% in 2023 and reaches just under 90% in 2030 in that scenario. These improvements hinge on increased domestic scrap sorting and processing infrastructure (significant amounts of metallic scrap are exported at present). In other regions, such as India and China, scrap availability and the share of scrap-based production increases progressively.

Figure 3.15 Scrap as a share of metallic inputs for steel and aluminium production in selected countries/regions, historical and in the Announced Pledges Scenario, 2000-2035



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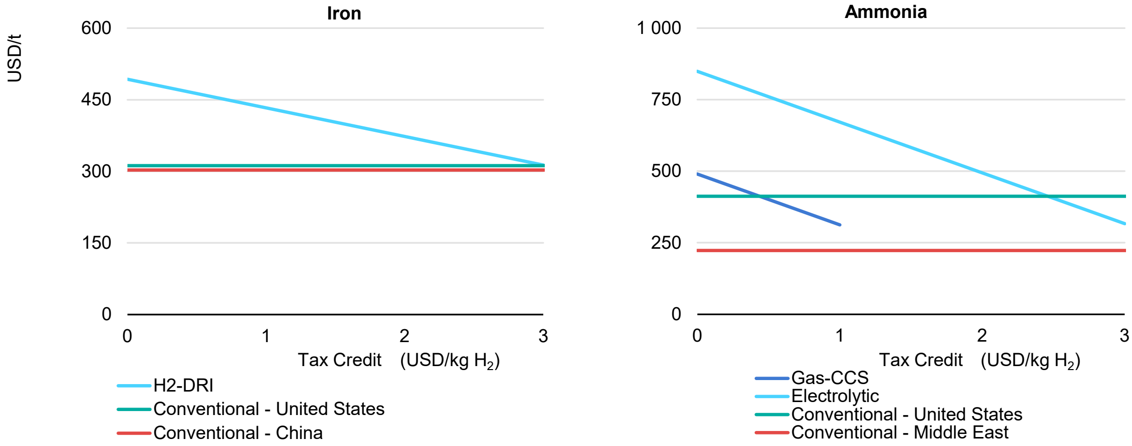
Note: APS = Announced Pledges Scenario.
Sources: IEA estimate based on data from World Steel Association and International Aluminium Institute.

As an advanced economy with mature stocks of materials embedded in its building and vehicle stocks, the United States uses large amounts of scrap for metal production.

The IRA and other policies are expected to drive increased investment in manufacturing using near-zero emissions technologies. This is particularly the case for steel and ammonia, where carbon capture, utilisation and storage (CCUS) and other low-emissions hydrogen-based technologies – for which the IRA provides attractive incentives – are commercially available or are rapidly becoming so. The IRA strengthened various provisions covering CCUS under Section 45Q of the US Tax Code, including an increase in the existing tax credit for every tonne of CO_2 captured and stored permanently in geological formations from USD 50/t to USD 85/t. The IRA also introduced a tax credit under 45V of the Tax Code for the production of low-emissions hydrogen, which varies according to the CO_2 intensity of the process (the largest maximum credit of USD 3/kg of hydrogen is available for projects with a carbon intensity of less than 0.45 kg CO_2 equivalent per kg of hydrogen [kg CO_2-eq/kg H2]) (US DOE, 2024).

Figure 3.16 Impact of the Inflation Reduction Act production tax credit for hydrogen on the levelized cost of production of iron and ammonia by technology in the Stated Policies Scenario, 2030



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Notes: H2-DRI = Hydrogen direct reduced iron; CCS = carbon capture and storage. The levelized costs of production (LCOP) shown here include the full value of the production tax credit, although the incentive duration of 10 years is lower than the lifetime used to calculate the system LCOP. Likely maximum tax credit level available for Gas-CCS ammonia projects is USD 1/kg H_2. Coking coal price = USD 116/toe for the United States and 114 USD/toe for China.

IRA tax credits for hydrogen production could make near-zero emissions technologies cost-competitive with conventional ones in the near future.

These incentives could soon make the production of steel and ammonia in conjunction with CCUS or hydrogen in the United States cost competitive with both materials produced domestically with conventional technologies and with imports. For example, in the STEPS in 2030, a tax credit of around USD 3/kg H2 would make near-zero emissions iron production at a cost of USD 490/t competitive with domestic conventional iron production and iron produced in China (Figure 3.16). Similarly, a credit of around USD 2.5/kg H2 would render electrolytic ammonia competitive with domestic conventional ammonia production, despite relatively low natural gas end user prices in the United States. A higher credit still (above USD 3/kg) would be required to make near-zero emissions production competitive with the lowest-cost producers, notably gas-producing countries in the Middle East.

3.2 European Union

The European Union is promoting clean energy technology manufacturing and industrial decarbonisation to strengthen its long-term competitiveness as well as accelerate the clean energy transition. The European Green Deal serves as an overarching framework for climate and environmental objectives in the region, providing strategic direction through various policy initiatives (Table 3.3).

Table 3.3 Selected domestic and trade policies in the European Union relevant to clean energy technology and materials manufacturing

Policy (enactment year)	Description
European Green Deal (2019)	A comprehensive framework of new and existing policies to guide the Union towards net zero GHG emissions by 2050. As part of the Deal, the Fit for 55 package aims to reduce emissions by at least 55% below 1990 levels by 2030 and includes revisions to the Renewable Energy Directive, the Energy Efficiency Directive and the EU Emissions Trading System (ETS) Directive, and a transitional reporting phase for a Carbon Border Adjustment Mechanism (CBAM).
Green Deal Industrial Plan (2023)	A major initiative of the European Green Deal that aims at enhancing Europe's competitiveness in net zero industries. It includes the NZIA (see below), the Critical Raw Materials Act and reform of electricity market design, which aim to bolster clean energy technology manufacturing, secure essential raw materials for the transition and decrease electricity price dependency on fossil fuels.
Net-Zero Industry Act (2024)	Aims for the Union to have sufficient manufacturing capacity for net zero technologies to meet at least 40% of its annual deployment needs by 2030, including key components of such technologies. Technologies included are, among others, solar, wind, battery/storage systems, heat pumps and electrolysers. It also sets the goal of having at least 50 Mt of annual CO_2 storage capacity by 2030.
REPowerEU Plan (2022)	Aims to reduce the EU dependence on fossil fuels, particularly from Russia, by improving energy efficiency, diversifying energy supplies and accelerating clean energy deployment. Among the initiatives initiated is the European Solar PV Industry Alliance, focusing on increasing domestic solar PV manufacturing capacity.
Temporary Crisis and Transition Framework (2023)	This framework, introduced in response to Russia's invasion of Ukraine, revises EU State Aid rules to enable member states to provide more support, such as grants, tax incentives or loans/guarantees, for clean technology manufacturing until the end of 2025. It includes provisions for "matching aid", i.e. the support a project could receive for an equivalent investment elsewhere.
Reciprocal preferential trade agreements	Trade agreements to facilitate tariff-free trade in industrial goods include the customs union with Türkiye (1995); the EU-Morocco Association Agreement (2000), which fully liberalises trade in industrial goods; the EU-Korea Free Trade Agreement (2011); and the EU-Japan Economic Partnership Agreement (2019). These agreements eliminate almost all tariffs on steel, aluminium and vehicles and address NTMs for vehicles, avoiding the need for EU manufacturers to produce market-specific cars and undergo costly compliance testing. There are trade negotiations with Australia, New Zealand, India, Indonesia and MERCOSUR. The Commission is also seeking to ratify preferential trade agreements with Chile, crucial for raw material supplies, and Mexico.
Countervailing duties to Chinese electric vehicles (2024)	See section below and Table 3.4.

Sources: European Commission (2022), (2023), (2023a), (2024), (2024a) and (2024b).

In response to concerns about losing competitiveness to China and the United States, and access to critical raw materials needed for the green transition, the European Union has implemented several key policies, including the NZIA, the Critical Raw Materials Act and the European Wind Power Package, as well as several initiatives to scale up EU manufacturing and diversify the imports of components and raw materials, such as the European Battery Alliance and the European Solar Photovoltaic Industry Alliance. Other initiatives are under discussion, such as the Heat Pumps Action Plan. Various financial support programmes, including relaxed state aid rules until the end of 2025, have been proposed. The European Union is also collaborating with the United States to address the potential impacts of the IRA and remains vigilant in monitoring global public support policies to ensure fair competition (EC, 2022a).

Box 3.2 The Net-Zero Industry Act in the IEA's Manufacturing and Trade model

Clean energy technology manufacturing goals

The NZIA sets a benchmark for net zero technology manufacturing capacity to meet at least 40% of EU annual deployment needs by 2030. This includes final products, components and machinery essential for the manufacture of clean energy technologies. Given the non-binding nature of this benchmark and the absence of clear policy instruments for its implementation, it is included in the APS but not in the STEPS. Accordingly, in the APS, at least 40% of each of the key components deployed in the Union is manufactured domestically. This benchmark is exceeded where there is already significant installed manufacturing capacity, such as for batteries or wind turbines. The NZIA also establishes a benchmark for the European Union to reach a 15% share of global production by 2040, except in cases where the capacity would be significantly higher than its domestic needs.

Diversification of supplies

The NZIA introduces non-price criteria into public procurement procedures, renewable energy auctions and other support schemes. Among other non-price criteria, the Act introduces the so-called "resilience contribution" to diversify supply sources in cases of high dependency. It imposes special considerations where a technology or its key components from a particular third country account for more than 50% of supply to the Union, or in the case of public procurement, where the import value of such components has increased by more than 10% in 2 years and meets more than 40% of EU demand. Member states can disregard resilience criteria if applying them would result in disproportionate costs, set at 15% for auctions and 20% for public procurement. The intended outcome of this regulation is implemented In the APS by gradually limiting imports from a single country towards 50% of the technology deployment while also limiting the growth rate of imports, without applying any price safeguard.

Faster administrative and permit-granting processes

The NZIA introduces the concept of “Net-Zero Strategic Projects”, which should be given priority by member states to ensure that they benefit from the fastest possible permitting processes in accordance with national and EU law. It sets time limits for the permitting process for net zero technology manufacturing projects, with a maximum of 12 months for projects below 1 GW, and 18 months for other projects, with shorter periods for projects with a strategic status. By the end of 2024, member states should establish or designate a single contact point for the permit-granting process. This is reflected in the APS by setting more ambitious production manufacturing scale-up rates compared with the STEPS.

Access to financial support

The Act recognises that private financing alone may not always be sufficient for manufacturing projects, and targeted public support is available through The Temporary Crisis and Transition Framework (see Table 3.3), as well as funding programmes such as the Recovery and Resilience Facility, InvestEU, Cohesion Policy programmes or the Innovation Fund, some of which are managed at EU level and others by member states. However, as financial support is not guaranteed from the outset and has to be applied for on an ad hoc basis – a process that can be cumbersome and uncertain as to the level of support projects will receive – no financial support is assumed in either scenario.

EVs and batteries

Current market and policy support

The European Union is historically a major player in the global car industry, with over a century of experience and a broad range of companies specialised in different segments of the supply chain, from steel production to component manufacturing, for different types of vehicles. The Union currently produces around 12 million cars per year, though there is capacity to produce up to 21 million.

The shift in demand towards EVs, driven by the EU regulation banning the sale of (plug-in) hybrid and ICE light-duty vehicles from 2035, requires repurposing the entire vehicle ecosystem. Most production facilities are still geared to making ICE vehicles, though some have been converted to EV manufacturing. The German OEM Volkswagen (VW), for example, recently converted its 360 000-unit Zwickau assembly plant. Other OEMs like Stellantis and Renault have also converted some of their assembly lines. Competitiveness rather than manufacturing capacity is likely to be the limiting factor for the ramp-up of EV production, with assembling vehicles and making batteries costing considerably more in most EU member states than in some other parts of the world. The price of batteries, whose production cost in the Union is around 50% more than in China, will be critical to the competitiveness of the EU automotive industry.

EU carmakers’ struggle to compete on international markets for EVs is reflected in the steady rise in imports from China, which reached 400 000 cars in 2023 – a rise of nearly 40% on the previous year (double the overall growth in the EU market). China now accounts for almost one-fifth of new EV sales in the European Union; most of the rest are made domestically. More than half of the imports from China were manufactured by OEMs headquartered outside of China, led by US-based Tesla and France’s Renault (with its low-cost brand Dacia). At the same time, EU car companies also export, mostly to other European countries and the United States, with exports being almost double the volume of imports from China in 2023.

Box 3.3 The struggles of the EU car industry in competing in emerging markets

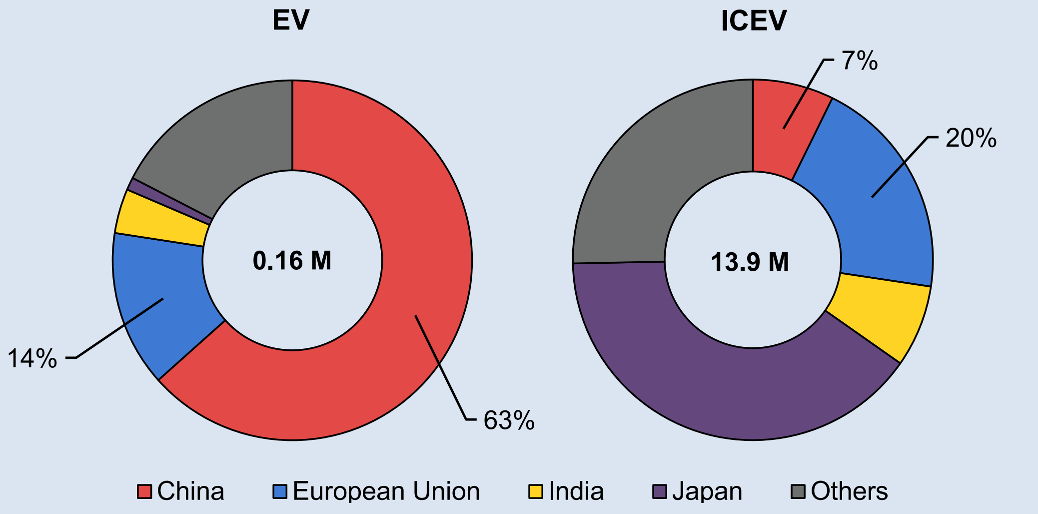
The automotive industry is a cornerstone of the EU economy, with its turnover contributing about 7% of its GDP and supporting 13 million jobs. The industry produced 12.1 million cars in 2023, of which 2.4 million were EVs. EU car imports totalled 3.3 million in 2023, of which more than 20% were EVs. The main sources of imports were, in order of importance, China (with one-fifth of total imports), Türkiye, Japan, Korea and Morocco. The region is a net exporter, with exports reaching 4.7 million units in the same year (of which more than 15% were EVs), generating a trade surplus revenue of USD 96 billion. The European Union remains a net exporter of EVs, but the number of EVs exported is now nearly equal to the number imported.

The region accounted for around one-third of global car exports in value terms in 2023 (ACEA, 2024). The main export markets were historical EU trade partners: the United Kingdom (with 26% of EU exports), the United States (17%), Türkiye (13%), China (7%) and Switzerland (4%). New car exports to EMDEs (excluding China) have been rising in recent years, accounting for nearly one-fifth of total EU exports in 2023, the majority of them being ICE vehicles.

As well as exporting ICE vehicles to EMDEs, European carmakers also produce in those countries, benefiting from lower costs and access to local markets. For example, Renault has factories in Morocco and India, Stellantis and VW in Brazil and Germany’s Mercedes and VW in South Africa. EU OEMs accounted for 20% of total ICE car sales, or about 2.8 million units, in EMDEs in 2023 (Figure 3.17). Overall, three-quarters of EU carmaker sales in EMDEs were manufactured in their locally-established assembly plants.

The rise of both EV imports from China and Chinese OEMs establishing manufacturing facilities in other EMDEs is threatening the market opportunity of incumbent EU carmakers. EU companies made almost three times more ICE vehicle sales than Chinese firms in EMDEs in 2023. China, by contrast, supplied over 60% of the EVs sold. Rising EV sales are, therefore, likely to boost the market share of Chinese OEMs to the detriment of EU OEMs in the near term, at least. Small Chinese EVs are already cheaper than the average small ICE vehicle in EMDEs, and this segment accounts for up to one-quarter of sales in these regions. In the case of SUVs, which remain the preferred type of vehicle in EMDEs, with up to 30% of new car sales, China-made electric models are currently 36% more expensive than the average conventional equivalent SUVs.

Figure 3.17 Car sales in emerging markets and developing economies by manufacturer headquarters’ location, 2023



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Notes: EV = electric vehicles; ICEV = internal combustion engine vehicles. M = million in number of units sold.

Source: Marklines (2024).

Developing a domestic Li-ion battery industry to reduce reliance on imports has been a key objective of the European Commission and some national governments since 2017. Until recently, there was practically no European battery industry, given that the technology was pioneered by Asian companies. However, surging interest led EU production to increase sharply, from 2 GWh in 2019 to over 60 GWh in 2023. Further rapid growth is in the pipeline: over 500 GWh of new manufacturing capacity was committed by the end of June 2024, which we estimate will involve USD 8.5 billion in annual investment on average over 2025-30.

Nevertheless, signs of a slowdown in developing battery projects are starting to appear, indicating risks for some of the projects in the pipeline (BNEF, 2024; FT, 2024). For example, NorthVolt, the biggest European battery maker, has delayed its plans to ramp-up production (Financial Post, 2024; FT, 2024a) and recently announced job cuts (Reuters, 2024b; Northvolt, 2024). In addition, the Chinese battery maker SVOLT recently halted plans to build a gigafactory in Germany (Automotive News Europe, 2024). This slowdown is affecting upstream parts of the battery supply chain, with the biggest cathode active material producer in Europe, Umicore, expected to barely break even in 2024 due to lower demand than expected (Umicore, 2024).

The EU battery 204evelizey is facing Intense competitive pressures from both China and the United States, and not only because of its higher production costs. Chinese battery-making heavyweights, including CATL and BYD, are innovating rapidly to produce the next generation of Li-ion batteries (Cars News China, 2024; CATL, 2023b). In addition, in the past 2 years, investment in battery manufacturing has been drawn away from the EU market to the United States, thanks to lucrative financial support under the IRA (BMI, 2023).

Growing concerns about the impact of cheap EV imports from China on EU carmakers, and alleged evidence of unfair subsidies in China, prompted the European Commission to introduce new duties on those imports from 2024, following an anti-subsidies investigation launched in October 2023 (EC, 2023b). Import duties will be imposed for the next 5 years (EC, 2024c). Findings of the investigation, including final tariff values, will be released by 30th October 2024 (EC, 2024d). Tariffs applied to each company will differ, depending on the level of subsidies it was found to receive, and its level of co-operation in providing the data requested by the EU Commission for the investigation (Table 3.4). These tariffs will be imposed on top of the pre-existing 10% import tariff for all cars imported from outside EU borders. Unlike the recent US tariffs increase on Chinese electric cars, the tariff levels proposed by the European Commission are not high enough to completely undermine the competitiveness of all Chinese carmakers relative to European OEMs, but they are likely to significantly reduce the incentive to sell EVs made in China in the EU market (Box 3.4).[3]

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[3] Electric car trade modelling in both the STEPS and the APS includes the latest proposed EU import duties on Chinese-made EVs (Table 3.4).

Table 3.4 Summary of EU proposed duties on EV imports from China

Company	Current tariff rate	Proposed duty rate	Total rate
BYD	10%	17%	27%
Geely	10%	19.3%	29.3%
SAIC	10%	36.3%	46.3%
Tesla	10%	9%	19%
Other (co-operating)	10%	21.3%	31.3%
Other (non-co-operating)	10%	36.3%	46.3%

Notes: The provisional duties came into effect on 4th of July 2024. Duties are added on top of current 10% import duty.
Sources: European Commission (2024e) and (2024f).

Box 3.4 Impact of proposed EU duties on imported Chinese EVs

The new import duties, if confirmed, will undoubtedly have an impact on company strategies and will likely slow down the growth of EVs manufactured in China in the short term. However, the current level of those duties is not sufficient to fully shift the balance in favour of production elsewhere.

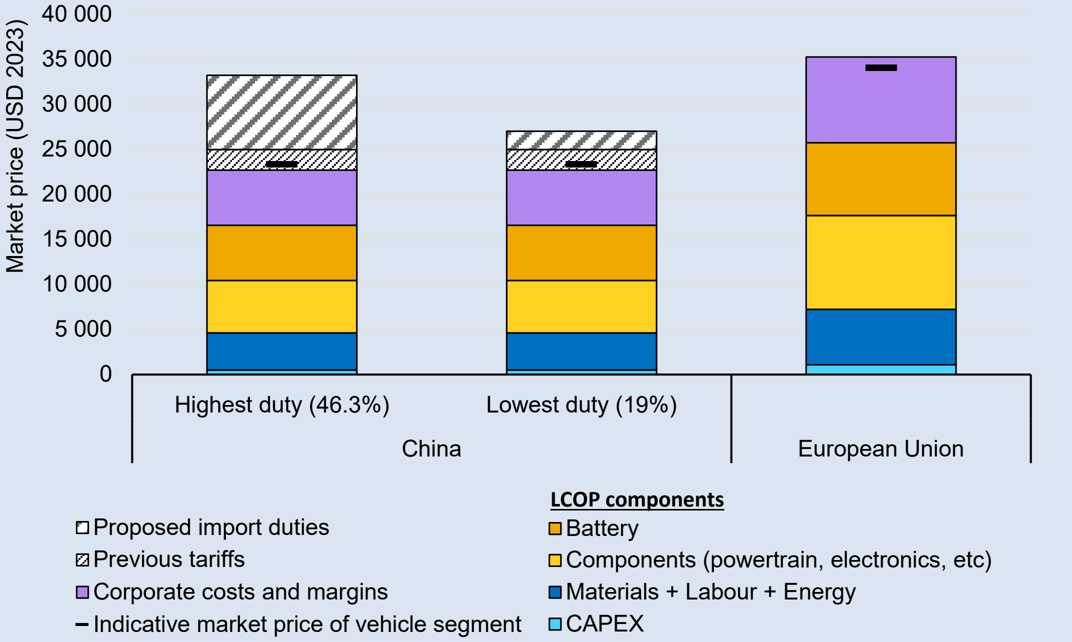
The duties could affect the car industries in both markets. In the short term, they may delay or limit Chinese OEMs plans to enter the EU market, in which case Chinese EV exports could be redirected to other non-EU countries with strong EV deployment targets, like the United Kingdom and Norway. The tariffs may also lead to a surge in imports of plug-in hybrid vehicles (PHEVs), which are currently exempt, as China is the world’s largest producer of such vehicles. In the medium term, there is also a possibility that Chinese OEMs could establish more manufacturing sites in EU countries. At the same time, it is possible that part of the tariffs faced by OEMs might be transferred to consumers, thus increasing the average price of EVs in the European Union.

The higher average EV retail prices that currently prevail in the EU market could, in any case, help Chinese OEMs to continue to export at a profit, which is especially attractive given fierce competition in the Chinese market. Chinese EV makers have stated clear ambitions for the European market. For example, BYD aims to capture a 5% EV market share in 2025 and 10% in 2030 (Rhodium Group, 2024), which would equate to around 700 000 cars (based on the STEPS). That is much higher than the 200 000-unit capacity of BYD’s sole planned European manufacturing plant. This suggests that BYD’s ambitions in Europe will rely to a significant extent on imports, either directly from China or from other countries where it has plans to build up manufacturing capacity, such as Türkiye (Firat Kozok, 2024) and Thailand (BYD, 2024).

The new import duties will not affect Chinese OEMs alone. European and other international OEMs that import EVs from their assembly plants in China are also subject to tariffs. In 2023, more than half of the Chinese EV imports to Europe were produced by OEMs headquartered outside of China. Most of the automakers that co-operated with the investigation are subject to lower tariffs (31.3% maximum), giving these companies a significant cost advantage over their competitors that did not co-operate (Figure 3.18).

Whether or not Chinese OEMs will be able to retain and strengthen their foothold in the EU EV market is not only a matter of production costs and sale prices alone; consumer brand-related preferences and supply chain risks are also at play.

Figure 3.18 Impact of provisional EU duties on the price of a compact electric SUV imported from China, 2023



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Notes: CAPEX = capital expenditure; SUV = sports utility vehicle; LCOP = Levelized cost of production. Price refers to the domestic market.

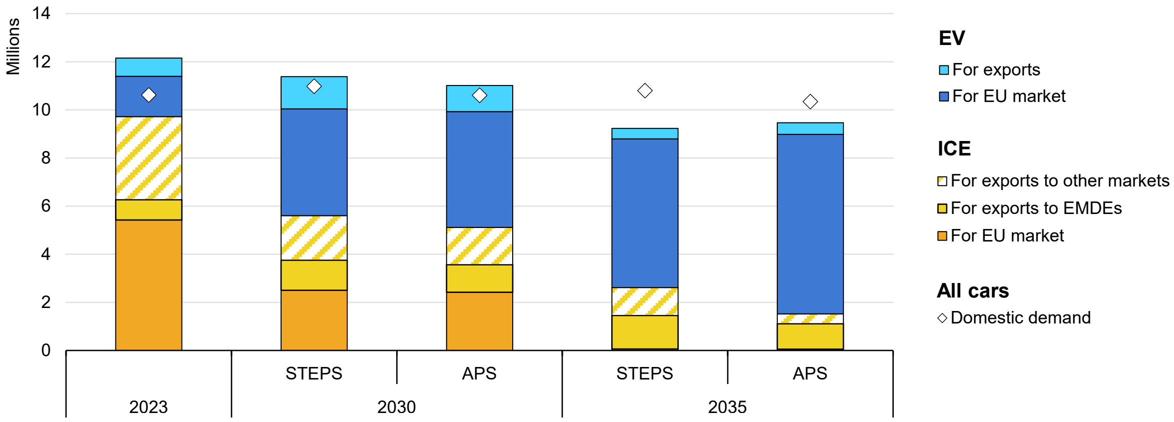
Sources: Tariffs are taken from EC (2024e); indicative market prices are taken from EV Volumes (2024); component cost estimates come from BNEF (2021) and (2024a).

Manufacturing and trade prospects

The prospects for the manufacturing of and trade in EVs in the European Union are closely tied to the complex interaction of policy decisions related to the economy, energy, climate, industrial development and trade. In both the STEPS and APS, overall EU car production declines progressively to 2035, with a sharp fall in the production of ICE vehicles more than offsetting a rapid expansion in that of EVs (Figure 3.19). In the STEPS, European ICE car manufacturing will continue to have a market mainly through exports, despite the complete phase-out of their sale within the European Union. This export opportunity is smaller in the APS, in which policies elsewhere, in particular in other advanced economies, accelerate the deployment of EVs to meet climate goals. In 2035, although the

European Union exports fewer ICE cars in the APS than in the STEPS, its increased domestic EV production more than compensates for the decline in ICE manufacturing. As a result, overall car production is slightly higher than in the STEPS, but still about 20% lower than in 2023. More broadly, the extent to which these export opportunities can be grasped is affected by the investment of non-European carmakers in EMDEs, especially Chinese ones (see China section below and Box 3.3).

Figure 3.19 Production of cars in the European Union by market segment in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; EV = electric vehicle; ICE = internal combustion engine (includes HEVs, non-plug-in Hybrid Electric Vehicles); EMDEs = emerging markets and developing economies (excluding China). Millions refers to units produced.

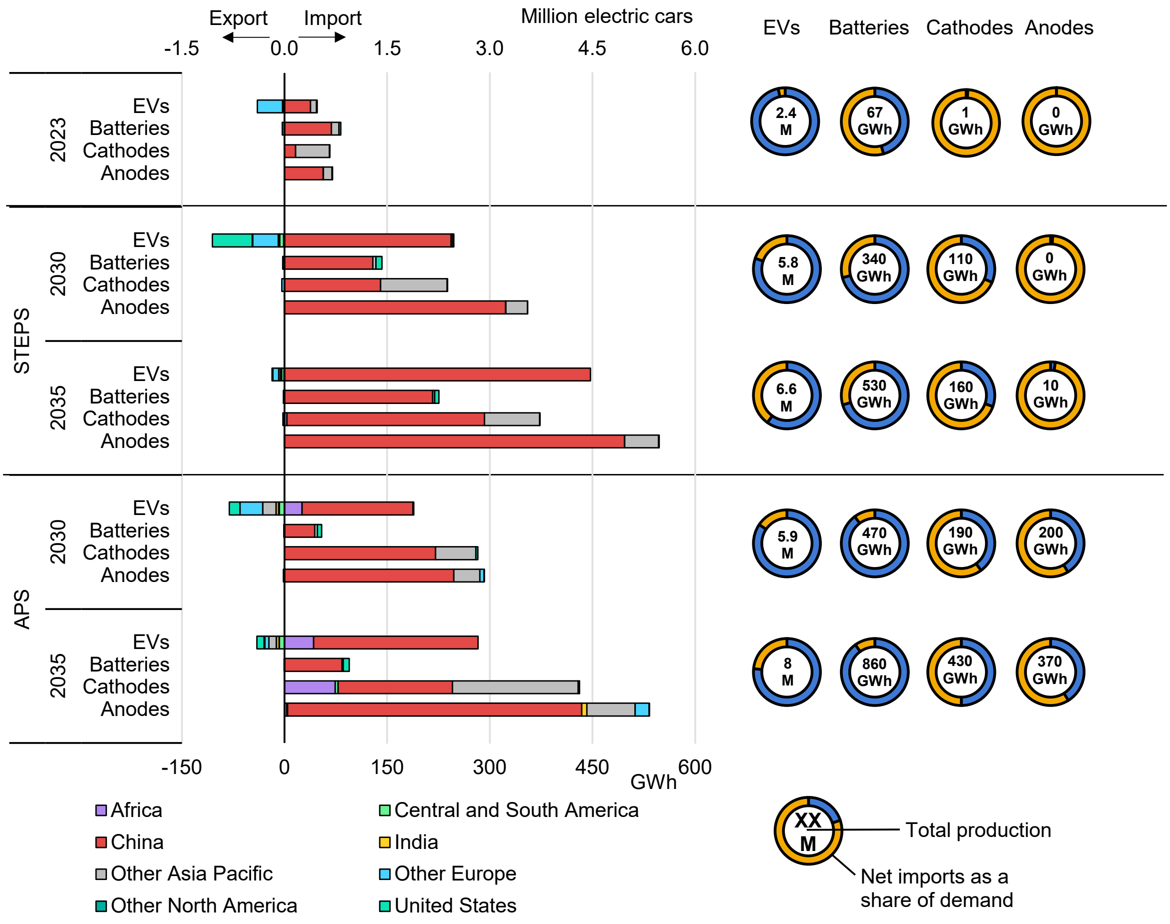
Sources: IEA analysis based on EV Volumes; Oxford Economics (2024); and ACEA (2024).

EU car production is set to decline to 2035, with a significant drop in the production of ICE vehicles more than offsetting a rapid expansion in that of EVs.

In the **STEPS**, domestic EU demand for EVs grows rapidly, from 2.4 million cars in 2023 to 7.2 million in 2030 and 10.7 million in 2035, when CO_2 emissions standards that effectively mandate an end to ICE and PHEV vehicle sales take effect. However, EU production falls short of domestic demand due to a combination of competition from China and the United States, a fragmented domestic battery industry, and high energy costs, which keep the overall cost of production relatively high and undermine the viability of investments to expand output. In particular, the cost of making battery cells remains significantly more expensive than in China in 2035, making manufacturing EVs domestically more costly. This results in a sharp increase in imports of cheaper EVs. By 2035, imports – almost exclusively from China – reach 4.5 million (over 40% of the EU market) (Figure 3.20). EU production of EVs reaches more than 6.5 million, with over 400 000 vehicles being exported, down from 1.3 million exported in 2030, of which more than a third were PHEVs, mostly to the United States and other European countries. Over the period to 2029, during which the new tariffs on Chinese imports will apply, imports from China continue to grow, but at a slower pace compared to the past 3 Years. While those tariffs help to shield the industry from lower costs in China, they also risk increasing EU average prices in the short term, and holding back efforts by EU carmakers to boost competitiveness in the long term.

The EU car industry continues to export ICEs in 2035, but volumes fall as lower demand from other advanced economies more than offsets modest growth in demand from the EMDEs, where overall demand for mobility remains strong. As a result, the share of ICEs in total EU car production drops from 80% in 2023 to about 30% in 2035.

Figure 3.20 EU market and import-export balance for EVs, batteries and selected components in the Stated Policies and Announced Pledges Scenarios, 2023-2035



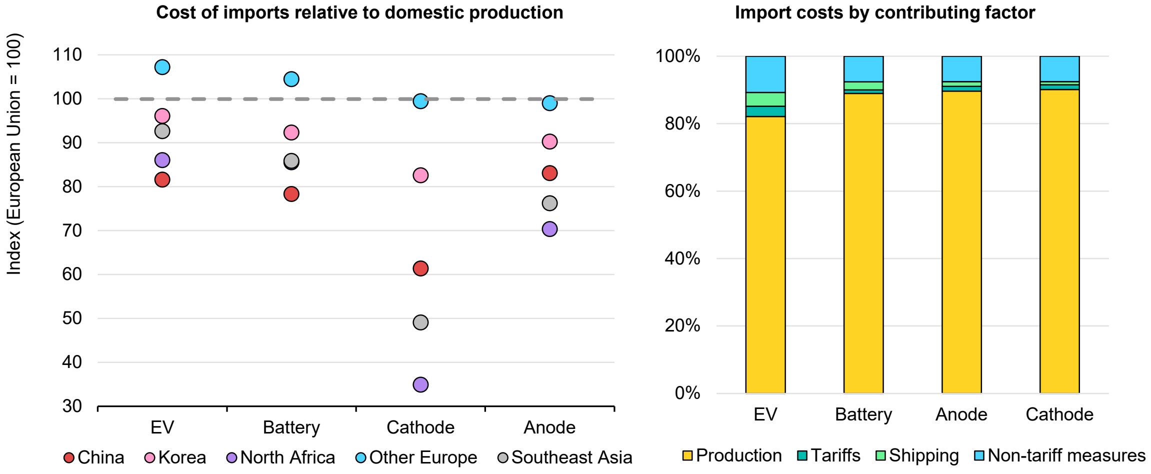
IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; M = million; EVs = electric vehicles, specifically passenger cars and pick-up trucks. Battery demand, production, and trade include all EV types and stationary storage. It is assumed that all countries and regions produce the global average chemistry share for both batteries and components. Cathode and anode refer to active materials. Demand for components is determined by the production of the subsequent component. EV data is reported in million units (top axis), while battery cell, cathode, and anode active materials in GWh (bottom axis). Import and export refer to net trade flows between the European Union and each of the regions displayed, while net imports as a share of demand refers to the net imports to the European Union accounting for all regions as a share of domestic demand.

EU EV production is unable to keep pace with domestic demand, especially in the STEPS, with imports of EVs, batteries and other components from China growing strongly to 2035.

Thanks to earlier investment, almost three-quarters of EU battery needs in 2035, equivalent to 530 GWh, are sourced from domestic production in the STEPS, with most of the rest being imported from China. A similar share could be achieved as soon as 2030, if all committed EU battery manufacturing capacity is brought onstream on time. Our analysis suggests that the costs of EU battery production are likely to remain above the cost of imports in 2030, notably from China, despite tariffs and NTMs. Cathode and anode active material production falls far short of that needed to cover demand over the period to 2035 in the STEPS. In 2030, only 30% of the cathode demand is met with local production, while for anode it is close to zero (1%). The remaining part of cathode demand is satisfied mostly by imports from China (40%) and Korea (25%), while 90% of the anode active material used in Europe is supplied by China. European production grows in the 2030s, following growth in demand, but the EU battery industry remains heavily dependent on imports for both cathode and anode materials.

Figure 3.21 Total production cost of EVs and batteries in the European Union compared with imports and EU import costs in the Announced Pledges Scenario, 2030



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Notes: EVs = Electric Vehicles (electric passenger cars exclusively). Total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in the European Union (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

EU battery production costs remain above the cost of imports, notably from China, in 2030, though the gap narrows compared to today when import duties are taken into account.

In the **APS**, stronger EU policies and investments to reduce dependence on imports lead to some EV exports and reduced imports, driving up EU production of both EVs and components after 2030 relative to the STEPS. Domestic EV demand is roughly the same in both scenarios. By 2035, EU EV production reaches 8 million cars – nearly 1.5 million or over 20% more than in the STEPS.

Higher EV production is supported by the full implementation of the NZIA, resulting in higher production of batteries and components and leading to a more integrated supply chain, which enhances the competitiveness of EU manufacturing. This results in a larger share of domestic EV demand being met by domestic production, thereby alleviating the impact of the fall in ICE output on total car production. By 2035, domestic production meets around three-quarters of total EU demand for EVs.

Imports from China in 2035 in that scenario amount to 2.4 million vehicles, accounting for over one-fifth of total EU demand, with other imports coming mostly from North Africa, and in particular Morocco (see Chapter 4).

Battery production is also a lot higher in the APS than in the STEPS, reaching 470 GWh in 2030 and 860 GWh in 2035 (40% and 60% higher, respectively) and meeting the vast majority of the region's battery demand. Higher investment and the full implementation of the NZIA pave the way for the rapid construction of a large battery industry, including cell and battery components producers working closely with car OEMs. This concerted effort underpins a more rapid fall in the cost of making batteries, reducing the cost gap with China. By 2030, there is a lower incentive to import batteries once trade costs are taken into consideration (Figure 3.21). Higher battery demand, and therefore higher domestic production, supported by the full implementation of the NZIA, is key to attracting investments, decreasing production cost and enhancing EU competitiveness. These gains could be further enhanced by innovation (Box 3.5).

Cathode and anode active materials production grows significantly faster in the APS than in the STEPS, with 40% of both cathode and anode demand being supplied by domestic producers in 2030, in line with the NZIA. Manufacturing capacity reaches almost 400 GWh for cathodes (nearly 35% higher than in the STEPS), and over 300 GWh for anodes (compared to only 15 GWh in the STEPS). Imports nonetheless remain the primary source of supply, with almost 10% of cathode demand being supplied by Korea and about 45% by China, while around half of anodes come from China. In 2035, EU production of cathode active material reaches over 400 GWh, meeting about half of the total demand, while anode production reaches over 350 GWh, meeting 40% of demand. Half of EU anode needs are served by imports from China, with the remaining 10% coming mostly from Southeast Asia, India and Korea – regions with existing battery industries or with low energy costs and plans to expand their battery-related industries.

Box 3.5 The role of innovation in increasing the competitiveness of the battery industry outside China

The cost gap between China and other regions in producing batteries is generally very large. In the European Union, for example, production costs today are almost 50% higher than in China based on the same chemistry mix. It might not be possible to close this gap entirely, but battery manufacturers outside China nonetheless have options for reducing it to a point where the advantages associated with being located in the European Union (such as access to the large internal market and a stable legal and political framework) outweigh the remaining cost difference.

Innovation and manufacturing optimisation are critical to competing in the fierce international battery market. Designing and producing batteries, starting from the choice and processing of raw materials through to battery pack assembly, is a very complicated process with hundreds of parameters that need to be optimised, in which even minor differences, like the addition of a small volume of selected additives, can enormously change the performance of the final battery.

Today China is largely recognised as the world leader in battery innovation, with companies like CATL and BYD being the front runners. BYD is the largest EV producer today (IEA, 2024a) with a fully integrated supply chain. It owns important innovations like its unique cell format, the blade battery, which enables compact packaging at the battery pack level, increasing energy density. The second generation of blade batteries is expected to be launched before the end of 2024 (Cars News China, 2024). CATL, which in 2023 had about 20 000 employees working on battery R&D alone (FT, 2023; CATL, 2024b), has also announced a large number of innovations in recent years, ranging from ultra-high energy dense (CATL, 2023a) and superfast charging batteries (CATL, 2023b) to batteries that shows almost no degradation for stationary storage application (CATL, 2024a). Chinese companies are not just improving Li-ion batteries; R&D is underway for other technologies, such as sodium-ion batteries. The largest stationary storage project in the world involving sodium-ion batteries was installed in China in 2024 (PV Magazine, 2024). China is also set to invest more than USD 800 million in R&D of solid-state batteries (Reuters, 2023g).

A key strategy for competing with Chinese battery makers is securing access to raw materials at low prices. In the European Union, about 45% of the cost for producing batteries[4] comes from the cost of materials, followed by energy cost (about 20%), annualised capital costs and maintenance (about 20%), and labour cost (about 15%). Ways of obtaining cheaper raw materials include establishing strategic trade relationships and long-term contracts with critical mineral producers and refining companies, or by directly investing in them.

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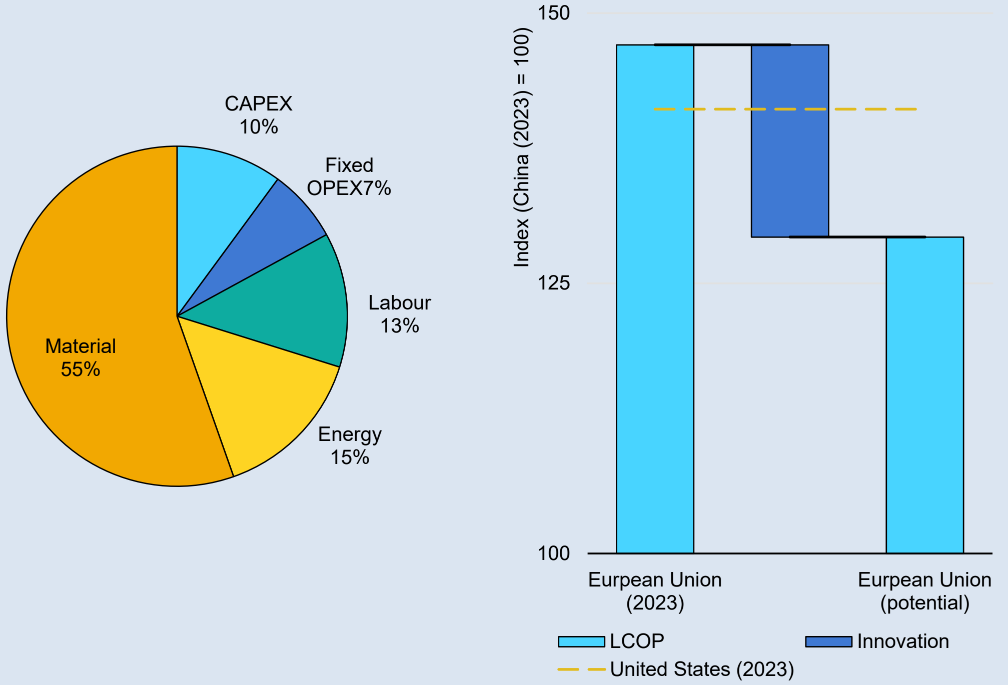
[4] Considering components (cathode and anode active materials) and cell production.

Another approach to cutting battery production cost is by using chemistries that require less costly or fewer minerals. Chinese OEMs, for example, are now mostly using lithium iron phosphate (LFP) batteries, which cost up to 30% less compared with high nickel chemistries, such as lithium nickel manganese cobalt oxide, or NMC, batteries – the dominant technology in Europe and the United States (Bloomberg, 2024). LFP batteries may not be best-suited for the European battery industry in the short term, given the lack of experience with this chemistry, the lower profit margins and the fact that greater driving ranges are achievable with NMC batteries, which is a priority for European customers. An alternative approach is to focus on increased manganese content in NMC batteries, which could help lower costs by up to 10% thanks to lower nickel content and slightly higher energy density; industrial production is planned in the next few years (Umicore, 2023). Nonetheless, it might 212evelizcial for EU battery producers to move towards higher LFP shares in the medium term, as the record low prices (Bloomberg, 2024) these batteries are reaching could bring down the price of EVs and encourage consumers to switch.

There is also potential for innovation to bring down energy costs, which are particularly high in Europe. Apart from critical minerals refining, cell manufacturing is the most energy-intensive step in the battery supply chain, accounting for more than 40% of total energy costs. Energy is needed for drying cathodes and anodes composites to produce the final electrodes (about 28%); for operating dry rooms (25%) in which batteries are produced; and for the formation steps (23%), during which the batteries are charged and discharged slowly a few times to ensure performance and test their safety. Innovation could cut these energy needs, such as through dry coating or near-infrared drying; tailoring the size of dry rooms or increasing their efficiency; faster or tailored formation processes; and using heat pumps for heating and cooling. In total, when accounting for cell, cathode and anode active materials production, energy needs could be reduced by about 20%.

In total, we estimate that the potential for innovation in cell manufacturing processes and battery chemistry could lower EU battery production costs by over 15 percentage points, cutting the cost gap with China by around 40% (Figure 3.22). Whatever approach to innovation is taken, economies of scale are essential for producing batteries competitively, as battery production is often a low margin business that requires extreme precision and efficiency, and therefore high yields and automation (Intercalaction Station, 2023).

Figure 3.22 Global average battery levelized cost of production per cost factor and potential impact of innovation on battery costs in the European Union, 2023



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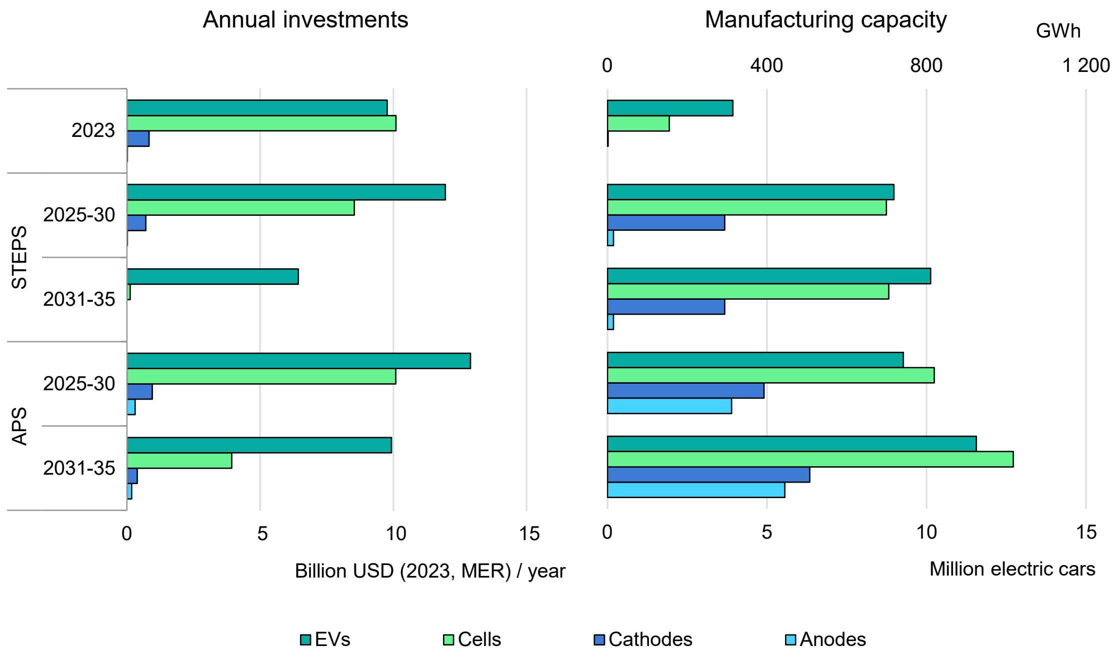
Notes: LCOP = Levelized cost of production. Based on world capacity-weighted battery chemistry shares and including the production of the battery cell, cathode and anode active materials. Excludes battery module/pack assembly. Mineral costs are based on spot prices.

Sources: IEA analysis based on data from BNEF; GREET (2024); Degen et al. (2023); and IEA (2024b).

Average annual investment in EV and battery manufacturing capacity in the APS reaches about USD 24 billion between 2024 and 2030 (15% more than in the STEPS), of which roughly USD 11 billion is for batteries and their components. This investment results in manufacturing capacity of about 10 million EVs in 2035, compared with almost 4 million units today. Battery manufacturing capacity reaches 700 GWh in the STEPS, and slightly above 1 TWh in the APS in 2035, compared with slightly above 150 GWh in 2023. Battery manufacturing capacity built by 2030 in the STEPS is sufficient to satisfy demand until 2035 and it is used at high utilisation rates – on average about 60% over 2030-35. Higher battery production in Europe in the APS drives more investment after 2030.

Figure 3.23 EU EV and battery manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. EVs = Electric Vehicles (electric passenger cars exclusively). Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refer to investment spending.

Investment in EV and battery manufacturing in the European Union averages around USD 20 billion a year over 2025-30 in the STEPS, and around USD 3 billion more in the APS.

Solar PV

Current market and policy support

The European Union is currently the world's biggest importer of solar PV modules, with domestic production meeting just under 15% of demand in 2023. By contrast, imports – mainly from China and Southeast Asia – were enough to cover more than demand, leading to a significant increase of inventories, which stood at approximately triple the level of annual installations in that year (IEA, 2024c). Reliance on imports is a result of strong demand, backed by ambitious deployment targets, combined with dwindling domestic manufacturing capacity in the face of intense competition from foreign suppliers. The Green Deal, as well as national laws and mechanisms, and more recently the NZIA (see Table 3.3) have been the principal policy drivers of solar PV deployment.

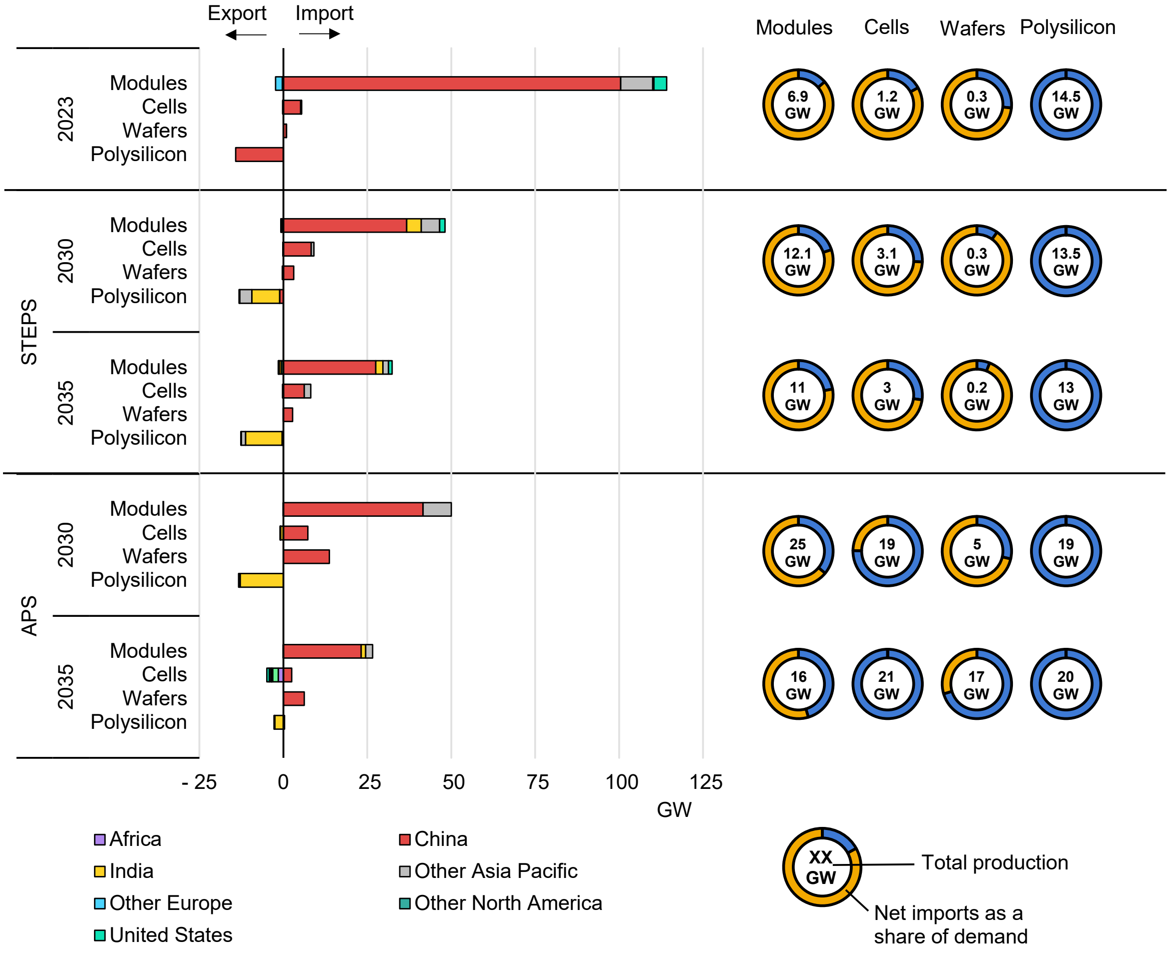
The European Union was a first mover in the solar PV sector, with support for innovation driving production and deployment. By the end of the 2000s, EU countries held about 20% of global production capacity for modules and polysilicon and over 10% for that of cells on aggregate. However, module manufacturing capacity has barely increased since then, with the production of some components like cells and wafers falling. Consequently, the EU share of global solar PV manufacturing capacity has plunged to less than 1%. The only exception to this trend is polysilicon, where the European Union holds 3% of global supply, thanks to the high-purity quality polysilicon produced in Germany, which is still being exported to China. High energy prices, especially since Russia's invasion of Ukraine, and the strong financial support now available for US manufacturers under the IRA, have put further pressure on the competitiveness of the EU solar PV industry, particularly polysilicon and wafers.

Manufacturing and trade prospects

In the **STEPS**, the European Union remains the world's biggest importer of modules in 2035, with the bulk still coming from China and the rest mostly from India and Southeast Asia (Figure 3.24). The main change is that some imports originate in the United States. Domestic production hovers at around 7 GW, as there are currently no significant announcements to expand output; on the contrary, there are signs that existing module manufacturing capacity could be scaled down (PV Magazine, 2024b). For cells and wafers, domestic production remains very low, and most needs are met by imports, primarily from China and to a lesser degree from Southeast Asia. In contrast, the region continues to export small amounts of polysilicon in net terms, directed more to India and Southeast Asia and less to China than is currently the case, as the former countries expand their domestic wafer industry and China's polysilicon demand is entirely sourced domestically. Despite the high energy intensity of polysilicon production, the polysilicon produced in Germany remains competitive due to its chemical industry expertise.

In the **APS**, the prospects for solar PV manufacturing are much brighter, thanks to the NZIA. Module manufacturing capacity climbs to around 25 GW in 2030, which can accommodate 40% of the demand in that year. Due to declining demand from 2030 onwards, the share of domestic capacity covering demand rises to 60% in 2035. This reduces but does not eliminate the need to import modules, with China remaining the leading supplier. Domestic production of cells almost keeps pace with modules, with output sufficient to meet 40% of demand being reached two years later for cells and five for wafers. This nonetheless represents a massive increase, from just 1 GW for cells and less than 0.5 GW for wafers in 2023.

Figure 3.24 EU market and import-export balance for solar PV in the Stated Policies and Announced Pledges Scenario, 2023-2035



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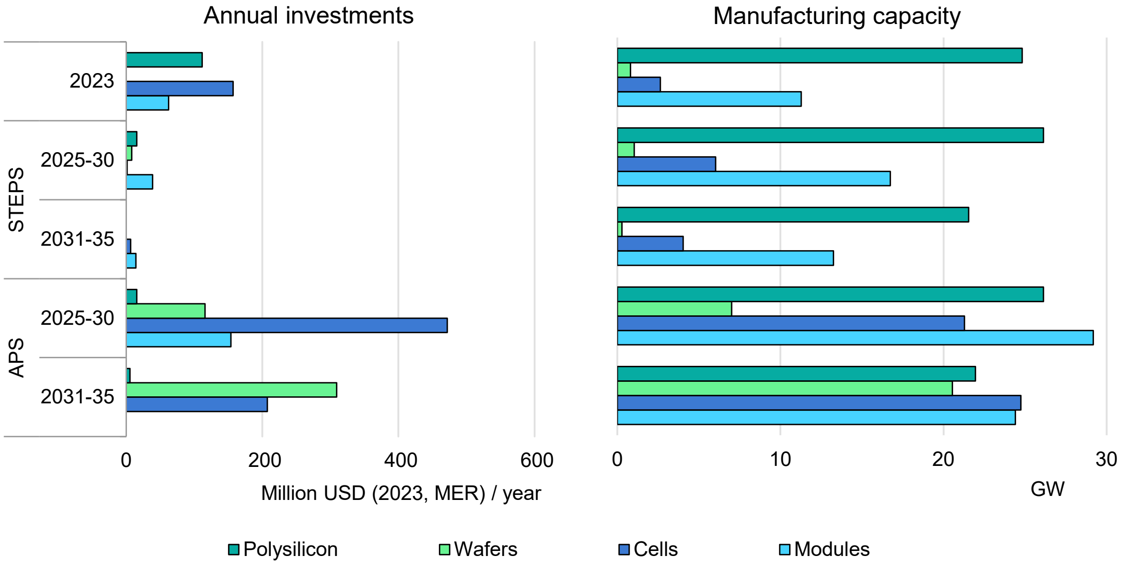
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; Demand for components is determined by the production of the subsequent component. Import and export refer to net trade flows between the European Union and each of the regions displayed, while net imports as a share of demand refers to the net imports to the European Union accounting for all regions as a share of domestic demand.

The prospects for solar PV manufacturing are brighter in the APS, thanks to the NZIA, with module production set to double in the APS by 2030 relative to the STEPS.

The extent of the task required to increase manufacturing capacity for cells and wafers (which are the most capital-intensive segments of the solar PV supply chain) is reflected in the size of the investments needed to 2035 in the APS. In total, investment in the EU solar PV supply chain averages around USD 650 million per year over 2025-35 in the APS (fifteen times more than in the STEPS), with over 80% needed for wafers and cells (Figure 3.25). Mobilising financing on this scale is certainly within reach, as has been demonstrated in other sectors in recent years but will require strong supportive measures under the NZIA.

Figure 3.25 EU solar PV module and component manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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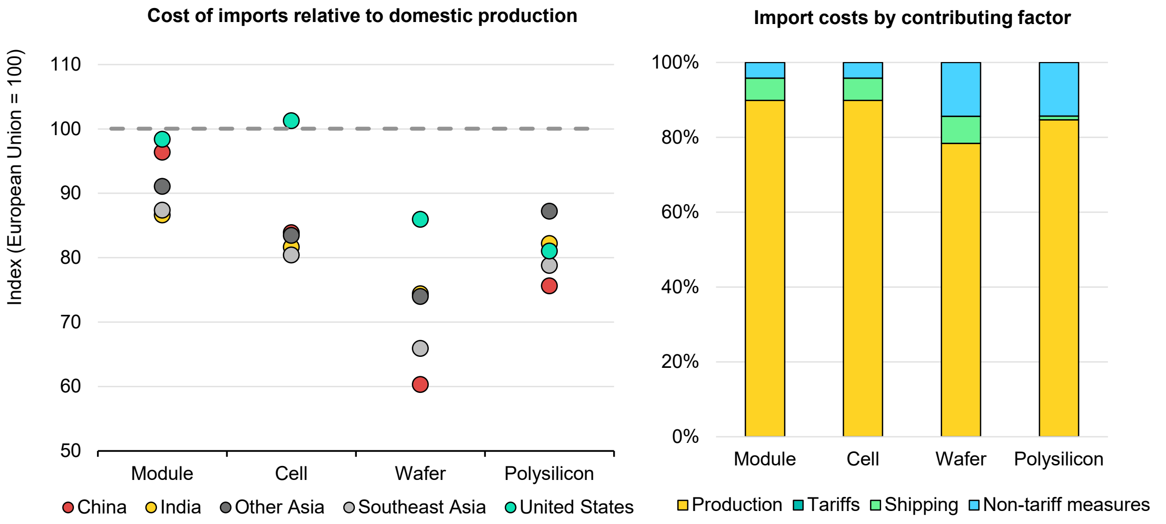
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

EU investment in solar PV manufacturing grows rapidly in the APS, averaging around USD 650 million per year over 2025-35 – fifteen times more than in the STEPS.

In both scenarios, the EU solar PV production supply chain remains generally less competitive than those in most other regions due to high energy and labour costs. In contrast to other regions of the world, the absence of import tariffs in the European Union increases the exposure of domestic manufacturing to competition from producers elsewhere. In the APS, the cost of producing modules, in particular, remains higher than that in China and the United States in 2035 (Figure 3.26), regardless of the 40% benchmark for manufacturing capacity to meet its annual deployment needs.

Figure 3.26 Total production cost of solar PV in the European Union compared with imports and EU import costs in the Announced Pledges Scenario, 2035



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Notes: Total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in the European Union (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

EU solar PV production remains generally less competitive than in most other regions due to high energy and labour costs, as well as the absence of tariffs on imports.

Wind turbines

Current market and policy support

The European Union has traditionally been a major producer of wind turbines and components, being home to several of the world's leading companies. At present, domestic production covers around 85% of the blades deployed in the Union, and all of the nacelles and towers. For some onshore components, the European Union has overcapacity today (IEA, 2024c). Germany, Denmark and Spain dominate the manufacturing of nacelles, while major blade manufacturing hubs are located in Spain, France and Denmark (Rystad Energy, 2023). Firms in these countries also export components to other European markets, including the United Kingdom and Norway, as well as to the United States and Australia.

The European Union is a net exporter of nacelles. About 25% of nacelles, 5% of blades and 20% of towers traded internationally today come from EU member states (excluding trade within the Union). Those exports, mostly nacelles, account for around 20% of domestic EU production. Despite exporting blades to other regions, the European Union is a net importer of blades. Imports come mainly from Türkiye (blades), India (nacelles and blades) and China (nacelles). The factories supplying these imports are mostly operated by European OEMs. For example, Vestas has a nacelle facility close to Chennai and a blade facility in Gujarat in India.

EU deployment of onshore and offshore wind in the last few years has been plagued by supply chain disruptions, grid congestion and long lead times, partly due to unclear regulations and permitting issues. Some of these problems have been addressed by recent regulatory reforms, such as the third revision of the Renewable Energy Directive (RED III), which shortens the maximum permitting times for wind farms, and policy initiatives under the RepowerEU, EU Green Deal and the European Wind Power Action Plan (EC, 2023c).

As a result of the latter, the European Commission has released auction guidelines (EC, 2024g), and the European Investment Bank (EIB) has provided counter-guarantees to improve access to finance for wind turbine manufacturers (WindEurope, 2023). In Germany, permitting procedures were improved in 2023, resulting in an increase of 70% in the amount of capacity obtaining a permit (WindEurope, 2024). The NZIA sets a manufacturing target of 36 GW per year for the entire wind sector by 2030, and provides for the inclusion of environmental and resilience criteria in renewable energy auctions and public procurement processes, which could support further development of wind parks. In these cases, sustainability and resilience will account for 15% to 30% of the decision-making criteria, but these requirements may be waived if the cost difference exceeds 10% (Box 3.2). With Chinese OEMs entering the European market, concerns have been raised over unfair trade practices. In response, the European Commission announced in April 2024 an inquiry into Chinese suppliers of wind turbines in five markets: Bulgaria, France, Greece, Romania and Spain (WindEurope, 2024a).

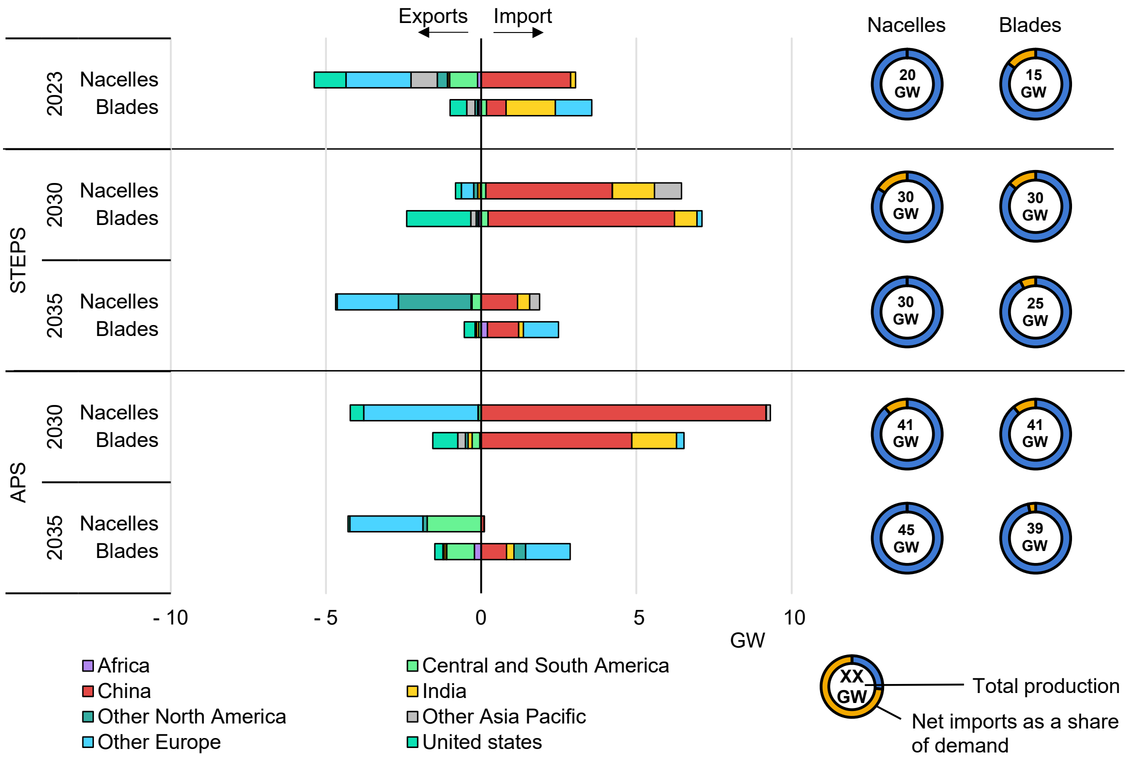
The European Union has already put in place several antidumping measures, such as on steel towers from China, which incur antidumping tariffs between 7% and 19% (EC, 2021). Glass fibre used in wind blade manufacturing imported from China, Egypt and Morocco is subject to duties between 20-70%, with additional countervailing duties up to 30% (EC, 2022b); (EC, 2022c). Some member states have also introduced initiatives to promote wind turbine manufacturing, such as the Danish Export and Investment Fund, which provides loans to developers outside the European Union to expand the reach of European OEMs (EIFO, 2024).

Manufacturing and trade prospects

EU policies and investment plans already in place are set to drive an expansion of wind turbine manufacturing in the next few years, mainly to meet increased demand for new offshore projects. The share of offshore additions in total wind installations rises from over 15% in 2023 to between 40% in the STEPS and 50% in the APS in 2030, with total deployment more than doubling in the former scenario and nearly quadrupling in the later. Announced manufacturing capacity expansions, taking into account committed and preliminary projects, are not sufficient to meet growth in demand in either scenario, resulting in a need to import more wind components. For offshore wind, the gap between announced capacity and domestic deployment is largest in the APS; by 2030, offshore deployment reaches around 20 GW, while announced manufacturing capacity totals just 11 GW for nacelles and 7 GW for blades. Nevertheless, thanks to the NZIA's sustainability and resilience non-price criteria, domestic manufacturing is projected to continue to grow roughly in parallel with demand in both scenarios.

In the **STEPS,** EU production of nacelles increases by 50% between 2023 and 2030. Despite this fast growth, it is insufficient to meet rising domestic demand, so the region becomes a net importer to meet its deployment goals, with a sixfold increase in imports from India, while imports from China grow from 3 GW to 4 GW. After 2030, when the peak in demand has passed, the European Union becomes a net exporter of nacelles to North America and the rest of Europe. Production of blades grows even more strongly, doubling to 2030 and decreasing thereafter, but net imports nonetheless increase to 2030, dropping back by 2035. As other countries have expanded their blade facilities too, the European Union does not become a major exporter of these components, causing the utilisation rate of domestic capacity to drop. Shipping costs more for blades than nacelles (Figure 3.28), so expanding manufacturing capacity for the former is generally more financially attractive for importing countries. Blade factories also require less investment, as the CAPEX required to build a facility is lower than a nacelle or tower facility.

Figure 3.27 EU market and import-export balance for wind turbine components in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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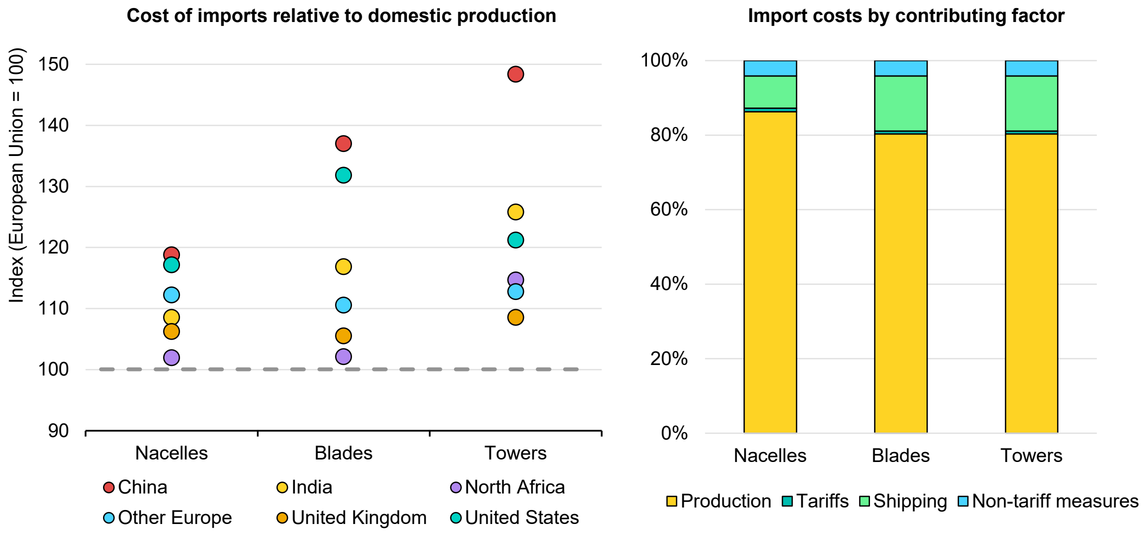
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Towers are not included. Import and export refer to net trade flows between the European Union and each of the regions displayed, while net imports as a share of demand refers to the net imports to the European Union accounting for all regions as a share of domestic demand.

Announced pledges – notably NZIA objectives – drive up utilisation rates and unlock a faster increase in wind blade and nacelle production capacity, boosting production.

In the **APS,** higher utilisation rates and a faster increase in capacity in line with the NZIA objectives boosts production relative to the STEPS, with output of nacelles and blades increasing to over 40 GW (more than doubling for nacelles and nearly tripling for blades) in 2030. The share of domestic production in the total supply of nacelles and blades both stand at 90%, falling slightly for nacelles and increasing for blades. EU production of both nacelles and blades remains competitive in 2035, with production costs below the cost of imports from the United States, China, India and other countries in Europe (Figure 3.28). Nevertheless, in order to meet rapidly increasing EU demand, manufacturing hubs such as India and North Africa could provide some components at slightly higher cost, providing opportunities to diversify its supply chain from China and Türkiye.

Import costs for blades are higher than those for nacelles due to the relatively higher shipping costs, but as labour costs have a larger share in the total production costs for blades than for nacelles there is still opportunity to outsource this to areas with lower labour costs which are relatively close, if production capacity in those regions is sufficient. Most of the investment in the EU wind component sector to 2030 is for manufacturing nacelles in both scenarios, with nacelles attracting the bulk of investment over 2031-35 (Figure 3.29).

Figure 3.28 Total production cost of wind turbine components in the European Union compared with imports and EU import costs in the Announced Pledges Scenario, 2035



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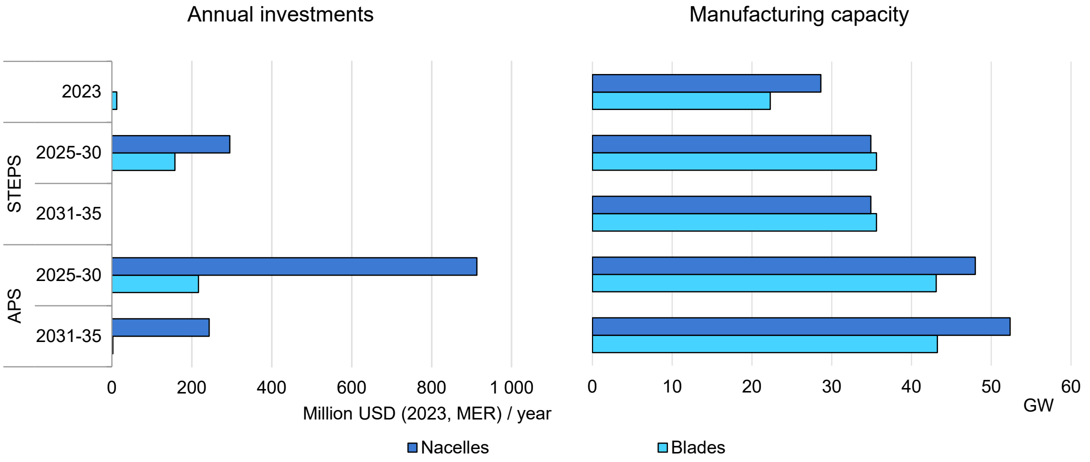
Notes: The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in the European Union (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

EU production of wind turbine components is generally competitive with imports, but nearby producers in Europe and North Africa are well-placed to meet part of EU demand.

Figure 3.29 EU wind turbine component manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

Manufacturing of nacelles sees the most investment in both scenarios over 2025-30, with the rapid scale-up in capacity reducing the need for investment in 2031-35.

Heat pumps

The European Union is a heat pump powerhouse, with the world's third-largest manufacturing capacity (about 20% of the world total) and the third-largest installed capacity (about 15%). Heat pumps are already the default option in most new buildings that lack a district heating connection, though there are practical barriers to their installation in some market segments, such as multi-family buildings. Deployment is being driven by their cost-competitiveness compared with fossil fuel alternatives in some markets, notably Scandinavia, and by policy measures such as grants, tax credits and building energy codes in countries such as Germany and the Netherlands.

More than 30 large heat pump manufacturers, representing about 10% of global capacity, are headquartered in the European Union. They include Ariston, Bosch Group, Groupe Atlantic, Johnson Controls, NIBE, Siemens, Stiebel Eltron and Vaillant. The Union has a strong track record in R&D, patents and innovation, leading the world in segments such as large heat pumps and hydrocarbon refrigerants (see Box 3.6). Germany alone registered 18% of global heat pump patents in 2020.

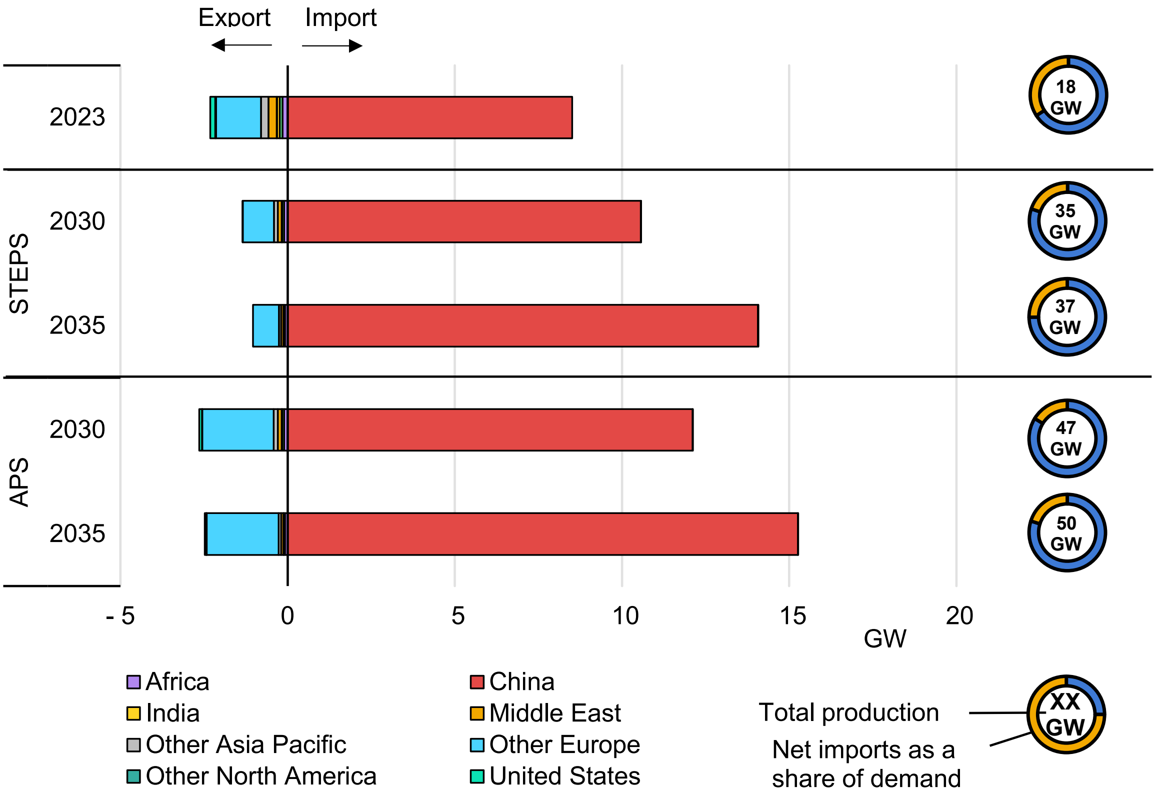
Until 2019, the European Union was a net exporter of air-to-water heat pumps, while importing small numbers from China and Southeast Asia (Lyons at al., 2023). However, imports from those countries, including air-to-water pumps, have since met a growing share of demand, turning the European Union into a net importer. In 2023, around two-thirds of heat pumps installations were produced domestically. This change is partly the result of an increase in demand that outstripped the ramp-up of manufacturing capacity, with sales doubling between 2019 and 2023 (accelerated by the shift away from natural gas-based heating triggered by high gas prices in the wake of Russia's invasion of Ukraine) and the ability of Chinese manufacturers to produce heat pumps at lower costs than their counterparts in Europe. On average, we estimate that Chinese production costs are around 35% lower than the world average and nearly 50% lower than in the European Union (see Box 1.4). Some countries are, however, starting to take measures to ensure imported products meet certain quality standards and to favour sales of domestically produced pumps. For example, Poland Clean Air Programme's subsidies apply only to heat pumps that are certified in Europe.

Announcements of new or expanded manufacturing capacity in EU countries have increased sharply since 2021, driven by an acceleration of heat pump installations, soaring natural gas prices and favourable market conditions. In the last 3 years, investments in new heat pump factories totalling over USD 3 billion have been announced, with another USD 4 billion for manufacturing components and R&D programmes (EHPA, 2023). If realised in full and on time, these additions would more than double capacity between 2023 and 2030. However, a slowdown in heat pump sales during 2023 and 2024, due to policy uncertainties, higher inflation and other factors, has cast doubts over some of these investments, with some major manufacturers having announced job cuts during 2023 in European factories, affecting around 3 000 workers (EHPA, 2024).

In the **STEPS**, EU heat pump sales return to growth over the rest of this decade, driven by organic market growth in France and the Nordic countries, as well as policies already in place to drive demand in Germany, Austria and the Netherlands. Sales increase on average by around 8% per year over this decade, doubling by 2035. The realisation of some of the announced investments lead to domestic production increasing almost as rapidly as sales – by 10% per year between 2023 and 2030, falling to around 5% per year over 2023-35 (Figure 3.30). As a result, the share of domestic production in total EU sales increases slightly between 2023 and 2030, but then falls back, reaching 70% in 2035, as imports from China continue to rise.

In the **APS**, further policy support under the REPowerEU plan and Green Deal, with the objective to install at least 10 million more heat pumps by 2027 and the ambition to deploy at least 30 million by 2030, is reflected in more ambitious national regulations, boosting heat pump demand in the short term. Production follows closely, with both installations and domestic production more than doubling by 2030. Imports from China continue to cover between 20% and 25% of domestic demand in the 2030-2035 period. Although the NZIA singles out heat pumps as one of the key clean energy technologies in the European Union's energy transition, the benchmark of meeting at least 40% of annual installation demand is a non-binding constraint, as manufacturing capacity today is already above this level and announced expansion plans maintain the share well above 40% in both scenarios.

Figure 3.30 EU market and import-export balance for heat pumps in the Stated Policies and Announced Pledges Scenarios, 2023-2035



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Import and export refer to net trade flows between the European Union and each of the regions displayed, while net imports as a share of demand refers to the net imports to the European Union accounting for all regions as a share of domestic demand.

Despite increasing imports from China and strong market growth, domestic production is to meet around 75% of EU demand for heat pumps to 2035 in both scenarios.

Box 3.6 Opportunities to switch from F-Gases to hydrocarbon refrigerants in heat pumps and air conditioners in the European Union

Recent policy developments with respect to refrigerants used in heat pumps, particularly in the European Union, could give a competitive advantage to EU manufacturers of equipment using non-hydrofluorocarbons (HFCs) refrigerants. Refrigerants used in heat pumps, air conditioners, refrigerators and other refrigeration devices – today most commonly fluorinated gases (F-Gases), and specifically HFCs – are potent GHGs and are not intended to be emitted to the air. However, leakages frequently occur during manufacturing, operation and decommissioning. As a result, their use is regulated. The Montreal Protocol process, brought in initially to stop ozone depletion and later to limit global warming, has been a very important driver of investments in new heat pumping technologies globally.

In the European Union, refrigerant components feature on the list of Critical Raw Materials (EC, 2023d), and the choice of refrigerant has an important impact on both climate risk and energy security. Over 60% of the global production of fluorspar (calcium fluoride), the base chemical for most HFCs, is concentrated in China, followed by Mexico and Mongolia, producing about 10% each. EU production accounts for less than 5% of global volumes (USGS, 2024). European manufacturers have been subject to the strictest regulations in F-Gases worldwide, based on explicit phase-out schedules for specific equipment using HFCs and a CO_2 equivalent quota system for HFCs. These regulations, first put in place in 2014, were reviewed in 2024, setting a steeper path for the quota allocation system and targeting a full phase-out of HFCs by 2050. In addition, heat pumps and air conditioners using refrigerants with a 100-year global warming potential (GWP) above 150, which includes all currently used HFCs, will be phased out starting from 2027, prompting a switch to non-HFC refrigerants. With the new quota system schedule, it is expected that the prices for HFCs, currently trading at about EUR 16/t CO_2-eq, will increase to EUR 68 in 2030 and EUR 161 in 2050 due to the steep price increase for the quota certificates (ATMOsphere, 2022).

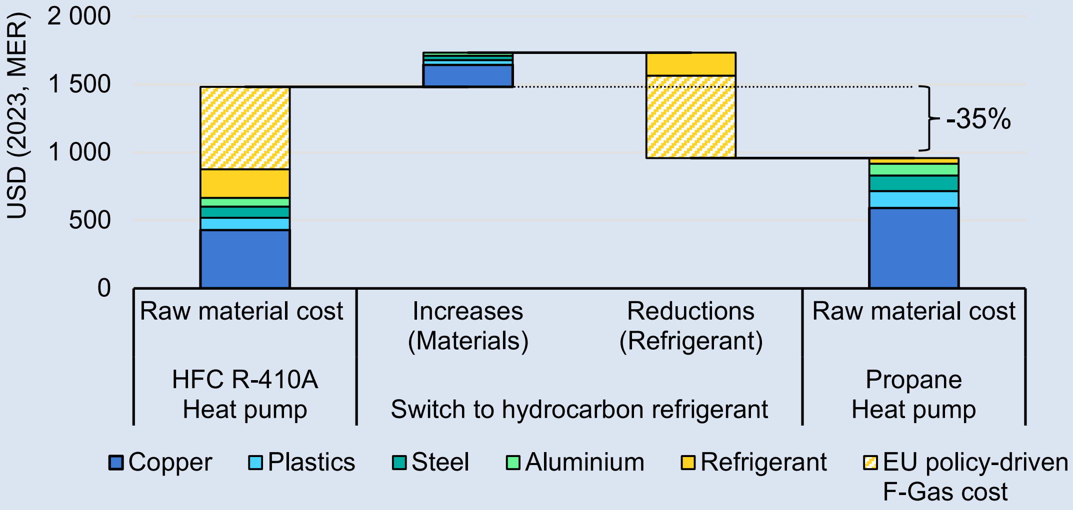
For equipment manufacturers, such regulations have major implications for their choice of refrigerant. The most common non-HFC alternative refrigerant in heat pumps and air conditioners is propane (R290), a hydrocarbon with a GWP of 0.02. European manufacturers have been carrying out R&D in the use of propane and other non-HFC refrigerants, and several heat pump companies have heat pump models with non-HFC refrigerants in their lineup (EC, 2022d). The quota allocation system of the F-gas regulation is a means to further accelerate the shift, and the price for trading propane, not subject to the quota system, is only about one-third of common refrigerants such as the HFC R-410A, which has a GWP of 2 088.

However, heat pump manufacturers face a trade-off between the cost of the refrigerant and that of the raw materials for making the pump. Unlike HFC R-410A, propane is flammable, and compressors and other heat pump components need to use stronger materials for added safety measures (HPT TCP, 2023). The compressors weigh up to 70% more than the ones used for HFC R-410A, requiring more materials such as steel, aluminium, copper or plastics in their manufacturing and increasing material costs.

Taking into account that the current quotas constitute about 75% of the market price of HFC R-410A, without the EU quota allocation system, the raw material cost for a 30 kW heat pump using propane would be about 9% higher than one using HFC R-410A, but with that regulation, the cost is about 35% lower (Figure 3.31).

To date, 160 parties have ratified the Kigali amendment to the Montreal Protocol that introduces different phase-out pathways for F-Gases depending on country groupings (United Nations, 2024). Other world markets may therefore pursue strategies involving lower GWP F-Gases to comply with their Kigali amendment commitments. For example, in October 2023, the United States mandated a steep phase-out pathway for HFCs, with the strongest reductions between 2025 and 2028, and limiting heat pumps and air conditioners to use refrigerants with a maximum GWP of 700, permitting the use of R-32, but prohibiting most other HFCs (EPA, 2024). In the longer term, the stricter regulations currently applied in the European Union could potentially give EU manufacturers a competitive advantage as the first movers on hydrocarbon refrigerants.

Figure 3.31 Raw material costs for making a heat pump using HFC R-410A F-gas and propane following the current EU F-Gas quota allocation, 2023



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Notes: Calculations assuming comparable 30 kW heat pumps. Refrigerant amounts and other system components are dependent on several design properties and therefore depend on the specific heat pump model. The cost includes only raw materials without any manufacturing step. HFC R-410A is a synthetic gas, costs apply to the final product.

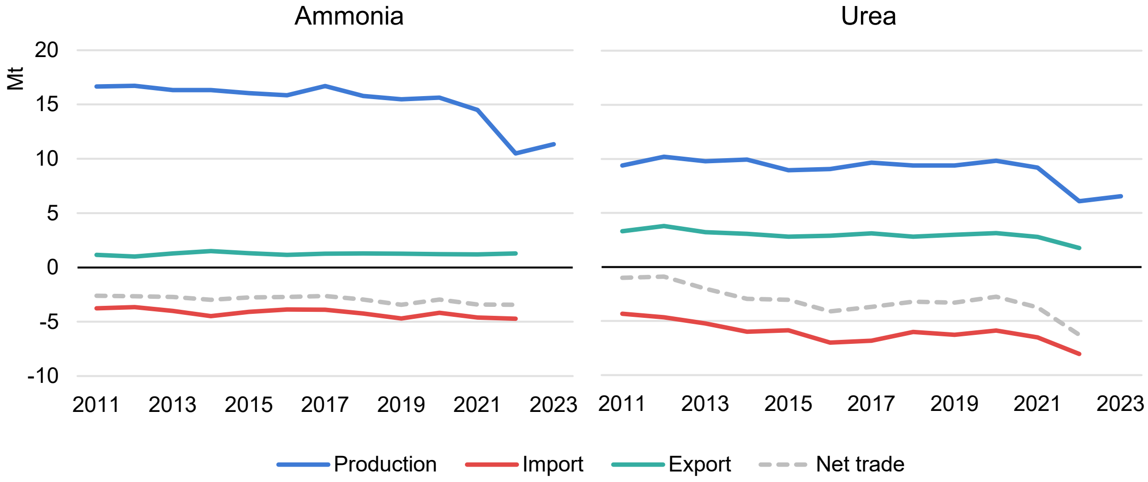
Sources: IEA based on HPT TCP (2023); Öko-Recherche (2024) and IIR Guideline for LCCP (2016).

Materials

Manufacturing accounted for around 17% of GDP in the European Union in 2023, a value which has remained stable for the past 20 years, though material production in the region has been on a declining trend over the same period. Nonetheless, the European Union remains a major producer of materials, accounting for 7% of global production of steel, 6% of aluminium and 6% of ammonia. GDP grew by 18% over the 10 years to 2023, while demand for aluminium grew by 20% and demand for steel and ammonia fell by 3% and 23%, respectively. A significant share of EU material needs is met by imports, the bulk of them coming from Russia and China in the case of steel (despite sanctions on some Russian products), Norway and the Middle East for aluminium, and North Africa for ammonia. There is also considerable trade between EU member states.

The competitiveness of materials production in the region has been hit badly by the surge in energy costs since 2021, especially following Russia's invasion of Ukraine. The subsequent spike in natural gas prices had a particularly severe impact on costs, leading to large amounts of capacity being shut as producers were unable to compete with those in other regions, including North America and the Middle East, where gas prices saw much more modest increases. Ammonia production – the most gas-intensive of the three materials covered in this *ETP* – was hit hardest, plunging by 30% in 2022, though it bounced back by around 8% in 2023 as gas prices fell back (Figure 3.32). Output is unlikely to return to its pre-2021 level in the foreseeable future, as a substantial amount of capacity is thought to have been closed for good.

Figure 3.32 Ammonia and urea production and trade in the European Union, 2011-2023



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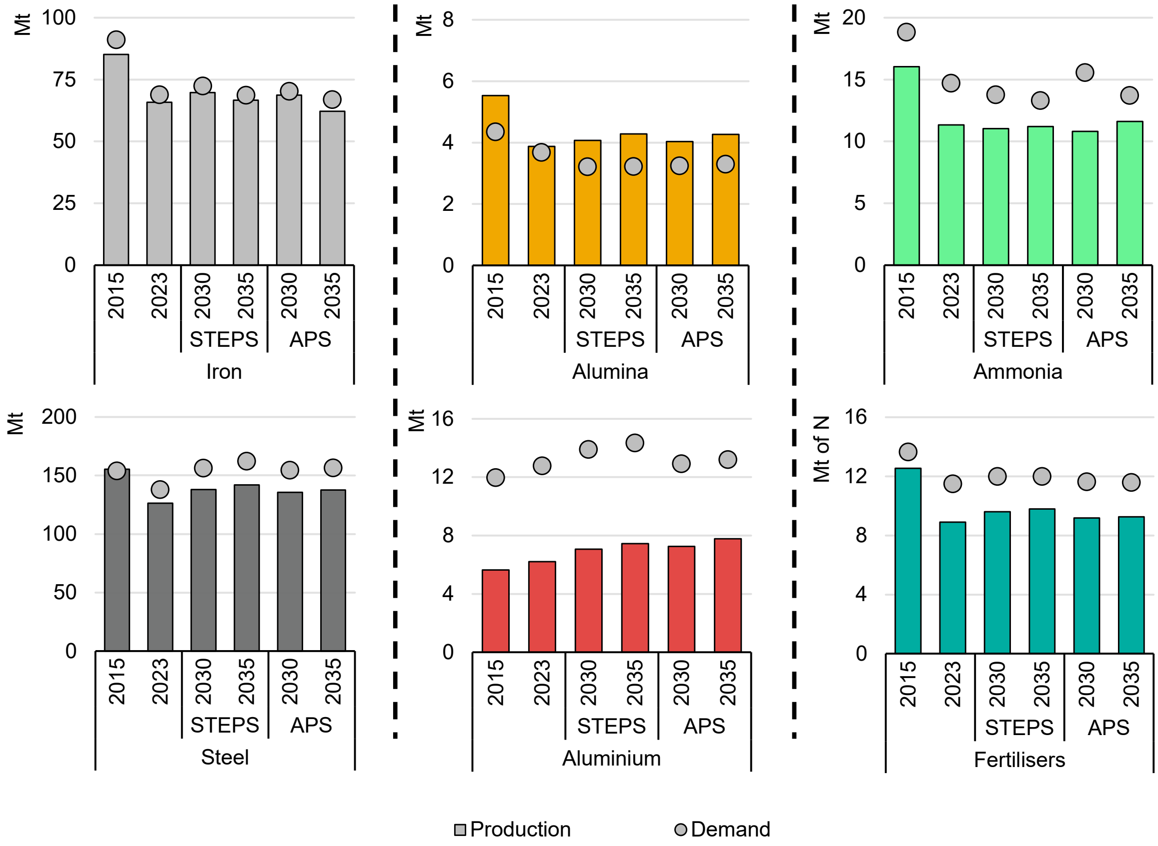
Note: 2023 production data are estimates.
Sources: IEA analysis based on IFA (2024) and CEPII (2024).

EU ammonia production plummeted by 30% in 2022 due to the spike in gas prices following Russia's invasion of Ukraine, with a lot of capacity now thought to be shut for good.

The outlook for the production of materials in the European Union varies by the type of material and policy settings. In the STEPS, there is a modest near-term rebound in iron and steel production and a stronger recovery in aluminium output, driven by rising demand and lower gas and electricity prices than those seen during recent years (Figure 3.33). Steel output is lower in 2035 in the APS, mainly due to stronger policy action to boost material efficiency, while demand for clean technologies – notably solar PV – drives a small increase in aluminium output. Ammonia production is also higher in the APS than in the STEPS, due to new segments of demand – particularly in the shipping and power sectors – opening up as countries make progress on decarbonising these sectors in line with their climate pledges. Ammonia production shifts increasingly to near-zero emissions technologies, including electrolysis, which uses electricity as its main energy input rather than natural gas.

Figure 3.33 Materials demand and production in the European Union, historical and in the Stated Policies and Announced Pledges Scenarios, 2015-2035

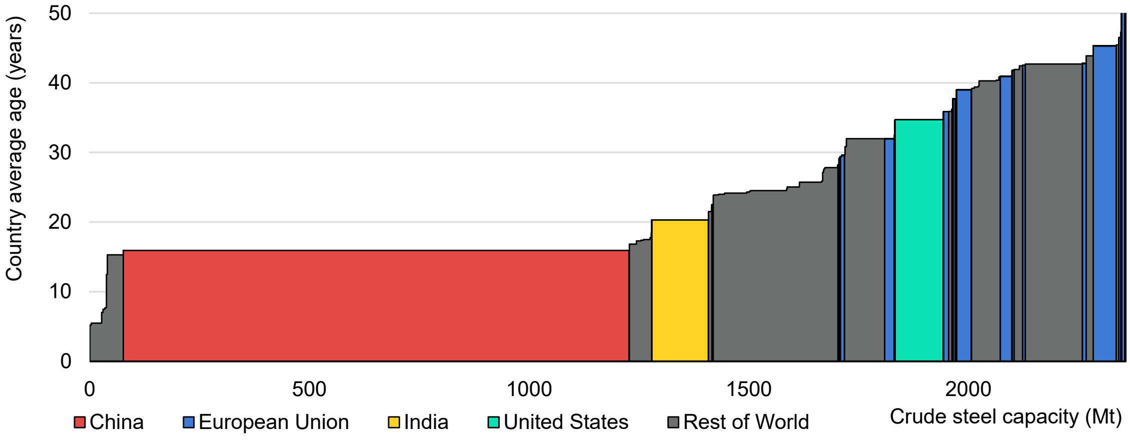


Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; Mt of N = million tonnes of nitrogen. Ammonia demand does not include international bunkers. The figures for alumina include only metallurgical alumina.

Production of steel in 2035 is lower in the APS than in the STEPS due to stronger policy action to boost material efficiency.

There is a pressing need to modernise EU materials production facilities to maintain their competitiveness and lower their emissions. A lot of existing capacity is older than that in the rest of the world. For example, the average age of steel plants is over 40 years compared with around 15 years in China and 20 years in India (Figure 3.34). Investment in near-zero emissions technologies for materials production is starting to grow, supported by EU policy initiatives such as the Innovation Fund’s EUR 143 million support to the HYBRIT demonstration project and EUR 250 million support to the Stegra (formerly H2 Green Steel) project (EC, 2022e; EC, 2024h). The European Commission has also approved around EUR 9 billion in state aid from member states (Germany in particular) to support the development of several near-zero emissions capable projects for iron and steel production, though most of them plan to initially operate with natural gas and only gradually switch to hydrogen at a later stage. In addition, there is also a strong demand-pull from steel buyers in Europe: 54 of the 59 publicly announced purchase commitments for steel made with near-zero emissions technologies are from companies in the EU. This simultaneous demand-pull and need for modernisation present a significant opportunity for the European Union to be a leader in near-zero emissions materials production.

Figure 3.34 Average age of steelmaking facilities by country/region



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Notes: Capacity data are from the OECD steelmaking capacity database and average ages of assets are based on the Global Infrastructure Emission Database. Age and capacity data is from 2019.
Sources: OECD (2024); He et al. (2021); and Xu (2023).

The average age of steel plants in EU member states is generally a lot higher than that in the rest of the world, notably China.

CBAMs, which take into account the difference in carbon prices between the exporting and importing country for selected sectors, are also expected to play a role in creating a level playing field for production using near-zero emissions technology in the European Union. When the EU CBAM enters its definitive period, producers of materials and chemicals within the policy's scope will be subject to an equivalent CO_2 price to that in the EU ETS (EC, 2024i). The policy will be phased-in gradually, such that in 2034, both domestic producers and those exporting to the European Union will be subject to a levy equal to 100% of the EU-ETS price for allowances.

It is difficult to make a detailed assessment of the policy's impact, given that several details – notably the treatment of downstream products and the extent to which non-ETS emissions pricing or equivalent measures in third countries will be treated – will be revisited before the policy enters its definitive period. For this reason, we have taken into consideration the intended outcome of the policy, i.e. to level the playing field with respect to emissions pricing for producers in and outside the European Union, in the APS. As a result, EU heavy industries decarbonise at the fastest pace among major markets, without this resulting in large-scale deindustrialisation. This takes into account potential synergies with trade partners for certain particularly energy-intensive elements of the supply chains of those industries (see Box 3.7)

Box 3.7 Potential impact of the EU CBAM on steel production costs and import opportunities

It is not possible to fully estimate the implications of the EU CBAM on international trade, but analysis of the APS can be instructive to illustrate some of the possible outcomes and opportunities for the EU steel industry and its potential trading partners. This assumes that the CBAM takes effect in 2026, as scheduled, and that carbon prices in the European Union and other advanced economies rise to around USD 160/t of CO_2 by 2035.

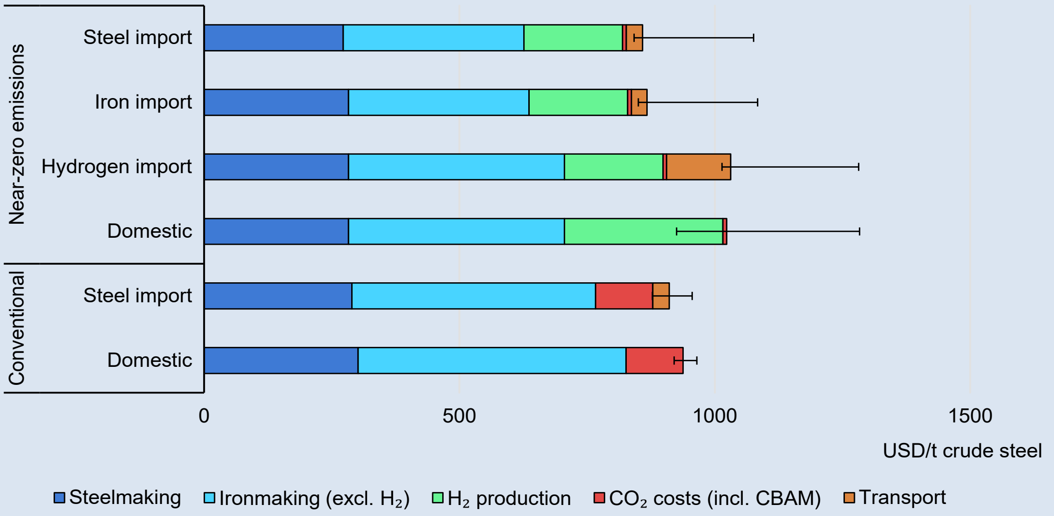
A conventional natural gas-based direct reduced iron (DRI) steelmaking facility using best available technology directly emits around 0.6 t CO_2 per tonne of crude steel produced. In the APS in 2035, when free allowances for trade-exposed industries in the EU-ETS have been phased out, such a plant in western Europe* is estimated to have a production cost of around USD 940/t crude steel, with 12% attributable to CO_2 costs. Steel produced the same way in Brazil and exporting its output to the European Union would cost around USD 910/t, including CBAM and transport costs. The lower cost in Brazil is due primarily to lower iron ore prices given the large reserves in the country, and slightly lower costs for operating the plant.

Our analysis suggests that domestic near-zero emissions steel production may struggle to compete with domestic conventional production, even at CO_2 prices of USD 160/t. A hydrogen (H_2)-based DRI steelmaking process with captive renewable electricity generation could see production costs of around USD 1 020/t in the European Union in 2035, around 10% higher than the conventional plant, but with a large range (USD 925-1 280/t), depending on where in western Europe the plant is situated. However, steel imports from a plant using the same technology in Brazil would have a production cost of around USD 860/t after accounting for transport and CBAM costs on the small quantity of residual emissions. This lower production cost is mainly as a result of the region's low-cost solar PV and wind resources that can be harnessed to produce renewable hydrogen (including storage costs) at just over USD 3/kg by 2035 in the APS, compared with nearly USD 5/kg in western Europe.

Given that specific parts of the iron and steel supply chain are particularly energy-intensive, it may be more attractive to import intermediate products such as DRI rather than finished steel. The delivered cost to Europe of steel produced with H_2-DRI in Brazil in the APS in 2035 is only slightly lower than the cost of importing the DRI and then proceeding with the steelmaking step domestically (USD 870/t). The added flexibility afforded to EU steel producers of retaining the steelmaking step close to final customers, including EV manufacturers, may outweigh these relatively small additional costs. Alternatively, steel producers could go one step further upstream and import the hydrogen from Brazil, but, at USD 1 030/t, this route represents the most expensive among the import options for near-zero emissions production examined.

This analysis points to an opportunity for the European Union to seek strategic partnerships with countries that can leverage their competitive advantages in specific parts of supply chains, in parallel to levelling the playing field with policy instruments such as the CBAM. Brazil is just one potential example of a strategic partner for the European Union in the iron and steel value chain. We explore these – and other – opportunities from the perspective of EMDEs in Chapter 4.

Figure 3.35 Indicative range of the levelized cost of production of steel in the European Union and costs of imports from Brazil in the Announced Pledges Scenario, 2035



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Notes: H_2 = hydrogen; CBAM = Carbon Border Adjustment Mechanism. Domestic refers to production in western Europe. Import is from Brazil to western Europe. Near-zero emissions corresponds to H_2-DRI technology, while conventional refers to a natural gas-based furnace, both of which are equipped with an electric arc furnace. In all cases, a 9% scrap share of metallics in the steelmaking furnace is assumed. Best available technology energy performance is assumed for all units. A cost of capital of 5.2% is assumed for western Europe and 7.5% for Brazil. Error bars show the impact of variation in H_2 costs for different locations in each region for the near-zero emissions route (USD 3.5-9.1/kg for the European Union and 2.9-6.5/kg for Brazil), and ranges of natural gas and electricity prices over the period 2015-2019 (natural gas: USD 11.3-13.9/GJ the European Union and 11.9-17.6/GJ for Brazil; electricity: USD 156-175/MWh the European Union and 163-179/MWh for Brazil).

* Western Europe refers here to France, Germany and Italy.

3.3 China

China aims to move from being primarily a manufacturer of energy-intensive commodities to a high value added producer, with innovation at the core of its development strategies, such as the “Made in China 2025” initiative (see Table 3.5). This approach aims to boost competitiveness by improving technological manufacturing capabilities and reducing reliance on imported technology.

Three decades ago, China adopted an export-led development model known as the “Great International Circulation Strategy”, which culminated in China joining the World Trade Organization in 2001. However, the 2008-09 global crisis exposed China’s vulnerability to the volatility of international trade: when trade contracted, China’s exports fell by almost 20% and its growth rate slowed (Li et al., 2012). Since then, the government has tried to rebalance growth by leveraging the country's vas’ domestic market, notably through the “Dual Circulation Strategy” it launched in 20’0.

China’s manufacturing sector has continued to expand, partly in response to the Belt and Road Initiative (BRI), which addresses infrastructure needs in other countries. However, China has more recently announced a shift to focus on smaller projects in order to limit large-scale overseas spending and to address the growing reluctance of countries to receive foreign investment in critical infrastructure (European Parliament, 2021).

Table 3.5 Selected domestic and trade policies in China relevant to clean energy technology and materials manufacturing

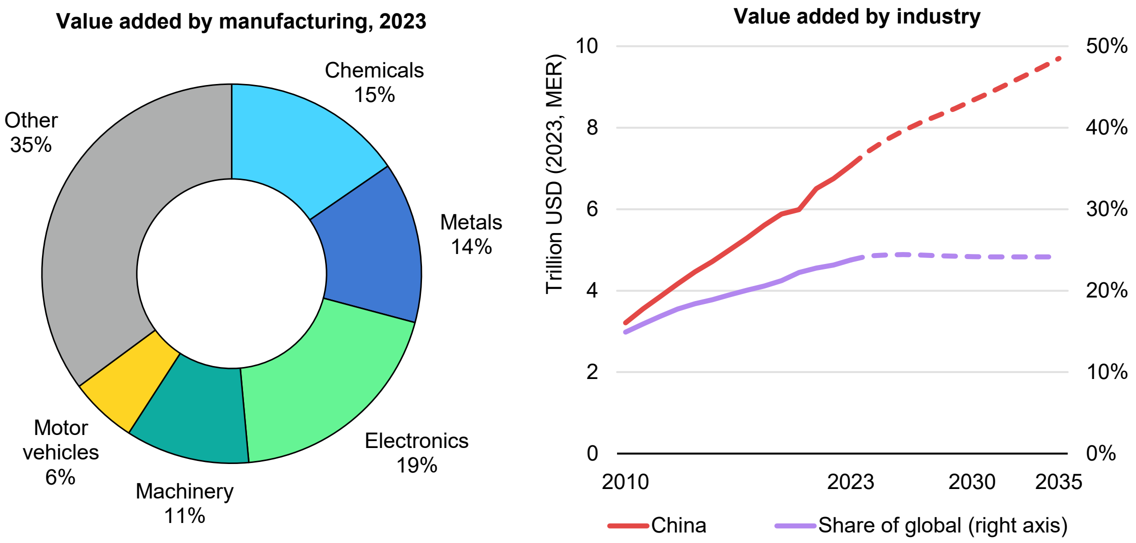
Policy (enactment year)	Description
Made in China 2025 (2015)	Aims to modernise China’s industrial capabilities, to strengthen its role in high-tech industries and to reduce its dependence on foreign technology imports by promoting domestic innovation. It targets ten key sectors, including EVs and clean energy technologies manufacturing. As part of the strategy, the government has mandated increased investment rates in corporate R&D.
Dual Circulation strategy (2020)	Aims to make China’s economy more resilient to external shocks by tapping into the potential of its large domestic market. Later incorporated into the 14th Five-Year Plan in 2021, the strategy focuses on the interplay between internal (domestic) and external (international) circulations, i.e. trade flows.

Policy (enactment year)	Description
Belt and Road Initiative (BRI) (2013)	The BRI is an infrastructure development strategy focusing on areas such as energy, industry, mining and transport. Among other things, it aims to improve trans-continental connectivity by land and sea, reducing the time and cost of trade. It links China with Asia, Africa, Europe, and Central and South America by developing infrastructure, particularly in regions that have traditionally suffered from underinvestment. Building new infrastructure also creates demand for cement, steel and other metals. In recent years, however, due to the need to limit overseas investments, China has cut back on financing and shifted its focus to smaller projects, which often imply lower project risks, lower political uncertainties and more effective involvement of private companies.
Regional Comprehensive Economic Partnership (RCEP) (2020)	The RCEP is a FTA between Southeast Asian countries, Australia, China, Japan, Korea and New Zealand that builds on and consolidates existing FTAs to create the world's largest free trade area. Key developments expected from its implementation include the reduction or elimination of tariffs on approximately 90% of goods over 20 years, intellectual property protection provisions, and harmonisation of rules of origin, which could facilitate trade within the region, even for non-RCEP members.
Export restrictions and bans on rare earths and critical minerals (2023)	In 2023, China began restricting the export of gallium, germanium and high-grade graphite, requiring approval from the Ministry of Commerce for their export. In addition, China banned the export of technology related to the extraction and separation of rare earth elements and the production of rare earth magnets. In 2024, China further reduced export quotas for medium to heavy rare earth elements, although it increased overall quotas for rare earth mining and smelting, including elements essential for the production of magnets used in EVs and wind turbines.

The importance of manufacturing and trade

China is the world's manufacturing powerhouse, supplying a large share of a wide range of manufactured goods to both its domestic market and other countries around the world. Its industry sector, including manufacturing, construction and mining, has contributed about 40% of its economic growth since 2010 and now accounts for nearly 40% of its GDP. Just five sectors – chemicals, metals, electronics, machinery and motor vehicles – contributed more than half the value added by China's manufacturing sector in 2023 (Figure 3.36). China produces more than half the world's steel and aluminium today, and 40-95% of the key clean technologies and components that are the focus of this report. Much of the expansion in China's industries has been achieved over a relatively short period: in total, value added by industry more than doubled between 2010 and 2023, its share of global industrial value added rising from 15% to 24% over the same period.

Figure 3.36 Value added by manufacturing and industry in China



Notes: Chemicals includes pharmaceuticals and fertilisers (ISIC Rev. 4 20-22); Metals includes basic and structural (ISIC Rev. 4 24-25); Electronics includes computer, electronic and optical products and electrical machinery (ISIC Rev. 4 26-27); Machinery includes mechanical engineering (ISIC Rev. 4 28); Motor vehicles includes all road vehicles and parts (ISIC Rev. 4 29); Other includes all manufacturing (ISIC Rev. 4 10-33) less that covered under the other categories disaggregated..

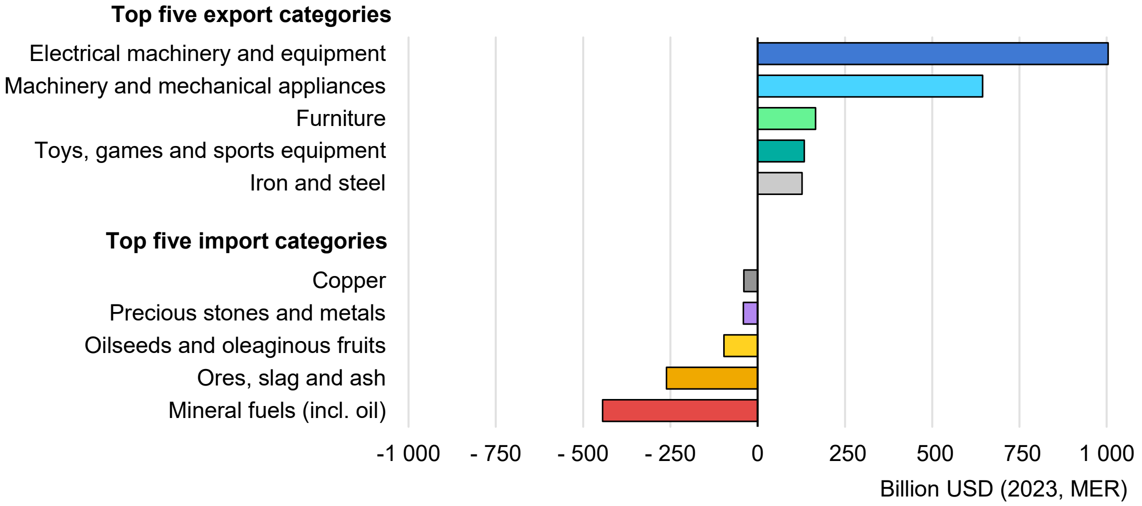
Source: IEA analysis based on Oxford Economics (2024).

China's share of global industrial value added has jumped from 15% to 24% since 2010.

The growth of the Chinese economy has begun to slow in recent years as its economy matures and population growth stagnates. In all our scenarios, industry value added grows at an average rate of 2.5% per year during 2024-35, but this represents a marked slowdown compared with the recent past; it averaged about 6% between 2010 and 2023 and more than 10% between 2000 and 2010. China's construction boom, underpinned by steel, cement and other manufacturing industries, continues to level off, as manufacturing shifts towards higher value added sectors, including the "new three" clean technologies (EVs, batteries and solar PV), other electronics, machinery and transport equipment. As a result, China's share of global industry value added looks to have already plateaued and to remain at around 24% by 2035, with other countries at an earlier stage of industrialisation, including India, Indonesia and other Southeast Asian countries, taking a larger share of the growth in manufacturing output.

China's economic development model has relied to a significant degree on export-oriented manufacturing. China is a net exporter of many categories of products and maintains a large trade surplus for goods, totalling more than USD 850 billion in 2022. The country's trade model is illustrated by comparing the leading net export and net import categories: the country mostly imports raw minerals – ores, fossil fuels, precious stones and certain inputs to food production – and exports mainly manufactured goods, including furniture, electronics and machinery (Figure 3.37). China's huge presence in international markets for manufactured goods has led to accusations that the country is selling certain goods below cost to make use of overcapacity, driving down prices, undermining investment opportunities in other parts of the world and cutting domestic producers' profit margins, though there is no firm evidence that utilisation rates are significantly lower in China for many steps in clean technology and material manufacturing (Box 3.8).

Figure 3.37 Net exports and imports by product categories in China, 2023



Notes: Top five net export categories correspond to HS 2022 2-digit chapters 85, 84, 94, 95 & 73; top five net import categories correspond to 74, 71, 12, 26, 27.
Source: IEA analysis based on Oxford Economics (2024).

China is a net exporter in value terms, importing mostly raw minerals such as ores, fossil fuels and certain inputs to food production, and exporting mainly manufactured goods.

Box 3.8 The utilisation rate of manufacturing capacity in China

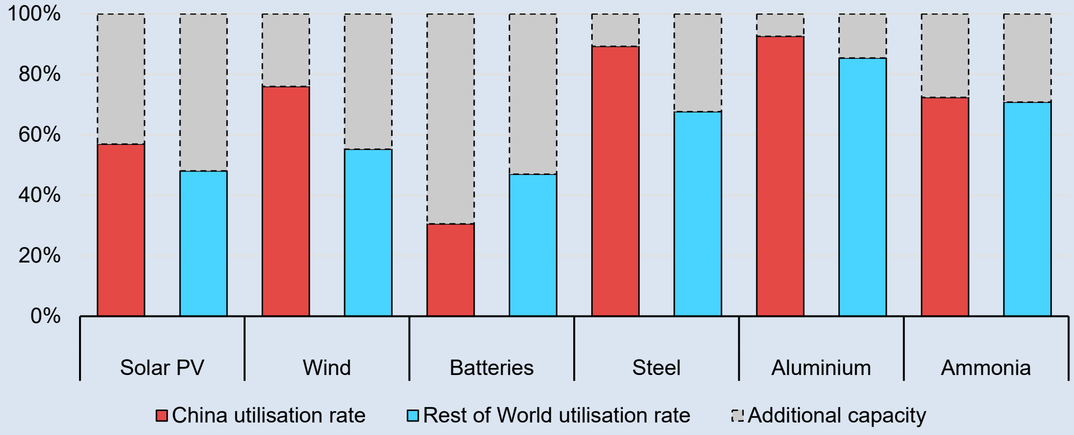
"Excess", "surplus" and "over" are commonly used prefixes for China's industrial capacity, though these terms have no internationally agreed definition as to a "normal" or "acceptable" utilisation rate for manufacturing facilities. Utilisation rates can be measured over different timeframes and various numerators and denominators can be used, depending on the way capacity is defined. In the fertiliser industry, for example, it is common to state capacity on a 330-day basis rather than for a full year. A newly installed electrolyser factory may state the rated capacity as the maximum the factory could accommodate if new production lines were to be installed later.

In the IEA's work, the utilisation rate of capacity for a given technology is typically derived by dividing actual production by the maximum rated capacity over a full year. In practice, therefore, it is almost impossible for the utilisation rate to reach 100%, given the need in most cases for periodic maintenance and other scheduled interruptions to production.

For key materials, there is little evidence that utilisation rates in China are substantially different to those in the rest of the world. Indeed, in some instances, they appear to be higher in China. According to the official capacity figures from the OECD Steel Committee – a body tasked with monitoring global excess capacity of the steel industry – and production figures from the World Steel Association, the utilisation rate of China's steel plants was 89% in 2023 – 20 percentage points higher than in the rest of the world. The country's aluminium smelters also have slightly higher utilisation rates, while those of its ammonia facilities are comparable to the rest of the world according to similar data from international trade associations.

The utilisation rates of clean technology manufacturing facilities are generally much lower than those for producing materials and fertilisers in both China and the rest of the world. Utilisation rates for solar PV module manufacturing facilities are also similar in China to the average in the rest of the world, at around 55%. Wind nacelle manufacturing facilities have higher utilisation rates in China, whereas battery cell manufacturing is one area where utilisation rates appear to be substantially lower in China (slightly over 30%) than elsewhere (almost 50%). Within China, there is significant variation in the utilisation rate of battery manufacturing plants, but the low rates for the many smaller producers bring the average for the country down. The higher average value of utilisation for the rest of the world would be higher still, were it not for the low utilisation rate of many recently built facilities that are still in the process of ramping up production.

Figure 3.38 Utilisation rate for manufacturing selected clean technologies and materials in China and the rest of the world, 2023



Notes: Aluminium covers only primary production. Batteries refers to cell manufacturing for all vehicle types and stationary storage; solar PV to module manufacturing and wind to nacelle manufacturing. Production that contributes to inventories is not included for wind and batteries. All capacity data presented on a 365-day operational basis. All data are for 2023, apart from for ammonia, which is for 2022.

Sources: IFA (2024); OECD (2024); CRU (2024); IAI; World steel; USGS; InfoLink (2024); S&P Global Commodity Insights by S&P Global Inc. (2024); EV Volumes; and Benchmark Mineral Intelligence.

China's car assembly plants also operate at a significantly lower utilisation rate (50%) than in the rest of the world (over 60%). The surplus capacity represents an opportunity for repurposing existing conventional car manufacturing facilities to produce EVs. In view of the surplus capacity in EV manufacturing, the Chinese government recently introduced a stricter licensing regime for new EV production facilities (FT, 2023a). However, new EV producers, such as the consumer electronics maker Xiaomi, are still establishing new manufacturing facilities in the country (CNN Business, 2024).

The prospects for China's export-oriented clean energy technology industries hinge to a large degree on policies in China as well as the rest of the world to encourage both the deployment of those technologies and the development of domestic manufacturing capabilities. In general, those countries that are heavily dependent on imports are already taking action to reduce reliance on China and other foreign suppliers by stimulating domestic investment with the aim of enhancing energy security and stimulating economic activity.

The strength and impact of those policies – covering the broad spectrum of energy, climate and economic development – on the demand for Chinese technologies in the medium term differs markedly between the STEPS and APS, and across technologies. In the former scenario, China's exports continue to play a central role in meeting the needs of the rest of the world, underpinned by low production costs thanks to large economies of scale and a high degree of supply chain integration. The APS paints a more mixed picture, with faster growth in global demand leading to increases in China's exports for certain technologies, but for others, the impact of other countries' policies to develop their own manufacturing capacities is to reduce the need for Chinese exports relative to the STEPS, particularly after 2030.

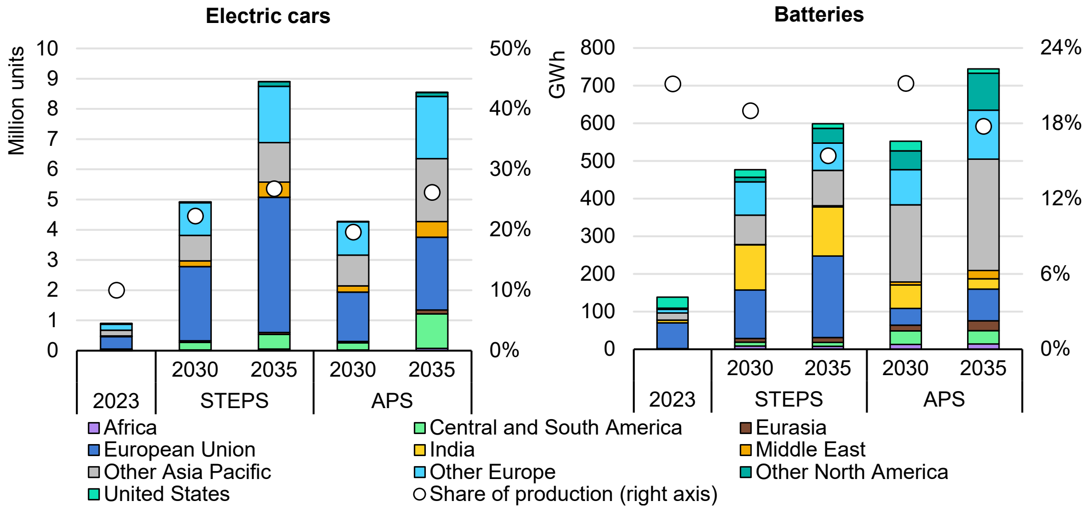
EVs and batteries

China's EV industry has boomed in recent years, driven mainly by the domestic market. In 2023, only around 10% of total Chinese production was exported, mostly to Europe (amounting to around 600 000 vehicles) and other Asian countries (almost 200 000 vehicles). EVs sales made up 18% of the global new car market in 2023 and global sales continued to grow over the first half of 2024, in particular in China. Competition between carmakers is strong, however, and has led to aggressive price reductions and thinner margins; in 2023, more than 60% of all EVs sold in China were cheaper than their ICE counterpart.

This competition is generally expected to result in a degree of consolidation across the sector in China, with some of the more than 150 carmakers potentially going out of business or being taken over by rival firms. The Chinese industry is expected to remain largely focused on the domestic market in the near future, but is looking to expand export sales in order to increase utilisation rates at newly built factories and boost cashflow. It is also investing in EV manufacturing in other countries, benefiting from the highly integrated EV supply chain that involves cheap batteries that are produced in China and can easily be shipped elsewhere. In Thailand, for example, EV sales reached 10% in 2023, of which 85% were produced by Chinese manufacturers. China's export of cheap EVs is already raising tensions with other countries, notably the United States and European Union, which have recently introduced new import duties on Chinese EVs (Box 3.1, Table 3.4). Chinese EV manufacturers are likely to increasingly compete with EV and ICE carmakers in overseas markets, including Europe, which could make EVs more affordable.

The prospects for Chinese exports of EVs and the batteries used to make them depend mainly on the policies of the importing countries. In both the STEPS and APS, China focuses on exporting electric cars – the higher value part of the supply chain – all incorporating batteries produced domestically and leveraging the highly competitive industrial battery ecosystem built in China over the past 15 years (Figure 3.39).

Figure 3.39 Chinese exports of EVs and batteries by destination in the Stated Policies and Announced Pledges Scenarios, 2023-2035



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; EVs = Electric Vehicles (electric passenger cars exclusively).

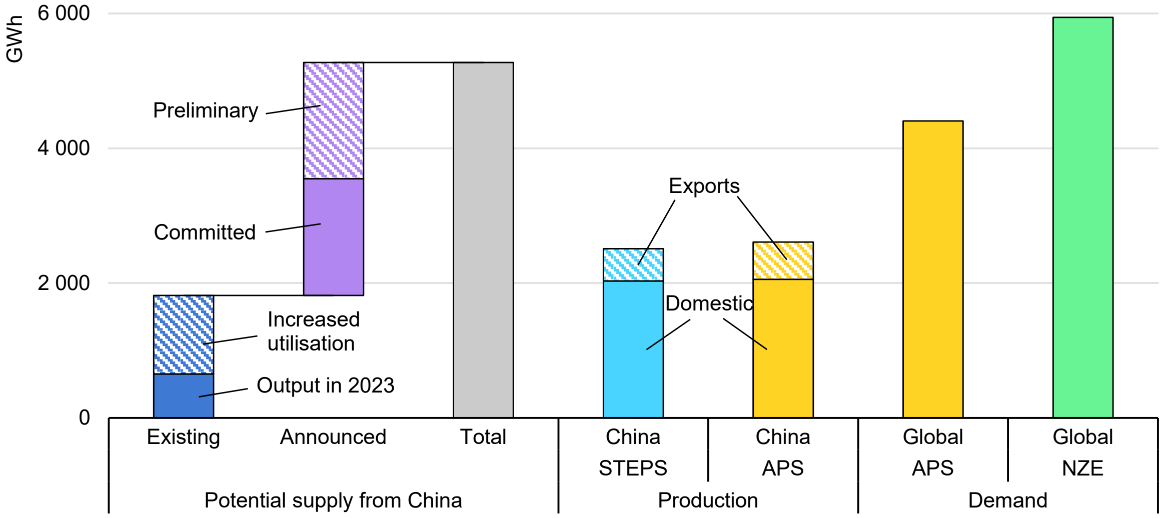
In both the STEPS and APS, China's exports of electric cars and batteries grow substantially, but most production is used domestically.

EV exports in absolute terms and as a share of the country's total production increase most rapidly in the STEPS, reaching 4.9 million vehicles (over 20% of total production) in 2030 and 9 million (over 25%) in 2035, driven by rising demand in the rest of the world and the strong competitiveness of Chinese carmakers. About half of these exports go to the European Union, with most of the rest going to the United Kingdom and the Asia Pacific region. In the APS, exports climb slightly less rapidly as policies in the rest of the world drive up domestic manufacturing capacities faster than demand, reducing the need to import relative to demand. In 2035, total Chinese EV exports are about ten times higher than in 2023 in both scenarios. The destinations of those exports are similar in both scenarios, with a significant decrease in exports to the European Union in the APS.

The picture for batteries is a little different. Thanks to investments around the world in new battery cell production and growing exports of EVs produced in China, Chinese battery exports more than triple between 2023 and 2030 in the STEPS and increase fourfold in the APS. Given that battery demand in China grows faster than that, the share of Chinese batteries being exported steadily decreases from about 20% in 2023 to around 15% in the STEPS and 18% in the APS by 2035. Export shares are higher in the APS than in STEPS because of higher demand in regions without a strong battery industry.

It is unlikely that domestic demand and export would be sufficient to absorb all of the planned increase in China's battery cell manufacturing capacity, including all preliminary projects, before 2030. The plants in operation today could already meet 90% of domestic battery demand in the STEPS in 2030 if their average utilisation rate was increased to 85%, from just over 30% today (Figure 3.40). Taking announced capacity expansions into account, total capacity in 2030 would be capable of supplying all of the world's battery demand in the APS, but 40% of this demand is supplied by other countries in that scenario, thanks to their investments in manufacturing capacity, supported by industrial and trade policies. If climate ambition were to be raised further, and the level of global demand in the APS (4.4 TWh) grew to that in the Net Zero Emissions by 2050 Scenario (NZE Scenario) – reaching almost 6 TWh – it would be equivalent to utilising a further 25% of the existing and announced capacity in China.

Figure 3.40 Opportunities to exploit the potential production from announced battery cell manufacturing facilities in China, 2030



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. 2023 output reflects an estimate of the actual utilisation rate in 2030. Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030.

The potential supply of batteries from China exceeds global demand in 2030 in the APS and could meet as much as 90% of global demand in the NZE Scenario.

Solar PV

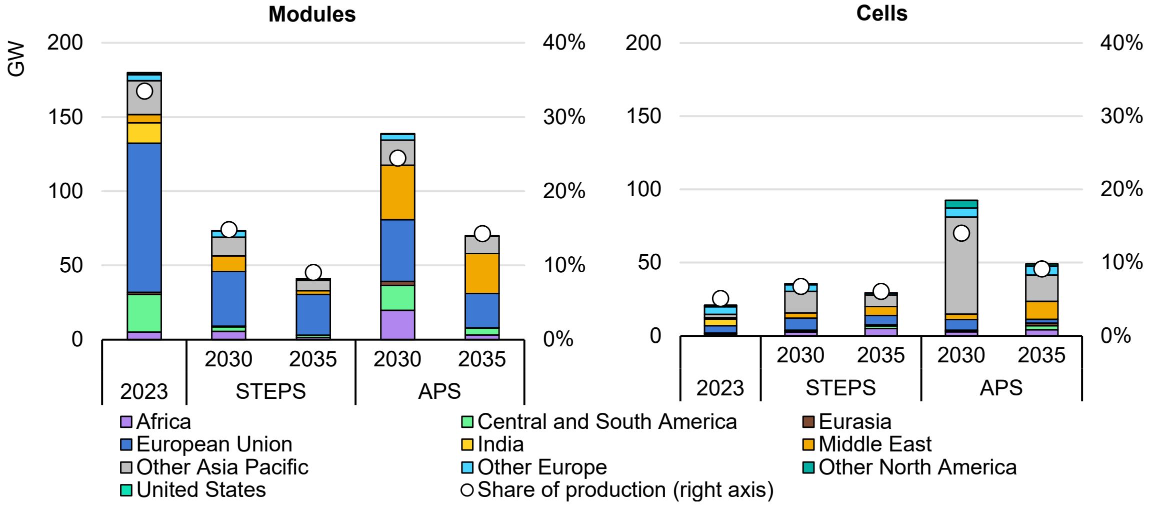
China’s lead in solar PV manufacturing is greater than for all the other clean energy technologies considered here. At least 80% of the world’s manufacturing capacity is located in China for all the segments of the solar PV supply chain, from PV-grade polysilicon production (mostly with capacity in the interior provinces) to the manufacturing of modules (mainly in the central coastal provinces) (IEA, 2023). In the case of wafers, this concentration exceeds 95%. Even in the case of polysilicon production, China now holds a 92% share of global output – up from just two-thirds in 2018 – thanks to recent large investments in new plants, with several megaprojects of up to 120 000 tonnes being brought online and others with capacity of 250 000 tonnes in the pipeline.

The bulk of China’s output of solar PV still goes to meet domestic needs. Deployment of new solar PV modules reached 260 GW in 2023, over 60% of the world total, boosting the country’s total installed capacity by almost two-thirds. China’s solar PV industry is highly vertically integrated, so most solar PV exports today are in the form of modules rather than intermediate products such as wafers and cells. In 2023, around 55% of modules exports went to EU member states, a quarter to Brazil, India, Australia and New Zealand, and most of the rest to Japan, the Middle East and Africa. In total, solar PV module exports accounted for around 40% of China’s production.

The recent surge in manufacturing capacity in China has outstripped domestic demand, pushing manufacturers to seek to boost exports. In late 2023, this led to fierce competition among Chinese firms and a slump in international prices, which in turn led to a significant amount of module stockpiling in export markets (BNEF, 2024b). It is estimated that, if the recent import trend continues, PV module inventories could remain at three times the installations expected in 2024 in the European Union, and double those of the United States by the end of 2024 (IEA, 2024c).

As with EVs, the outlook for Chinese solar PV exports is very much dependent on policies to both drive the deployment of new capacity and develop new manufacturing capabilities in the rest of the world. Trade policies, including tariffs and NTMs to restrict imports, will be of particular importance, given the highly competitive nature of China's solar PV industry.

Figure 3.41 Chinese exports of solar PV modules and cells by destination in the Stated Policies and Announced Pledges Scenarios, 2023-2035



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The 2023 export numbers take into account production that has ended up in inventories of the importing countries as well as inventory increases inside China.

Sources: IEA analysis for 2023 with assumptions for supply, demand and prices based on InfoLink (2024); BNEF (2024b); SPV Market Research (2024); and UN Comtrade (2024).

China's solar PV module exports decrease in the STEPS, but in the APS solar cell exports grow to nearly 100 GW, driven by rising demand in other Asia Pacific countries.

China remains the largest producer of solar PV modules to 2035 in both the STEPS and the APS, though the level of China's exports varies as production from other regions, like Southeast Asia, India and the United States scales up – particularly over the rest of the current decade. The 2023 production and exports considerably exceeded the needs for global PV installations and were absorbed by inventories, however, in the long run global production will tend to follow the respective demand. In the STEPS, exports fall by around 60% between 2023 and 2030, as large amounts of new production capacity currently under construction or at the planning stage come online in some of the major import markets globally, notably the United States and India. By contrast, Chinese module exports fall by less than a quarter over the same period in the APS, as demand in China's export markets outpaces the expansion of manufacturing capacity (Figure 3.41). Global demand for solar PV modules outside China increases by over 250 GW over 2023-30 (over 150 GW more than in the STEPS), with China capturing about 65 GW of this increase. The decline in exports to the European Union are partly offset by higher shipments to other regions, especially the Middle East and Africa.

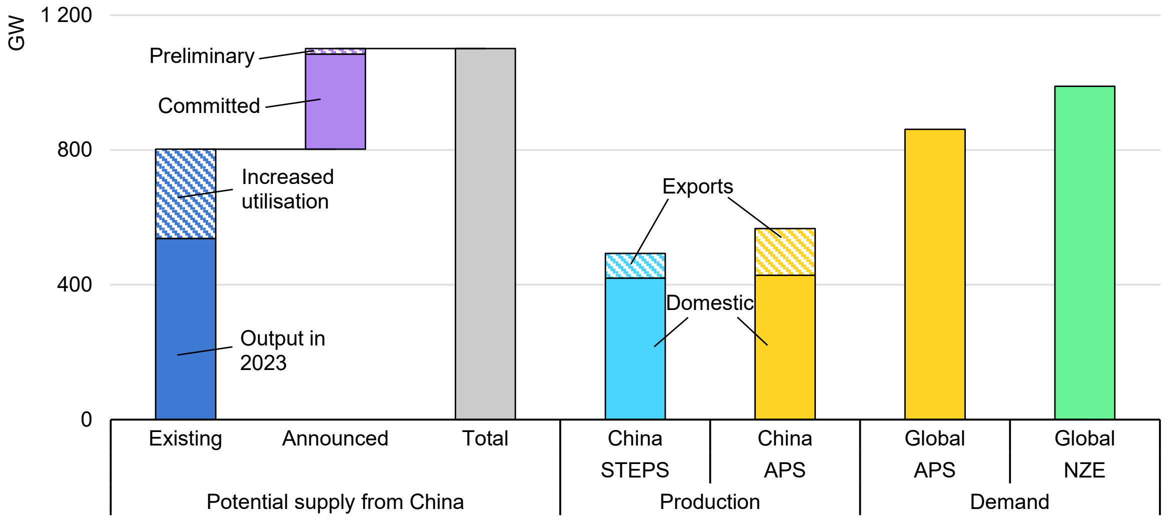
After 2030, the difference in Chinese module exports decreases in the two scenarios, falling to around 40 GW to 70 GW in 2035 as production capacity in the rest of the world catches up with demand. This forces Chinese manufacturers to focus on meeting domestic demand, which rises strongly and remains high with more rigorous policies to accelerate deployment across the country. Exports to all markets decline, but to a lesser extent in the European Union, which accounts for around two-thirds of total Chinese exports in 2035 in the STEPS and just around one-third in the APS. The rest of the decline in exports between 2030 and 2035 originates from the Middle East, Africa and Central and South America in both scenarios.

Chinese manufacturers – which currently make up the entire top ten list of producers worldwide in terms of capacity – are already starting to respond to the prospect of tighter trade policies, including more stringent local content requirements, by investing overseas. If manufacturing capacity expansions overseas continue to be focused on modules and cells, as is currently the case, there would be a need for more exports of the respective upstream components (i.e. cells for modules or wafers for cells) from China, barring any policies that explicitly prevent the indirect import of these upstream components.

China's solar PV module manufacturing capacity is likely to remain well above global demand over the next few years (Figure 3.42). Manufacturing capacity in 2023 is already capable of producing about 60% more solar PV modules than the Chinese production in the STEPS in 2030. Announced projects – both committed and preliminary – would boost existing capacity by more than one-third, resulting in production of about 500 GW and leading to a capacity utilisation rate of nearly 40% by 2030 in that scenario, unless existing older production lines start being decommissioned earlier.

There may be opportunities to boost that rate, depending on the pace of the clean energy transition in China and elsewhere. In the APS, stronger climate policies in China and the rest of the world lead to an increase in production in China to over 550 GW, equivalent to a utilisation rate of the existing and announced capacity of about 45%. Further increases are possible, but hampered by other countries' trade and industrial policies, without which the utilisation rate in China could rise to 65%. An increase in climate ambition – as per the NZE Scenario – would also unlock additional demand, which could lead to a further increase in utilisation of 10 percentage points.

Figure 3.42 Opportunities to exploit the potential output from announced solar PV module manufacturing facilities in China, 2030



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. 2023 output reflects an estimate of the actual utilisation rate in 2030. Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030.

China's solar PV module manufacturing capacity is likely to remain above global demand through 2030, by when existing and planned capacity could meet NZE Scenario demand.

Wind turbines

China's wind turbine manufacturing industry serves mainly its massive and growing domestic market. Installations of wind capacity have grown exponentially over the last 5 years at an average annual rate of growth of 30%, with installed capacity reaching over 440 GW at the end of 2023. Total sales of wind turbines in China, all of which were supplied by domestic manufacturers, reached nearly 80 GW – about 20 GW up on the year before.

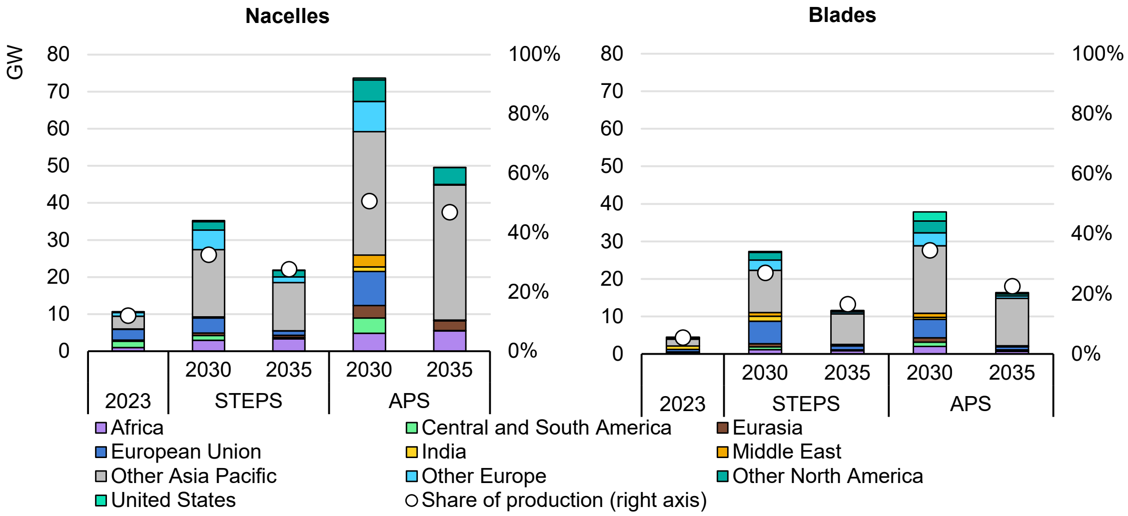
This surge in demand was anticipated, with the leading manufacturers investing heavily in new production facilities. In 2023, exports accounted for about 12% of China's output of nacelles and 6% of blades. Those exports represented about half of all nacelles and 16% of blades traded inter-regionally. There are areas in the supply chain where Chinese turbine manufacturers still depend on foreign expertise and materials. For instance, the country depends on imported design software, testing platforms and wind resource measurement technologies, rather than fully utilising domestic capabilities. In addition, critical components such as bearings for large wind turbines, converters, and carbon fibre are partly sourced abroad, mainly for quality reasons (ICON, Tsinghua University, 2024).

The recent rapid expansion of Chinese turbine manufacturing capacity has led to intense competition, causing Chinese turbine prices to fall to around USD 300 million/GW on average in 2023. This contrasts with trends in other parts of the world, where prices have tended to rise as a result of higher raw material or other input prices. The prices of Chinese turbines sold outside of China are now around 30% lower than those of turbines made by companies from Europe and the United States, but still nearly double the prices they are sold for inside China (BNEF, 2024c). Consequently, turbines made by Chinese OEMs have become more attractive to wind farm developers in other parts of the world, where turbines were traditionally procured from western companies. Until recently, securing financing for wind parks using Chinese technology has been difficult due to inadequate information on the track record of its performance outside China. This has started to change, with Chinese OEMs such as Goldwind and Envision now supplying turbine components for wind parks overseas. In addition to uncertainty about performance, concerns have been raised about unfair public subsidies, hindering the potential for future exports. In April 2024 the EU Commission announced an inquiry into Chinese suppliers of wind turbines under its Foreign Subsidies Regulation (WindEurope, 2024a). Some Chinese OEMs are now moving production outside of China due to local content requirements and other trade restrictions, as well as to be closer to other markets, given that large components are costly to ship. For example, Senvion starting producing blades in India in 2023 (Senvion, 2023), Mingyang Smart Energy has committed to building nacelle and blade manufacturing facilities in Korea and the blade maker Aelon is building a factory in Morocco (Aeolon, 2023).

Chinese exports of nacelles and blades are set to increase significantly over the next decade or so (Figure 3.43). Based on recent announcements of capacity expansions and projected demand in China and overseas, exports of nacelles more than triple by 2030 in the STEPS, accounting for close to 35% of China's total output. Export markets are fairly diversified, with significant shares going to Europe and to other Asia Pacific countries. The increase in exports to 2030 in the APS is even bigger, at sevenfold, accounting for more than half of total output, with exports to Asia Pacific countries, in particular, increasing the most relative to the STEPS. This changes after 2030, with exports falling back in both scenarios by around 35% as demand from other regions shrinks with the growth in overseas manufacturing capacity.

Exports of blades are also expected to increase substantially in the near term, growing sixfold to 2030 in the STEPS and eightfold in the APS. Total exports of blades, nonetheless, remain smaller than nacelles due to higher shipping costs. Like nacelles, blade exports also fall back after 2030, with overseas manufacturing capacity increasing even faster than that for nacelles.

Figure 3.43 Chinese exports of wind nacelles and blades by destination in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

Chinese exports of nacelles and blades peak in 2030 in both scenarios, with exports of nacelles rising twice as fast in the APS to reach 75 GW, or 50% of total output.

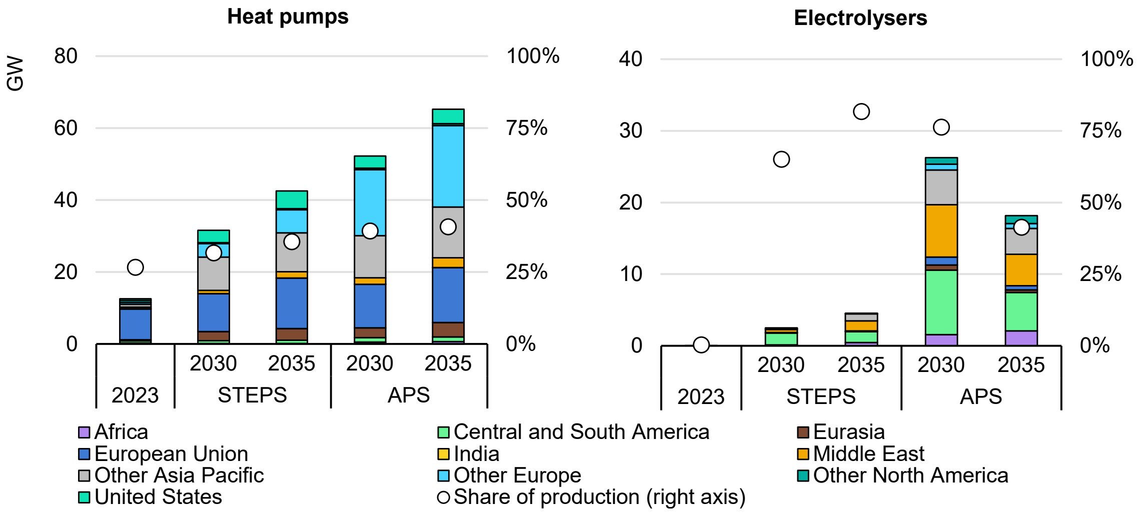
Heat pumps

China is the world’s largest manufacturer and exporter of heat pumps for buildings, with a share of around 40% of global capacity and about half of all exports. In 2023, China exported about 25% of its heat pump production. About two-thirds went to the European Union, where demand has been surging in recent years. The rest went mainly to North America and other Asia Pacific countries. The bulk of Chinese heat pumps are reversible air-to-air units, although exports to Europe also include air-to-water units.

China is expected to remain an attractive location for manufacturing heat pumps, providing a base for expanding exports in the medium term. While most Chinese manufacturers focus mainly on the domestic market, several others that are headquartered in other regions also produce in China in order to benefit from its more favourable business conditions, notably access to cheaper skilled labour, infrastructure and components such as compressors. Nonetheless, labour costs are not a primary driver of these siting decisions, as they typically represent only about 5% of the total cost of making heat pumps in China. Chinese manufacturers are increasing investments in R&D, with Chinese patents more than doubling since 2010 and reaching 21% of the global total in 2019-20. This could pave the way to meeting stricter energy efficiency standards in place in the main overseas markets (see Box 2.2). Chinese heat pump technology inventors are also increasingly seeking intellectual property protection abroad through the World Intellectual Property Organization and at patent offices in the European Union and United States, signalling interest in expanding exports (IEA, 2024d).

China remains the principal global exporter of heat pumps in both the STEPS and APS, its global market share climbing to about 75% in 2030 and to 80% in 2035 in both cases. This is driven by China's continued strong competitive advantage in heat pump manufacturing. Production in the main consuming regions outside China grows strongly, but is not sufficient to meet rising demand in both scenarios. By 2035, net exports from China are roughly 50% higher in the APS than in the STEPS due to faster deployment worldwide, but following similar trade dynamics. The European Union remains a major export market for Chinese heat pumps in both cases, but exports to other markets – especially other European and Asia Pacific countries – grow more quickly in the APS.

Figure 3.44 Chinese exports of heat pumps and electrolysers by destination in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario.

China remains the principal global exporter of heat pumps and electrolysers in both the STEPS and APS, driven by its continued strong competitive advantage in manufacturing.

Electrolysers

China is a front-runner in global electrolyser manufacturing, with around 15 GW of manufacturing capacity at the end of 2023, accounting for 60% of the global total. The majority of China's capacity is for alkaline electrolysers. Based on announced projects, total capacity in China could reach 50 GW by 2030, of which 55% is already in operation or has already reached the final investment decision (FID) stage – a share that is almost three times larger than that in the rest of the world. This expansion is being driven by a growing pipeline of electrolytic hydrogen projects in the country. Installed electrolyser capacity is likely to reach 3.6 GW by the end of 2024, compared with just 0.2 GW in 2022 and 0.02 GW in 2020. The size of the hydrogen plants being built in China is generally above the hundreds of MW scale – larger than most plants in other countries.

As the Chinese market for electrolysers grows, it is attracting companies from different manufacturing sectors, such as the solar PV companies Trina and Sungrow, who are now among the largest electrolyser manufacturers: around one-third of China electrolyser manufacturing capacity today comes from companies active in the solar PV industry. China's largest EV manufacturer, BYD, has obtained a patent for electrolyser equipment, signalling that it also sees potential to enter the market.

Chinese manufacturing of electrolysers is set to continue to expand over the next decade, though at a slower pace than in the rest of the world. Annual manufacturing output from Chinese facilities rises more than threefold to almost 6 GW in 2035 in the STEPS and to more than 40 GW in the APS, driven mainly by strong domestic demand. In both the STEPS and the APS, China's share of global production declines to around 60% in 2030, from over 70% in 2023, and further declines to around 50% in 2035 in the APS. This shift reflects an increased production in other countries and regions, mainly the United States and the European Union.

China's exports of electrolysers are currently minimal, but the country is set to emerge as a major supplier to the global market over the next decade. In both scenarios, it is the leading exporter, accounting for more than 95% of global exports in the STEPS in 2035, most of them going to Central and South America, the Middle East and other Asian countries. Three Chinese electrolyser manufacturers recently secured a combined 65 MW of orders from projects in Oman, Thailand and Uzbekistan (Hydrogen Insights, 2024). In the APS, export demand is much higher, increasing more than tenfold compared to STEPS in 2030. By 2035 though, the share of exports in production decreases substantially in the APS, reaching around 40%, due to other regions ramping up production to serve their domestic markets, and relying less on imports after 2030. In this scenario, China maintains its leading role, accounting for more than 95% of total electrolyser exports, mainly to the same destinations as in the STEPS.

The cost of making electrolysers is expected to remain significantly lower in China than in the rest of the world. Costs remain highly competitive in both scenarios thanks to the lower capital cost, the country's large existing manufacturing capacity and economies of scale, and lower labour and energy costs (IEA, 2024b). On average, the levelized cost of production is 25% and 40% lower in China than in the United States and the European Union respectively in 2030 in both scenarios. Factoring in tariffs and NTMs, the weighted average import price of Chinese electrolysers is around 5-40% less than domestically produced ones in many countries.

Materials

China's energy-intensive industries for producing materials like steel, cement, aluminium and chemicals have undergone unparalleled growth since the turn of the millennium. Steel production has risen eightfold, cement threefold, aluminium thirteen-fold and primary chemicals fivefold. Much of this growth has been driven by the domestic housing and infrastructure boom, but steel and aluminium remain important inputs to its manufacturing sector, including for clean technologies. As China's economy increasingly derives its growth from "new quality productive forces" a partial pivot away from growth in energy-intensive industries is anticipated, along with an increased focus on higher value added manufacturing, including solar PV, Li-ion batteries and EVs.

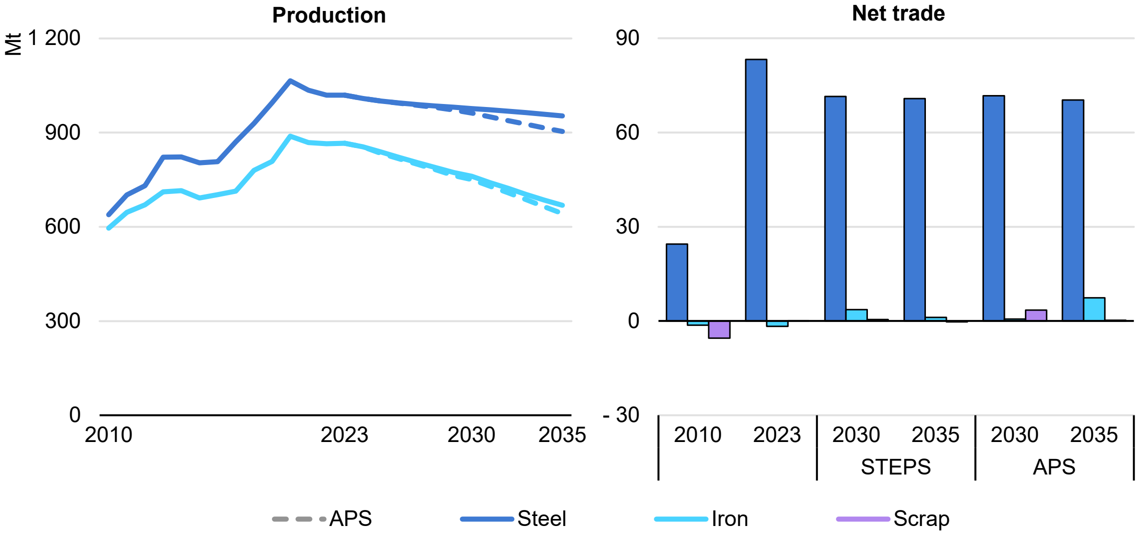
Steel

China is a net exporter of steel products today, though the volume of exports is small relative to domestic production. Exports of steel products amounted to over 94 Mt in 2023, compared with nearly 1 billion tonnes of total crude steel production. On a net basis, the country imported virtually no iron or scrap, but was by far the world's largest importer of iron ore. Iron ore imports from Australia and Brazil alone, which totalled almost 1 billion tonnes, accounted for around 15-20% of the total tonnage of goods traded via bulk carriers (see Chapter 5).

Iron and steel production in China peaked in 2020 and is set to continue on a shallow downward path over the next decade or so as the country's construction boom comes to end, falling slightly faster in the APS than in the STEPS thanks to faster material efficiency gains, including through lightweighting, life extensions and increased re-use of steel products. Net steel exports decline slightly to 2030 in both the STEPS and APS, and they continue to account for a modest share of total production.

The overwhelming dynamic in China's steel industry in the coming years will be the decommissioning of hundreds of megatonnes of blast furnace capacity. This is in response to lower demand and a rapid increase in the availability of scrap from its domestic building, infrastructure and vehicle stocks that were built up rapidly from the turn of the millennium and will progressively reach the end of their lives. The time lag between steel entering the domestic stock and re-emerging as scrap to be recycled, which averages around 30-40 years, aligns well with the typical lifetimes of the blast furnaces (which is close to 40 years), though they are normally fully depreciated after 25 years. China is expected to remain largely self-sufficient during its switchover to scrap, with its share in total metallic inputs to steelmaking rising from around 23% in 2023 to around 40% in 2035 in the STEPS and a similar level in the APS. Correspondingly, iron production falls precipitously in both scenarios, by around 23% over 2023-35 in the STEPS and 26% in the APS.

Figure 3.45 Production and trade in the steel supply chain in China, historical and in the Stated Policies and Announced Pledges Scenarios, 2010-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Steel production is shown in crude steel terms; steel trade shown in semi-finished product terms. Iron refers to reduced iron in all forms, including pig iron and direct reduced iron.

Steel production in China peaked in 2020 and is set to continue on a shallow downward path over the next decade or so, mainly in response to falling domestic demand.

The switch to scrap-based production alongside declining output drives down CO_2 emissions in both scenarios, though the deployment of near-zero emissions technologies, notably H_2-DRI production, starts to make a significant contribution in the 2030s in the APS, driven by the national target of reaching net zero emissions by 2060. This production route leverages the abundant and relatively low-cost variable renewable electricity potential in the country.

Aluminium

China is the world's biggest aluminium producer and consumer, accounting for 60% of primary production (from bauxite), 50% of global output of aluminium (including that produced from scrap) and 49% of global demand. It has been a net importer of unwrought aluminium ingots since around 2020, despite rising domestic production. China is the largest importer of bauxite globally, with imports of over 135 Mt in 2023, accounting for 83% of the global total. Guinea is the main supplier, with more than 80% of its exports going to China. This trade route accounts for approximately 50% of the global trade in bauxite (see Chapter 5).

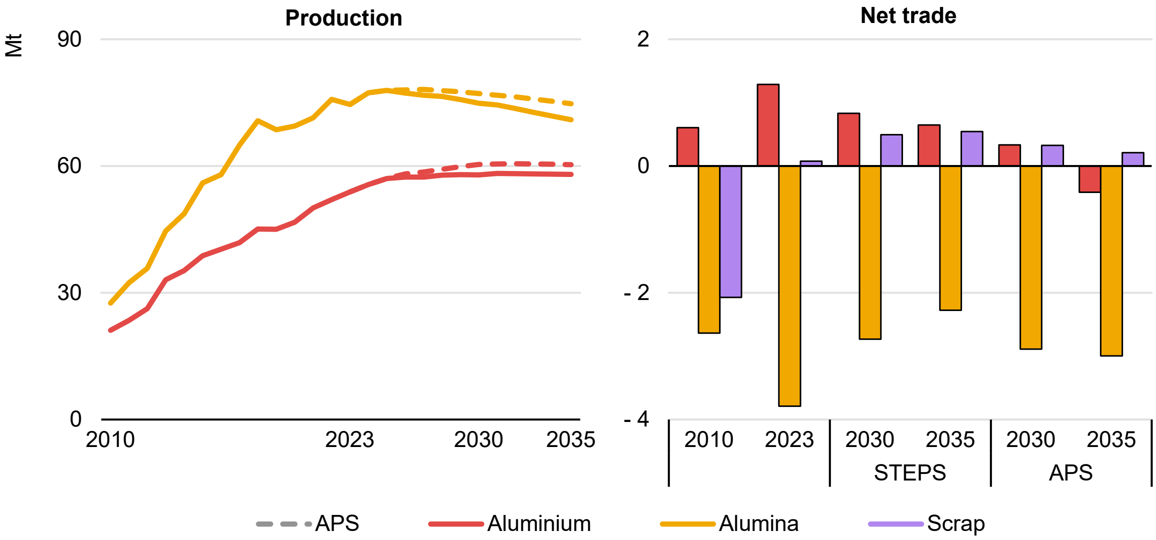
China is also the world’s largest exporter of semi-finished and finished products made from aluminium. These exports have been the subject of a series of trade disputes, with several countries accusing China of unfairly subsiding its aluminium industry, leading to artificially low prices for its exports and undermining the health of their domestic industries. For example, in April 2024, the United States announced increases in its tariffs on Chinese aluminium, which combined with existing measures, brings the effective tariff rate to 35%. China went from being a marginal net exporter of aluminium ingots in 2010 to seeing significant net imports in 2023 of close to 2 Mt, equivalent to less than 5% of its production. Imports of ingots from Russia also increased substantially in 2023, as Russian exports to the United States and European Union fell following Russia’s invasion of Ukraine (Reuters, 2024c). China also imported similar quantities of alumina to feed its aluminium smelters.

Primary aluminium production in China is often co-located with coal power generation. These plants, which are often captive (i.e. used and managed by the industrial site for their own use), provide a low-cost, but highly emissions-intensive source of electricity. It is estimated that around 70% of the electricity used to power aluminium smelters in 2023 in China was based on coal, compared with 3% in North America and 1% in Europe (IAI, 2024). The Chinese government has been implementing stricter regulations in recent years, which have led to older, less efficient plants being closed and a significant increase in the proportion of aluminium plants powered by hydroelectricity. While technology improvements have led to reductions in emissions, there is no evidence that government financial support in this sector has generally led to improved environmental performance (OECD, 2023a).

As with iron and steel, the prospects for China’s aluminium industry are largely driven by the country’s needs for manufacturing and construction. Demand is already slowing as the construction boom levels off, but the drivers in the manufacturing sector – transportation equipment, consumer goods and electrical equipment, much of which is eventually destined for export – remain robust, with output in these higher value added sectors remaining relatively strong in both scenarios. In the STEPS, both demand and domestic production grow by just under 10% between 2023 and 2035, with net exports dropping by 50%. Output increases slightly faster in the APS, and China becomes a slight net importer of aluminium by 2035. This is due to stronger demand for solar PV, EVs and long-distance power lines (which are deployed more quickly and to a greater extent than in the STEPS), which use substantial amounts of aluminium. At their peak output in the APS (565 GW of modules by around 2030), China's solar PV manufacturing facilities require over 4 Mt of aluminium, or over 6% of China's entire production. An important driver of supply in both scenarios – as in China's steel industry – is the increasingly important role of secondary (scrap-based) production with the growing availability of post-consumer scrap as the country's large stocks of buildings and vehicles come to the end of their life. This leads to progressively lower alumina production in both scenarios, after production peaks in the near term.

Production is cleaner in the APS than in the STEPS, in response to the need to meet the domestic carbon neutrality target (alumina and aluminium production account for around 8% of China's electricity consumption and directly account for 1% of China's CO_2 emissions) and pressures from importers of Chinese products made with aluminium to reduce their associated emissions. In addition to the shift to secondary production, this is achieved mainly through the deployment of smelters supplied with renewable electricity and equipped with inert anodes (as opposed to carbon-based anodes that oxidise to CO_2 during use), and through the use of low-emissions fuels in the Bayer process for producing alumina.

Figure 3.46 Production and trade in the aluminium supply chain in China, historical and in the Stated Policies and Announced Pledges Scenarios, 2010-2035



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Notes: Aluminium net trade considers unwrought ingots and semi-finished products. Alumina production includes only metallurgical alumina.

Robust demand for aluminium from the manufacturing sector is set to offset declining demand for construction in China over the coming decade.

3.4 India

India has introduced several policies to reduce import dependence, strengthen domestic manufacturing and promote export-led growth across all sectors. The “Make in India” initiative, launched in 2014, aims to transform India into a global manufacturing hub by improving the ease of doing business and attracting foreign direct investment. In 2020, the vision of “Atmanirbhar Bharat” was introduced, emphasising self-sufficiency and resilience. As part of this vision, Production Linked Incentive (PLI) schemes were introduced, offering direct grants to manufacturers of clean energy technologies through a competitive bidding process. To further support domestic manufacturing, India has adjusted import tariffs and implemented NTMs for products such as solar PV, batteries and EVs. These measures include special import duties to incentivise foreign manufacturers to set up domestic manufacturing capacity.

Table 3.6 Selected domestic and trade policies in India relevant to clean energy technology and materials manufacturing

Policy (enactment year)	Description
Make in India (2014)	Focuses on improving infrastructure in industrial clusters, creating jobs, promoting innovation, protecting intellectual property, facilitating business and attracting foreign direct investment. It targets 15 manufacturing sectors, including automobiles, chemicals, electrical machinery and renewable energy. In 2020, the vision of “Atmanirbhar Bharat” (Self-Reliant India) was introduced as a complement, boosting domestic production and strengthening the overall economy.
Production Linked Incentive (PLI) Schemes on clean energy technologies (2020)	PLI schemes provide incentives to both foreign and domestic manufacturers to expand production and exports and enhance competitiveness. They offer direct grants for fixed periods of time based on output and sales. Schemes have been introduced for technologies including solar PV, batteries and EVs. These schemes often include domestic value addition thresholds that must be met to qualify for financial support or to access greater financial support.
National Green Hydrogen Mission (2023)	Aims to position India as a leading global hub for the production, use and export of “green” hydrogen and ammonia, with a production target of 5 Mt by 2030, backed by financial and non-financial measures. Aims to develop at least two hydrogen hubs. The Strategic Interventions for Green Hydrogen Transition (SIGHT), akin to the PLI scheme for the hydrogen sector, provides incentives for electrolyser manufacturing.
National Steel Policy (2017)	Aims to increase India’s steel production capacity to 300 Mt by 2030 (up from 125 Mt in 2017), and includes implementation of the Domestically Manufactured Iron & Steel Products Policy to promote the use of “Made in India” steel in government procurement. Adjustments in basic customs duty on steel products and raw materials and trade remedies on certain steel products are aimed at improving the sector’s competitiveness. Further, in 2019, India issued the Steel Scrap Recycling Policy. The PLI scheme for specialty steel, introduced in 2021, targets production of 25 Mt by 2030-31, reduced imports of specialty steel and increased exports. In 2024, India released guidelines for implementing pilot hydrogen projects in the steel sector under the National Green Hydrogen Mission.

Policy (enactment year)	Description
E-vehicle policy	Several tariff measures have been introduced to regulate the import of EVs and to promote domestic manufacturing and reduce import dependence. The tariff rate on EV imports has been increased to 70-100%, depending on the value. However, in 2024, India announced reduced import duties of 15% for manufacturers that commit to invest at least USD 500 million domestically, start manufacturing EVs within 3 years and achieve 50% domestic value addition within 5 years. In 2021, the government tripled the tariff on EV battery packs to 15% and doubled the tariff on Li-ion cells to 10%.
Tariffs and non-tariff measures for solar PV	In 2022, India increased tariffs to 40% on solar PV modules and 25% on cells, replacing an earlier safeguard duty of 15% on modules from China and Malaysia, aiming to reduce import dependence and promote domestic manufacturing. In addition, the Approved List of Models and Manufacturers (ALMM) mandate was re-introduced in April 2024, requiring all modules and cells to be listed, except for non-subsidised off-grid projects. Panels on the ALMM must comply with the Bureau of Indian Standards and meet the ministry's module efficiency criteria.
Preferential trade agreements	The ASEAN-India FTA (AIFTA, 2010) eliminates tariffs on more than 90% of goods traded between ASEAN and India. The South Asian Free Trade Area (SAFTA, 2006) which covers India and Afghanistan, Bangladesh, Bhutan, the Maldives, Nepal, Pakistan and Sri Lanka, also reduces tariffs on traded goods, though its effectiveness is limited by extensive exemptions. The India-Korea Comprehensive Economic Partnership Agreement (CEPA) (2010) and the India-Japan CEPA (2011) both reduce or eliminate tariffs on products including steel and automobiles. Ongoing negotiations for the India-European Union Free Trade Agreement and the India-Australia Comprehensive Economic Cooperation Agreement aim to further reduce tariffs.

EVs and batteries

Current market and policy support

The electrification of road transport is a key technology pathway in India's strategy to reduce GHG emissions and improve air quality while fostering economic growth. India aspires to become a global leader in new mobility solutions and battery manufacturing (NITI Aayog, 2019) and has introduced a number of measures, on both the consumer and manufacturer side, to promote the deployment and manufacturing of EVs.

Incentives to encourage EV purchases were first introduced under the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme in 2015, which initially predominantly targeted two- and three-wheelers, given their dominance in road transport (passenger cars made up just 17% of new vehicle registrations in 2023) (ICCT, 2024), and buses. After FAME II ended in 2024, a four-month Electric Promotion Scheme (EMPS 2024) was introduced. This was subsequently followed by the latest initiative, titled PM Electric Drive Revolution in Innovative Vehicle Enhancement (PM E-DRIVE). Set to be implemented from 1st October 2024 to 31st March 2026, with a budget allocation of USD 1.3 billion, this scheme focuses on promoting electric two- and three-wheelers, buses, trucks and the deployment of charging infrastructure, while specifically excluding electric cars. However, a number of state-level policies, such as the reduced rate of Good and Services Tax, direct subsidies and tax credits, encourage electric car sales across the country. In 2023, electric car sales reached 80 000, accounting for 2% of new car registrations – an annual increase of 70%. About three-quarters of these electric cars were produced by the domestic OEM, Tata Motors, which aims for a 30% share of electric cars in its sales by 2030.

India promotes investment in the EV supply chain through production incentives and trade policies. The national government's PLI scheme for Automobile and Auto Components (AUTO) and for manufacturing of Advanced Chemistry Cell (ACC) Battery Storage (MHI, 2021) aim to attract investments in domestic EV and battery manufacturing and other clean energy technologies. The PLI AUTO scheme, which is approved to run for a period of 5 years until fiscal year 2027-28, has a budget of USD 3.1 billion for producer-targeted incentives, both for Indian and foreign investors (MHI, 2024). The amount of subsidy granted to each manufacturer under the scheme is determined by the company's domestic total sales value. The scheme aims to boost manufacturing capacity to 50 GWh by 2030 – equivalent to production of about 800 000 EVs – with a budget of around USD 2.2 billion, to be disbursed over 5 years based on the volume of battery cells manufactured and sold. A first tender has already allocated to 30 GWh of capacity and a second tender is ongoing (MHI, 2024a). The battery manufacturers obtaining subsidies must commit at least 25% of domestic value addition (i.e. 25% of the added value in the battery manufacturing process must occur in India) within 2 years and a minimum of 60% value addition within 5 years (MHI, 2024b).

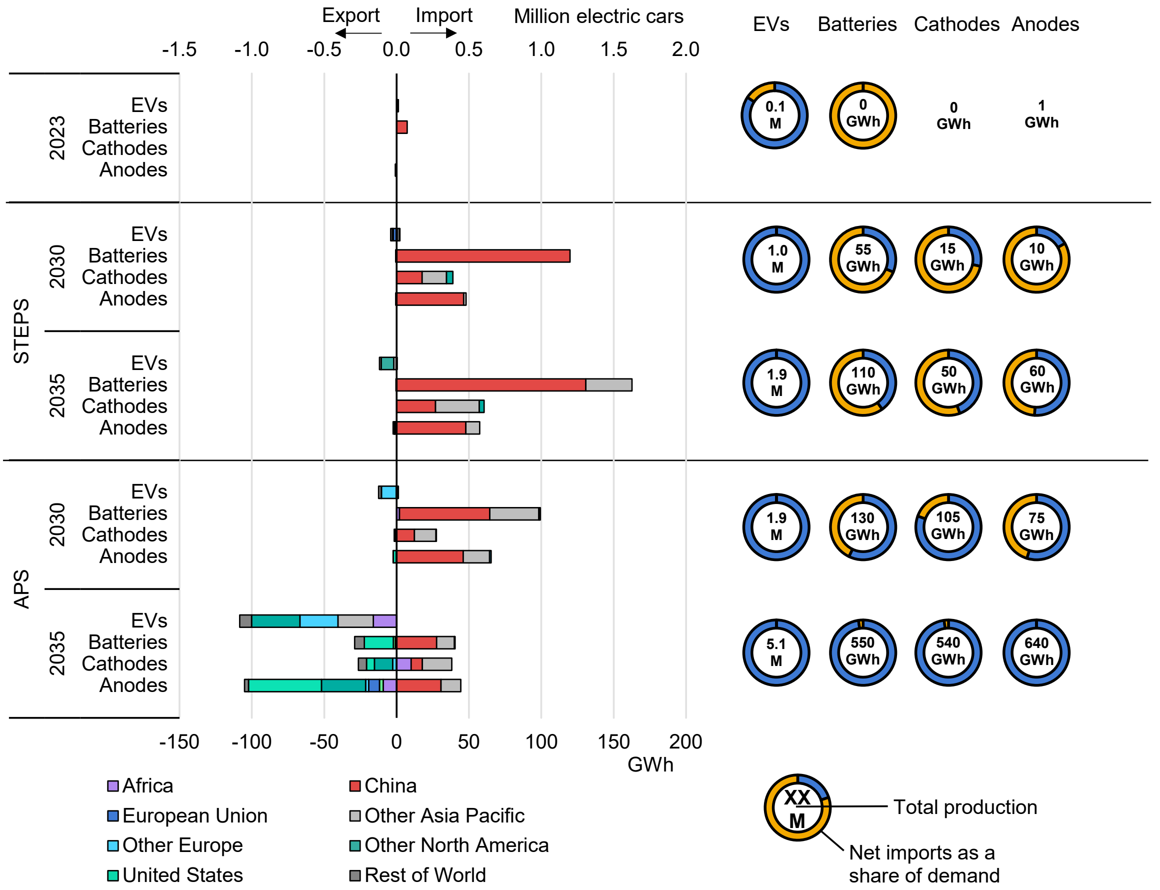
India also levies very high tariffs on imported vehicles, including EVs, to protect its domestic automotive industry. Consumers must pay import duties of up to 70% of the cost of the vehicle if its retail price does not exceed USD 40 000, and 100% for pricier models. The government announced in April 2024 that it would reduce these tariffs to 15% for OEMs (including China-headquartered EV makers) willing to invest a minimum of USD 500 million to start up domestic production within 3 years (Nikkei Asia, 2024).

As a result of these local manufacturing incentives and protective tariffs, several foreign OEMs have announced plans to build or expand manufacturing facilities in India. The Vietnamese OEM, VinFast, has announced the construction of a 150 000-unit EV manufacturing plant, which is expected to start production in 2026 (Vietnam Briefing, 2024). Korean manufacturer Hyundai already has capacity for over 800 000 units in the country, producing various electric models, and is planning to expand this to 1 million by 2025. The Chinese OEM SAIC Motor, under its brand MG Motor, has also acquired EV manufacturing facilities in the country to benefit from cheaper labour and energy. There is also considerable potential to repurpose existing ICE car manufacturing capacity in India, which currently exceeds 8 million units.

Manufacturing and trade prospects

The prospects for manufacturing EVs in India and trade in those vehicles hinge on policy settings. In the **STEPS**, both the supply-side PLI incentives and the import duty policy enable India to meet all its demand for electric cars of 1 million vehicles (almost one-fifth of all passenger car sales) from domestic production by 2030 (Figure 3.47). In 2030, EV production costs in India reach about the same level as in China, but high import duties make an imported EV at least 50% more expensive than a locally produced one (Figure 3.48). By 2035, domestic production reaches 1.9 million units, exceeding demand by around 100 000 units and making India a net exporter, with most of the surplus going to Canada. This reflects the impact of existing subsidy and trade policies aimed at boosting the competitiveness of India's electric car industry.

Figure 3.47 Indian market for EVs, batteries and components in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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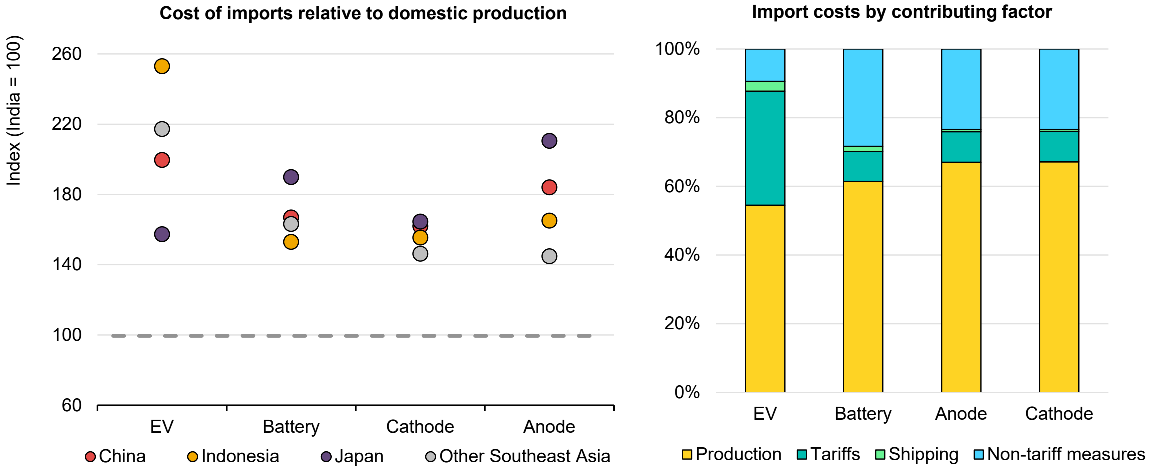
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; M = million; EVs = electric vehicles, specifically passenger cars and pick-up trucks. Battery demand, production and trade include all EV types and stationary storage. It is assumed that all countries and regions produce the global average chemistry share for both batteries and components. Cathode and anode refer to cathode and anode active materials. Demand for components that are not the final product are determined by the production of the subsequent component. EV data is reported in million units (top axis), while battery cell, cathode and anode active materials are in GWh (bottom axis). Import and export refer to net trade flows between India and each of the regions displayed, while net imports as a share of demand refers to the net imports to India accounting for all regions as a share of domestic demand.

India becomes a net exporter of EVs by 2035, but has to import some batteries in the STEPS, whereas it is self-sufficient in the APS.

Despite strong demand from EV manufacturers and relatively low costs, India is set to remain dependent on imports of batteries and components due to a lack of projects today. Investment in the Indian battery industry is growing, with about 80 GWh of manufacturing capacity already announced, of which three-quarters is committed. Announced projects are, however, insufficient to meet the needs of the growing domestic EV, electric 2- and 3-wheeler and stationary storage markets, accounting for about one-third, one-fourth, and one-third of the total battery demand in 2030 in the STEPS, respectively. Battery production reaches 55 GWh in the STEPS in 2030, corresponding to about 30% of demand, but then grows rapidly to 110 GWh in 2035, satisfying 40% of demand. In both 2030 and 2035, the shortfall is met by imports from other Asian countries, mostly China. The output of cathode and anode active materials follows a similar trend to that for batteries. By 2030, domestic production will meet only 30% of cathode and 15% of anode demand, but by 2035, nearly half of the demand for both will be locally produced. The remaining supply will rely on imports, predominantly from China, Southeast Asia and Korea.

Figure 3.48 Total production cost of electric cars, batteries and components in India compared with imports and Indian import costs in the Announced Pledges Scenario, 2035



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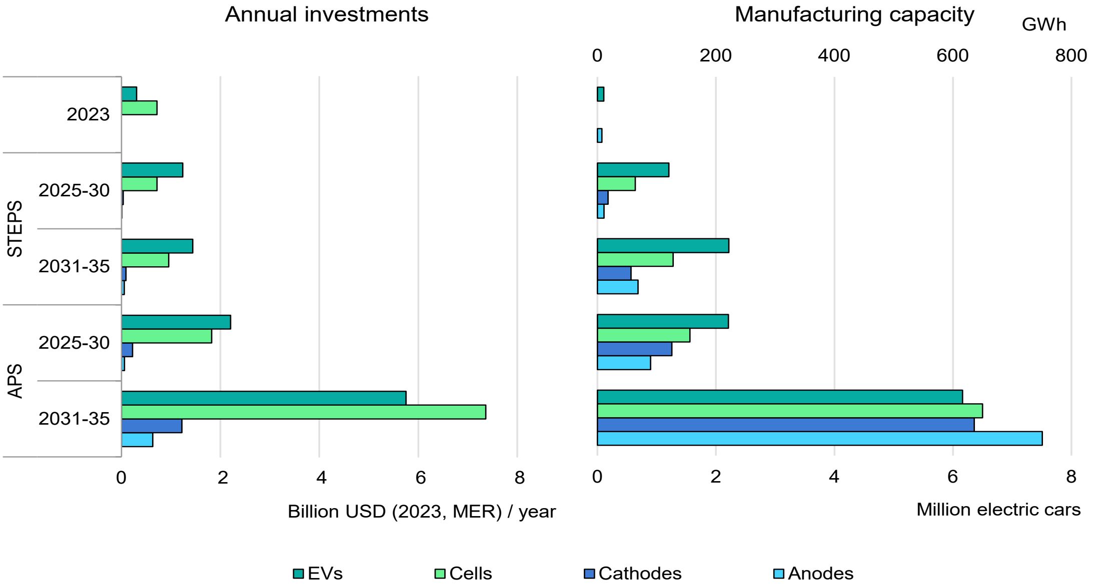
Notes: EVs = Electric Vehicles (electric passenger cars exclusively). The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in India (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

Under announced pledges, importing an electric car into India in 2030 would cost at least 50% more than a locally produced one, mainly due to import duties.

Demand and production of EVs, batteries and components are much higher in the **APS** than in the STEPS, reflecting the assumption that India makes good on its pledge (announced at COP 26) to reach a 100% share of zero emission vehicles in total light-duty vehicles sales by 2040. Electric car sales reach 1.7 million in 2030, accounting for over 30% of new registrations, and 4 million in 2035 (60%). All the growth in demand is met by domestic production on the assumption that all preliminary projects that have been announced are implemented and that investment continues to ramp up beyond 2030. By 2035, electric car production exceeds domestic demand by more than 1 million, with India becoming one of the new major electric car exporters.

Thanks to significantly greater level of ambition and investment, battery production in 2030 in the APS is more than double that in the STEPS, reaching 130 GWh. Thanks to larger domestic production and more diversified imports, only one-quarter of the demand is satisfied through imports from China, compared with almost 70% in the same year in the STEPS. In 2035, India reaches its target of becoming a large battery producer and its battery and cathode production is sufficient to satisfy its domestic needs. India also becomes a net exporter of anode active materials, with a surplus of around 10% of its production being shipped to North America and, to a lesser extent, Europe and North Africa.

Figure 3.49 Indian electric car, battery and component manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; EVs = Electric Vehicles (electric passenger cars exclusively). Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

Investment in India's battery supply chain is substantially higher in the APS, with the bulk of investments going to cars and battery cells manufacturing capacity.

Investment in India's battery supply chain is substantially higher in the APS compared with the STEPS, resulting in much faster growth in manufacturing capacity (Figure 3.49). It reaches around USD 2 billion/year for electric cars and roughly the same amount for batteries and components on average over 2025-30 – about two times higher than in the STEPS – and USD 6 billion and USD 9 billion in 2031-35 (almost six times higher than in the STEPS), respectively.

Solar PV

Current market and policy support

India has ambitious plans for expanding the deployment of solar PV capacity. The country has more than enough module manufacturing capacity to meet current demand. Manufacturing capacity increased by 60% over the course of 2023 to 35 GW at end-year, far exceeding demand of nearly 20 GW, but many factories make modules incorporating older technologies, which are less competitive and for which demand has dropped. As a result, only around a quarter of nominal capacity is actually used – well below the average rate in the rest of the world – so India has to import modules to fill the gap. Most imports in 2023 came from China and the rest from Southeast Asia, more than offsetting small quantities of exports to the United States. India also had about 10 GW of capacity for making cells at the end of 2023, but has no factories for making wafers or polysilicon.

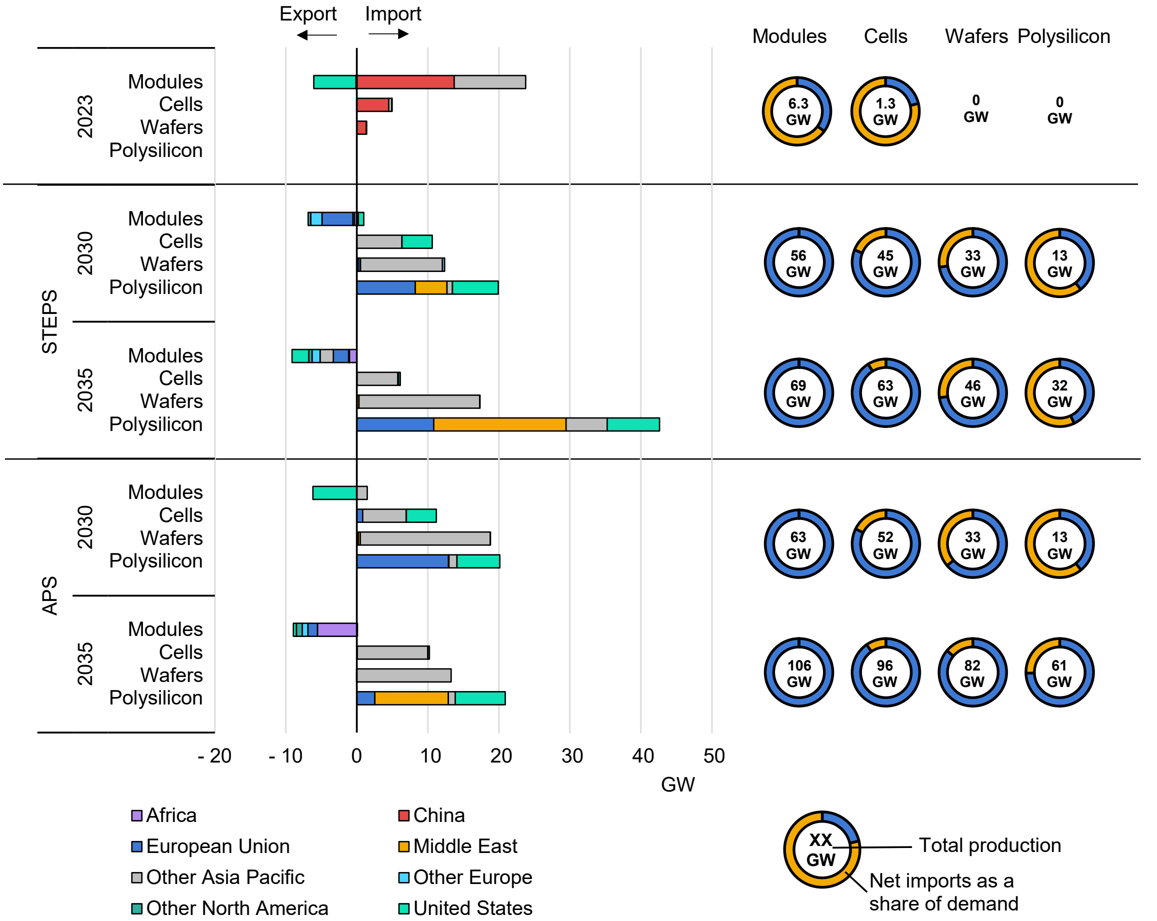
There is significant scope, in principle, for expanding solar PV manufacturing facilities in India, given the country's favourable market conditions, including a large potential domestic market and relatively low energy prices and labour costs. In addition, India already has a very strong presence in related industries, such as steel. The government's economic policy framework, characterised by its "Make in India" initiative (Make in India, 2024) targeting the expansion of manufacturing as a source of economic development and job creation, also provides a business environment that is conducive to attracting investment at various segments of the solar PV supply chain. Renewable energy and other manufacturing activities in chemicals and electronic systems with strong synergies with solar PV technology are among the 27 targeted sectors in that initiative.

The PLI Scheme for PV Modules is the main pillar of support for building up high-efficiency module manufacturing based on cutting-edge technologies. Two tranches of funding have so far been awarded: the first one, issued in April 2021, provided around USD 550 million in grants for three projects, while the second, in September 2022, awarded USD 2.4 billion for 11 projects (MNRE, 2024). In total, the projects involve around 48 GW of manufacturing capacity. The process of awarding the grants took into account the degree of integration between modules, cells, wafers and polysilicon manufacturing. The successful bidders have either entered into technology agreements with leading solar PV companies or have invested in them. The funding rounds have already borne fruit, with cell manufacturing capacity expected to double to 20 GW and the first wafer factories due to come online in 2024. Just as for EVs, India also protects its solar PV industry from foreign competition through high tariffs on imported components, which amount to 40% for modules and 25% for cells (Reuters, 2023h). In parallel, India removed tariffs for the import of manufacturing equipment for solar cells and modules, and critical minerals such as silicon in order to support the development of its domestic manufacturing (PV magazine India, 2024).

Manufacturing and trade prospects

Manufacturing capacity for solar PV is set to grow rapidly over the next decade to meet rising deployment, driven by strong policy support. In both the STEPS and APS, the growth in manufacturing outstrips growth in domestic demand, turning India into a net exporter of modules by 2030 (Figure 3.50), backed by specific targets under the PLI scheme, and experience gained through scale-up. In both scenarios, the expansion in capacity is bigger downstream (for modules and cells) than upstream (wafer and polysilicon) due to the lower barriers to market entry for the former, and the fact that an established manufacturing base already exists.

Figure 3.50 Indian market and import-export balance for solar PV modules and components in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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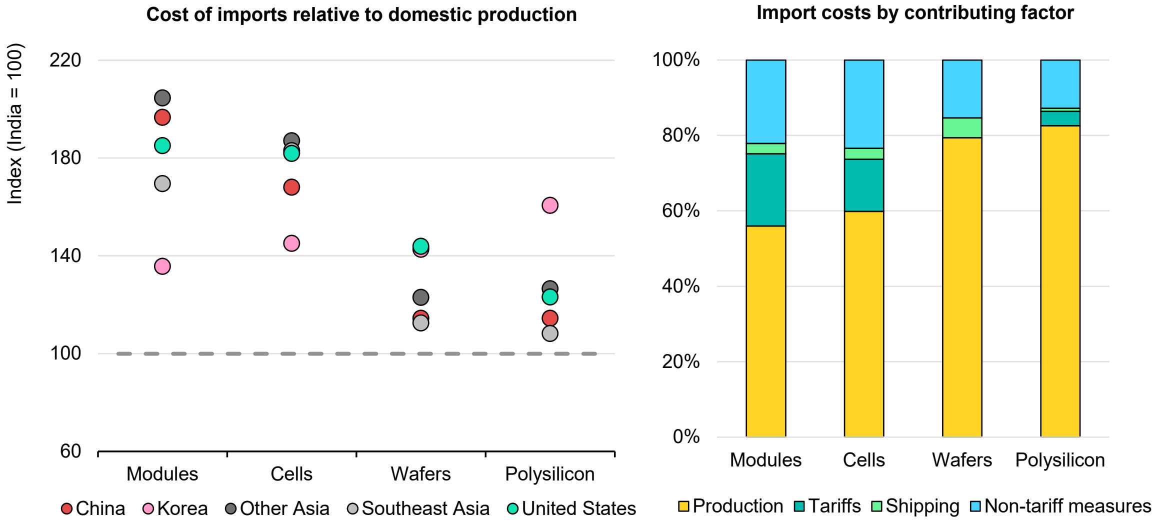
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Demand for components that are not the final product are determined by the production of the subsequent component. Import and export refer to net trade flows between India and each of the regions displayed, while net imports as a share of demand refers to the net imports to India accounting for all regions as a share of domestic demand.

In both the STEPS and APS, the growth in manufacturing outstrips growth in domestic demand, turning India into a net exporter of modules by 2030.

In the **STEPS**, module manufacturing reaches over 55 GW in 2030, of which about 6 GW goes to export (primarily to the European Union and other European countries). Total annual installation of solar PV modules reaches nearly 50 GW in 2030 and 60 GW in 2035. Output and exports increase further to 2035, reaching around 70 GW and nearly 10 GW, respectively. Cell production also rises, but to a lesser extent than modules because its production starts from a lower base today, with India becoming self-sufficient by around 2035. By contrast, the production of polysilicon and wafers fails to keep pace with the domestic industry's needs, such that India remains a net importer through 2035. Polysilicon is imported from the European Union and the United States (which are already established suppliers to the Indian market), as well as from the Middle East, whereas wafers are imported from Southeast Asia. There are high barriers to entering the polysilicon and wafer markets, reflected in the current high concentration of production globally compared with modules and cells.

In the **APS**, manufacturing capacity for solar PV modules and components grows even faster than in the STEPS, reflecting India's ambition to achieve net zero emissions by 2070. By 2030, a slightly higher share of the country's production of modules – around 90%, or 55 GW – goes to meeting domestic needs as deployment expands more rapidly. As in the STEPS, exports grow through to the mid-2030s, mainly to Africa. For cells, wafers and polysilicon, the expansion of production follows a slightly more rapid upward trajectory than in the STEPS, reflecting greater policy ambition. For cells and wafers, domestic production lags slightly the increase in demand. The gap is larger for polysilicon, where, again, the European Union, the United States and countries in the Middle East are the main trade partners.

Figure 3.51 Total production cost of solar PV modules and components in India compared with imports and Indian import costs in the Announced Pledges Scenario, 2035

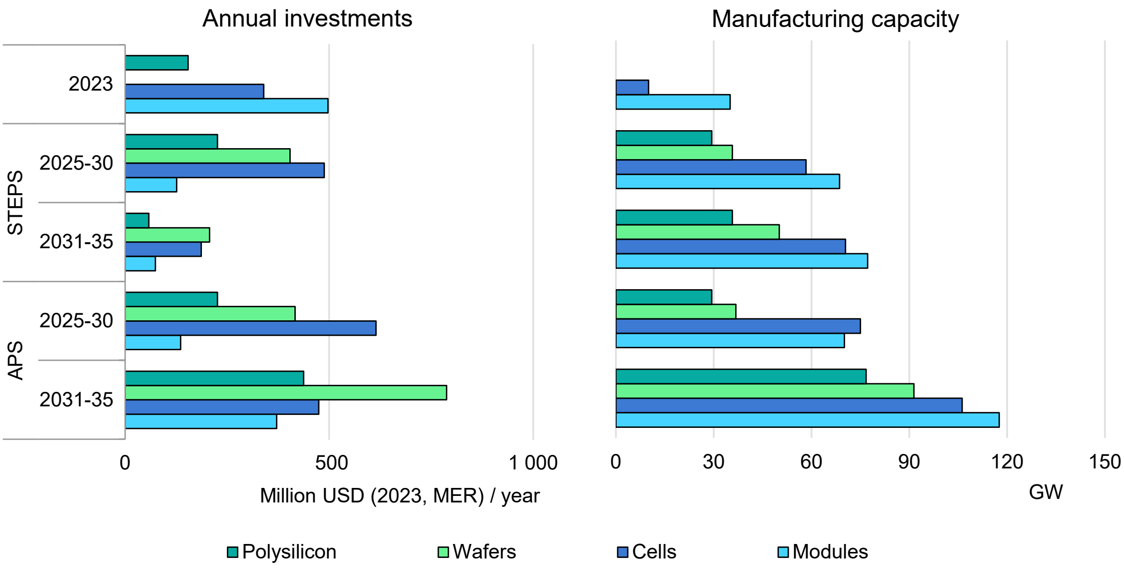


Notes: The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in India (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

Manufacturing of solar PV modules and components in India is generally very cost competitive, in large part due high tariffs and other non-tariff trade measures.

Domestic manufacturing of solar PV modules and components is generally cost competitive compared with other regions; modules and cells are most cost competitive and wafer and polysilicon less so (Figure 3.51). This is in large part due high tariffs and NTMs. The investment needed to expand solar PV manufacturing capacity ramps up significantly to 2035, especially in the APS (Figure 3.52). Most future investment goes to manufacturing wafers and cells, which are more capital-intensive than modules and polysilicon.

Figure 3.52 Indian solar PV and component manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

Most future investment in solar PV goes to wafer and cell manufacturing, which are more capital-intensive than modules and polysilicon.

Electrolysers

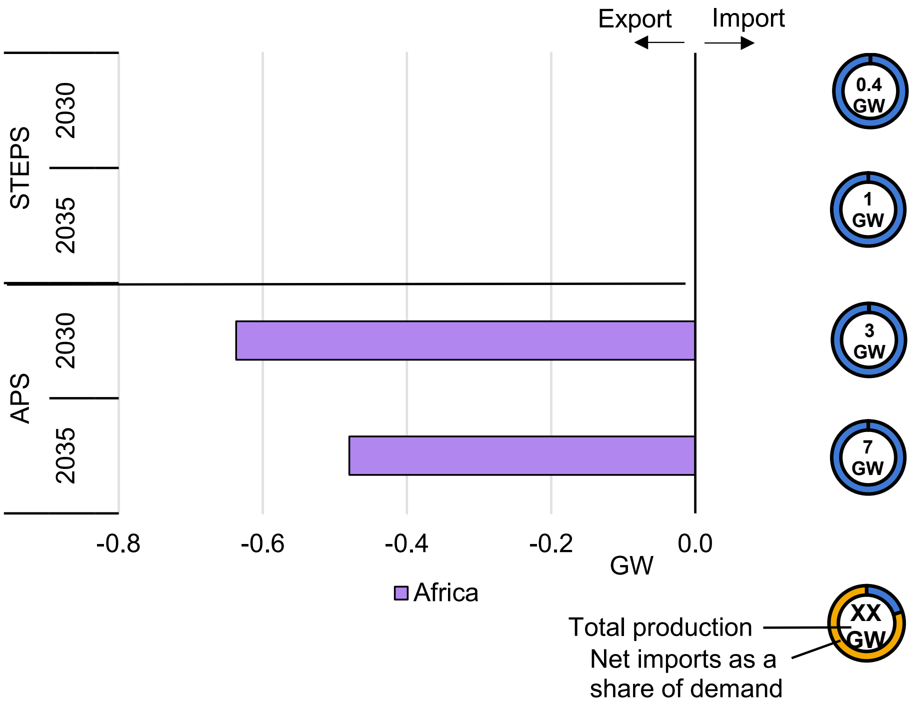
India is currently a very small producer of electrolysers, with less than 1 GW of manufacturing capacity in operation, mainly at the Ohmium plant in Bangalore (Recharge News, 2022). That is set to change, with a number of projects in the pipeline. Announced capacity additions could push total electrolyser manufacturing capacity to over 12 GW by 2030, though less than 10% of the more than 11 GW of planned additions has reached FID. Of the capacity that could be in place by 2030, 80% is being developed by companies headquartered in India. The leading Indian company, Reliance Industries, has secured licensing rights to manufacture alkaline electrolysers using technology from the Norwegian Nel (Nel Hydrogen, 2024). The deal will also benefit Nel by giving it access to the growing Indian market.

As part of its National Green Hydrogen Mission, in January 2024 the Indian government announced the SIGHT scheme, which provides financial support to domestic electrolyser manufacturing and hydrogen production from renewable energy. In the first tender, which targeted 1.5 GW of capacity, 1.2 GW was for any technology, while 0.3 GW was set aside for domestically developed stack technology. Reliance Industries, Ohmium and the joint venture John Cockerill-Jingli are among the companies that won the first tender, which reached full capacity and assigned a total of USD 214 million. A second tender, in August 2024, selected 13 companies for another 1.5 GW of capacity (1.1 GW for any stack technology, 0.3 GW for domestically developed stack technology and 0.1 GW for domestically developed stack technology smaller units). Waree Energies got support for 300 MW, the maximum allowed by the tender for a single company or conglomerate. Several companies, including Adani Enterprises, participated in both rounds of the tender.

In the **STEPS**, India's demand for electrolysers reaches almost 0.4 GW by 2030, a level that could be easily met by the country's current manufacturing capacity of 0.8 GW, and never exceeds 1 GW per year throughout the period to 2035. (Figure 3.53).

In the **APS**, demand for electrolysers rises to around 2 GW by 2030, five times the demand in STEPS. Demand for electrolysers grows quickly to reach about 7 GW in the period 2031-2035, following growth in deployment of low-emissions hydrogen. In the APS, India meets its own electrolyser demand with domestic manufacturing, and starts exporting, mainly to Africa, where manufacturing capacity remains limited in this scenario. However, despite this export potential, India's presence in the global electrolyser market remains very modest compared to China's.

Figure 3.53 Indian market and import-export balance for electrolysers in the Stated Policies and Announced Pledges Scenarios, 2030-2035



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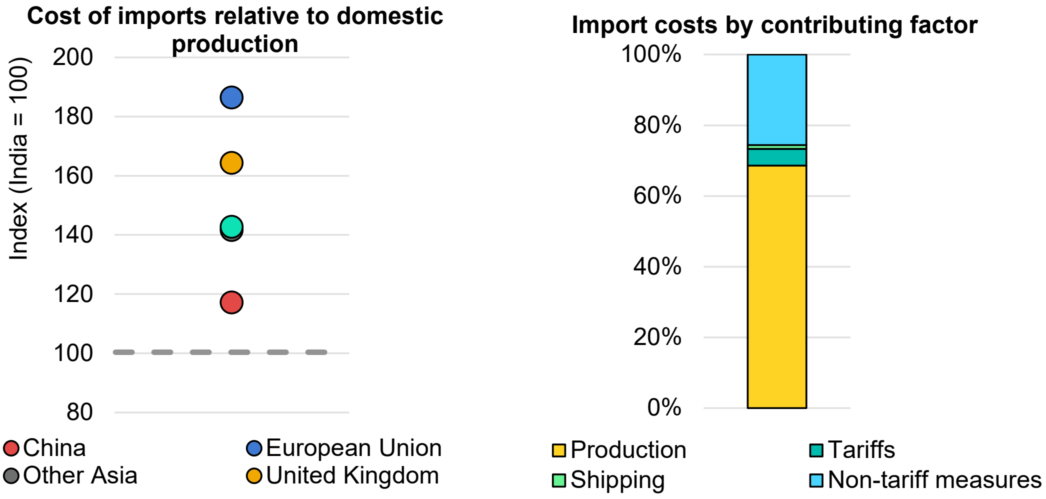
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Import and export refer to net trade flows between India and each of the regions displayed, while net imports as a share of demand refers to the net imports to India accounting for all regions as a share of domestic demand.

India becomes a net exporter of electrolysers in 2030 in the APS, with production capacity outstripping domestic demand growth thanks in large part to incentives to manufacturers.

Our analysis suggests that electrolyser manufacturing in India could satisfy domestic demand cost competitively, as a result of production subsidies and avoided import costs. In the APS, production costs are about 55-70% of the total cost of importing electrolysers made in Europe or the United States, including shipping and other trade-related costs (Figure 3.54). The cost of supplying Chinese electrolysers is also slightly higher. While manufacturing costs are lower in China, trade costs applied to imported electrolysers make them more expensive than locally manufactured ones; labelling, certification and performance requirements usually add significant additional costs for companies importing into India. On average, trade costs (including shipping, tariffs and NTMs) account for almost one-third of the total cost of an electrolyser imported into India, with manufacturing costs accounting for the remaining two-thirds. Nonetheless, there is considerable uncertainty as to how trade costs may evolve in the coming years, given the nascent nature of the electrolyser market both in India and globally.

Figure 3.54 Total production cost of electrolysers in India compared with imports and Indian import costs in the Announced Pledges Scenario, 2035



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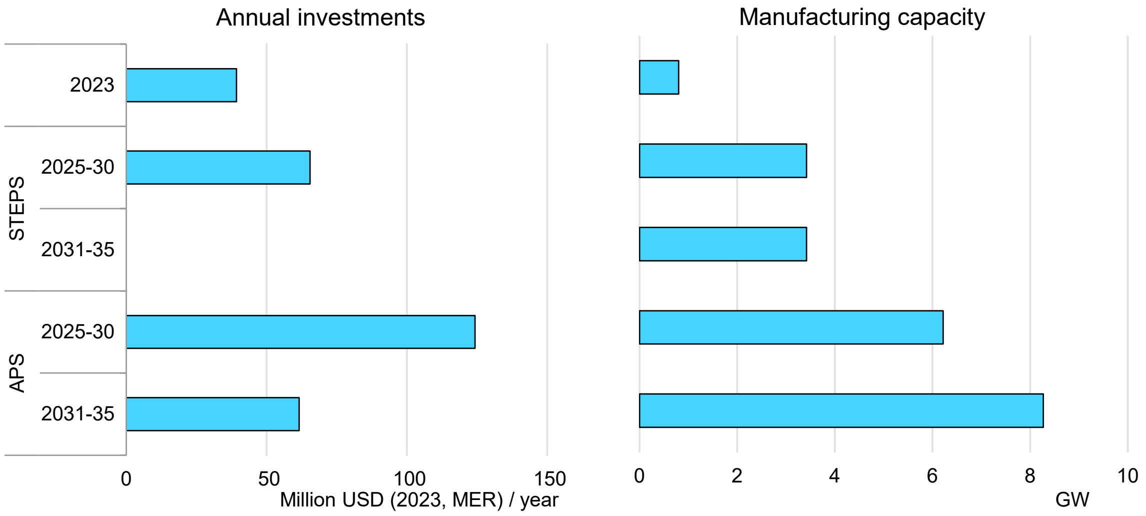
Notes: The total production costs include the value of public financial support. The left-hand graph shows the ratio between total import cost from different sources and the production cost in India (dashed grey line). Total import cost includes manufacturing cost in the producing region, shipping costs, import and export tariffs and non-tariff measures.

Electrolyser manufacturing in India could be very cost competitive, thanks to manufacturing incentives and trade costs.

In both scenarios, most of the investment in electrolyser manufacturing up to 2035 takes place before 2030, reflecting the capacity that would be added under the tenders of the SIGHT scheme (Figure 3.55). Under this scheme, the manufacturing capacity of 3 GW by 2030 is well above India's domestic demand in the STEPS. At the same time, the capacity under the SIGHT scheme alone would not be enough to supply the demand in the APS. In this scenario, additional company announcements could lead to over 12 GW manufacturing capacity by 2030. As a result, in the APS the annual investment rate during 2025-2030 doubles compared to STEPS.

Figure 3.55 Indian electrolyser manufacturing investment and capacity in the Stated Policies and Announced Pledges Scenarios, 2023-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Investments in manufacturing capacity for 2030 are calculated as the annual average of overnight investments for 2025-30, while for 2035 they are calculated as the annual average for 2031-2035. Investments in 2023 refers to investment spending.

Most of the investment in new electrolyser manufacturing capacity takes place before 2030 in both scenarios, reflecting financial support measures.

Materials

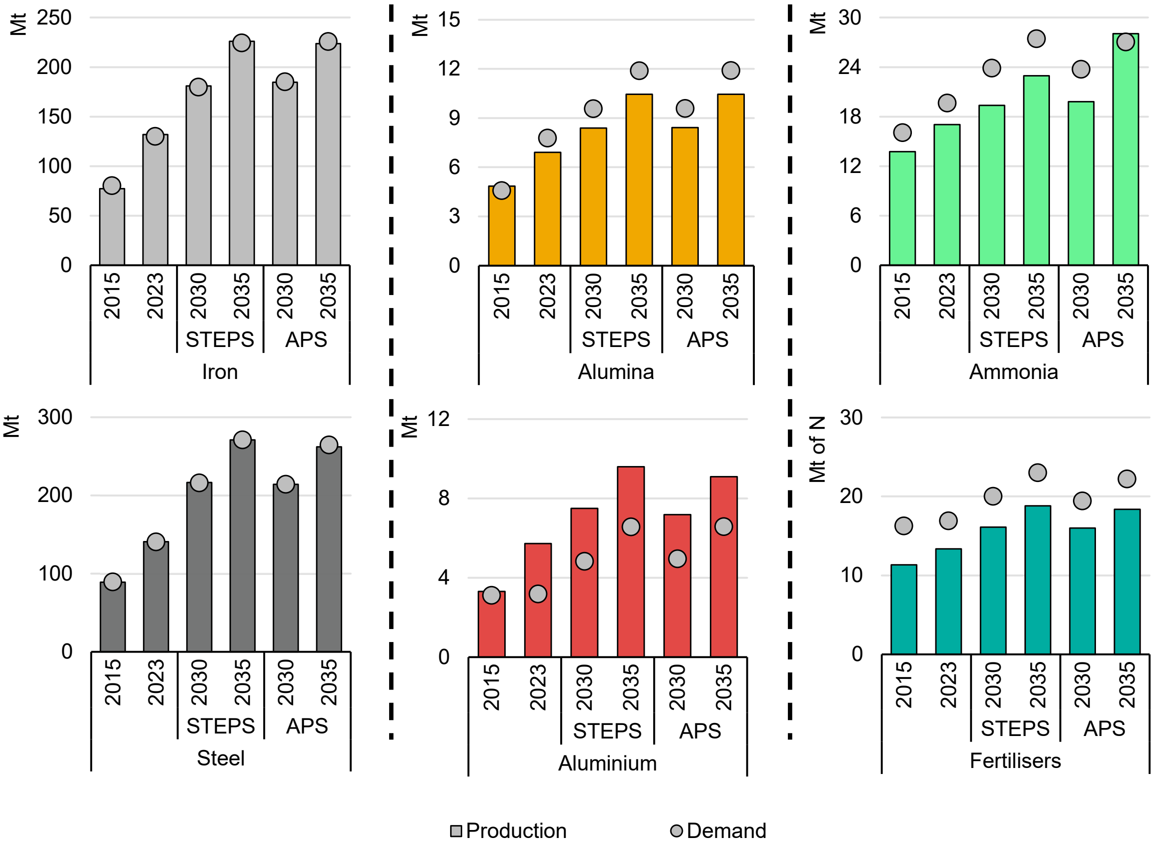
Demand for materials in India has been growing strongly in recent years, driven by rapid economic growth and industrialisation. GDP increased by 77% between 2013 and 2023. During this period, demand for steel, aluminium and ammonia grew by 74%, 23% and 31%, respectively (Figure 3.56).

India’s steel industry has been expanding rapidly to meet the country’s growing needs for manufacturing and construction, contributing about 2.5% to national GDP today. India’s steel industry is the second-largest in the world after China. The government’s National Steel Policy, which was updated in 2017, sets a target to increase production capacity to 300 Mt by 2030-31 compared with about 140 Mt today (India, Ministry of Steel, 2017).

A number of measures have been introduced to help support this target, aimed particularly at small and medium-sized companies, including policies promoting scrap steel collection and usage (India, Ministry of Steel, 2019a), prioritisation of domestic production for public procurement (India, Ministry of Steel, 2019b), tariffs of 15% on exports of scrap and higher import tariffs for semi-finished steel products than the world’s average. For now, there is no production of steel using near-zero emissions technologies, but opportunities for technology transfer do exist: several multi-national companies, some already operating in India, are planning to invest in DRI plants in Europe that will be capable of using hydrogen instead of natural gas, which is the most common fuel for these facilities today, and they could apply the knowledge gained to projects in India.

In addition to these policy measures, India enjoys a strong competitive advantage in steel production, driven, to a large extent, by domestic resources of iron ore and non-coking coal, as well as a vast and rapidly growing domestic market, relatively low labour costs and several dynamic, international big players with strong roots in the country. Around 600 000 people work in the steel industry in India (and another 70 000 in the aluminium industry) (Worldmetrics, 2024; IAI, 2019). Although labour costs are low by global standards, labour productivity is also low: 4.3 workers are needed to produce a tonne of steel in India compared with just 1.1 in China. The availability of skilled workers can also be a bottleneck. Only 3% of the population has undergone formal vocational training, or 17% if informal training is included (Srija, 2023). This is far from the OECD average of 44% of upper secondary students being in vocational training (OECD, 2023).

Figure 3.56 Demand and production for key materials in India, historically and in the Stated Policies and Announced Pledges Scenarios, 2015-2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; Mt of N = million tonnes of nitrogen. Ammonia demand does not include international bunkers. The figures for alumina include only metallurgical alumina.

India's output of materials is set to continue to grow with domestic demand, underpinned by its comparative advantage in steel and, to a lesser extent, aluminium and ammonia.

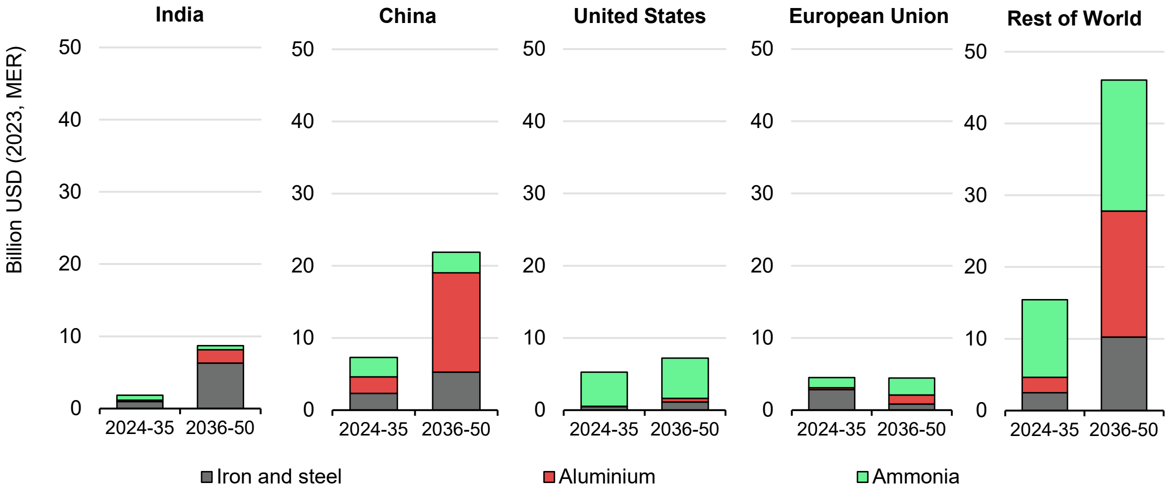
In the STEPS, production for steel, aluminium and nitrogen fertilisers grows by more than 90%, almost 70% and around 40% respectively between 2023 and 2035. It grows less rapidly in the APS, by around 85%, 60% and 35% respectively, mainly due to greater efficiency in the use of these materials. Conversely, ammonia production grows faster in the APS than in the STEPS (around 65% and 35% respectively between 2023 and 2035) thanks to higher global demand for new applications in shipping, power and as a hydrogen carrier.

India's population grew by 11% between 2012 and 2022. Over the same period, the production of wheat and rice grew by 14% and 24% respectively, mainly thanks to increasing yields (+11% and 15%) (FAO, 2023). Part of this improvement is thanks to a greater use of nitrogen-based fertilisers: India is one of the countries where demand for fertiliser has grown the most (by 12% over the ten years to 2021 compared with 4% globally). The country has historically been a net importer of ammonia and fertilisers, mostly from China and the Middle East, because low-cost coal and natural gas respectively confers a competitive advantage on those regions that is not fully compensated by India's lower labour costs. In the APS, this situation changes with the development of electrolysis-based ammonia based on the country's ample solar potential, which allow it to become a net exporter by 2035.

India imports alumina, mainly from Brazil and Australia, and produces aluminium for the domestic market and for export. In 2021, it was among the top five largest aluminium exporters in gross terms (CEPII, 2024). One contributing factor is that the country is also the world's largest aluminium scrap importer, which helps to lower production costs.

Building additional production capacity requires major investments. The investments needed in the APS for near-zero emissions materials production in India are around a quarter of those required in China to 2035. India's steel, aluminium and ammonia production are around 15%, 10% and 30% of China's today, but those shares grow to around 55%, 25% and 60% respectively by 2050 in the APS, requiring investment in near-zero emissions production in India be four times larger over the period 2035-50 compared to the period 2024-2035 (Figure 3.57).

Figure 3.57 Average annual investment in near-zero emissions materials production in India, China and the rest of the world in the Announced Pledges Scenario, 2024-2050



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Notes: Ammonia includes both energy and existing applications. Investment is defined as the annual average of overnight investments in the time period indicated.

Annual investment needs for near-zero emissions materials production in India and the rest of the world would grow significantly to 2050 assuming current climate pledges are met.

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Chapter 4: Opportunities in emerging markets

Highlights

- The clean energy transition provides an opportunity for emerging markets to establish or expand manufacturing of clean technologies and near-zero emissions materials. Those countries account for less than 5% of the global value generated in these sectors today.
- The extent to which emerging markets will be able to exploit that opportunity depends on a range of enabling factors, including the business environment, energy and transport infrastructure, and availability of resources and domestic markets. A comprehensive analysis carried out for this ETP report has identified the potential for countries in Latin America, Southeast Asia and Africa to develop manufacturing capabilities for the main clean energy technologies and materials.
- Southeast Asia has considerable potential to expand solar PV and electric vehicle (EV) manufacturing, given its skilled workforce, experience in related sectors and favourable energy resources. In the Announced Pledges Scenario (APS), Southeast Asian countries more than double their share of global solar PV wafer and polysilicon production, from 2% in 2023 to over 5% in 2035. The region produces some 5.7 million EVs by 2035 (from about 40 000 in 2023), of which about half are exported.
- Latin America has favourable enabling conditions for developing wind turbine and battery manufacturing and near-zero emissions ammonia production. Brazil produces over 5% of all wind blades today and is an important steel producer and exporter of iron ore with relevant port infrastructure. Further improving transport infrastructure and its links to manufacturing locations, as well as reducing investment risks, would contribute to Brazil fully exploiting its high potential, and increasing wind blade exports sixfold from today to 2035.
- Africa's current business environment and infrastructure, and low domestic demand, make it harder to attract large investments in manufacturing, but in some sectors and countries there are major opportunities that could support economic development and job creation. North Africa, particularly Morocco, becomes an EV manufacturing hub in the APS, exporting 65% of the 1.8 million EVs produced by 2035 to Europe and North America. Africa also builds on its iron ore and renewable energy resources to produce iron with electrolytic hydrogen. In a High Potential Case, exports to Europe, Korea and Japan reach around USD 6 billion in 2050.

The clean energy transition offers a potentially enormous economic opportunity for emerging markets.[1] Developing or expanding manufacturing industries in the area of clean energy technologies and associated materials could, in many cases, provide a springboard for economic and social development, job creation and prosperity. A growing number of emerging market economies are building up or planning to develop such capacities, but not all countries have the same starting conditions and near-term prospects, and there are few announced projects for the manufacturing of clean energy technologies in place there today.

This chapter looks at the prospects for those countries to exploit that opportunity. It first analyses the principal enabling factors across three important dimensions – business environment, energy and transport infrastructure, and resource availability and domestic markets. The enabling factor analysis is intended to reflect the current conditions in a country and avoids speculation on future developments, including those related to policies, costs and demographics. Scenario analysis is then presented to explore in detail the outlook for manufacturing clean technologies and near-zero emissions materials, based on current government ambitions and prevailing enabling conditions, as reflected in the APS, and an additional High Potential Case. This explores the potential for countries and regions that can build on their enabling conditions more effectively to reap the economic benefits from the new clean energy economy, through establishing supportive policy frameworks in order to attract investment, further enabled by international support. It focuses on the manufacturing opportunities associated with solar PV, wind, EVs[2] and batteries, and near-zero emissions iron and near-zero-emissions ammonia in Latin America, Africa and Southeast Asia.

4.1 Enabling factors for manufacturing investment

Investment decisions are largely driven by cost-related factors, but non-cost related factors can sometimes play a decisive role (see Chapter 1). In many instances, an investor is faced with a choice between two or more different locations for a new operation or expansion of an existing one. A range of enabling factors determine which location the investor ultimately chooses. We have identified 12 enabling factors, which we categorise here under the business environment, energy and transport infrastructure, and resources and domestic markets (Figure 4.1). Some of those factors that affect cost – the primary driver of the economic and financial viability of a clean energy investment – are intrinsic to a particular country, notably mineral and renewable energy resources, and proximity to overseas markets and suppliers. Other factors such as the ease of doing business may be strongly influenced by policy. Current policy settings,

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[1] The term “emerging markets” refers to new or emerging markets for clean technologies and near-zero emissions materials in this chapter, which focuses on countries in Latin America, Africa and Southeast Asia.

[2] In this publication, EV refers to electric passenger cars unless otherwise noted (see Box 1.2).

including trade agreements and production incentives, are not directly considered as an enabling factor in this analysis.

Figure 4.1 Enabling factors for establishing clean energy technology and material supply chains

Business Environment	Energy and transport infrastructure	Resources and domestic markets
• Ease of doing business • Industrial competiveness • Finance costs	• Energy infrastructure • Reliability of electricity supply • Access to low-emissions energy • Energy price • Transport infrastructure	• Resources and material inputs • Domestic demand • Market size of related industries • Workforce skills/human capital

Notes: Indicators for each enabling factor are described in the Annex. The indicators are meant to reflect the current status of enabling conditions.

Investment decisions about new manufacturing facilities are determined by several factors related to the business environment and access to infrastructure, resources and markets.

The specific indicators used to assess some of these factors cut across manufacturing supply chain segments and the type of clean technology product being manufactured. The overall business environment in a country will always be a consideration regardless of the technology. Indicators on political stability, ease of doing business and the cost of financing, obtained mainly from the World Bank, are here used to assess the business environment.[3] Access to energy and transport infrastructure can be essential to ensure smooth operations along the supply chain, from resource extraction and transformation to transporting manufactured goods domestically and exporting them. Site selection may also depend on supply-chain specific factors like the availability of raw and manufactured material inputs for a particular product, especially where they cannot easily be imported. Businesses may also choose to locate where there is significant demand for their product, or where there is a competitive pre-existing industry or similar industry, which may give confidence to new market entrants.

The importance of each of these enabling factors varies depending on the specific technology or commodity, and the respective step in the manufacturing supply chain (Table 4.1). The assessment presented here is based both on expert judgement and information gathered in industry surveys, including the IEA survey of the factors driving investment in manufacturing (see Chapter 1). For example, the energy- and labour-intensity of a given manufacturing process can determine the relative

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[3] See the Annex for a full list of indicators and sources.

importance of the associated costs; energy prices are relatively important for the energy-intensive manufacturing processes such as those used to make polysilicon for solar PV, while workforce skills are relatively more important for high-tech manufacturing such as making batteries. The ease of doing business and industrial competitiveness have been evaluated as moderate to high importance for manufacturing across the selected clean technologies and materials.

Based on the relative importance of each of the enabling factors set out in Table 4.1, we have systematically reviewed the degree to which these enabling conditions for the manufacturing of various clean technologies and materials apply to selected emerging markets. The results indicate the countries' relative strengths with respect to the enabling factors by clean technology and material. The analysis was carried out for all countries in Latin America,[4] Africa and Southeast Asia. These regions were selected as they are markets for which demand for the selected clean energy technologies and materials is growing but current manufacturing capacity is low. The results may not be perfectly aligned with actual investment decisions, as selection criteria and priorities may differ by decision maker and the indicator proxies for various enabling conditions may be imperfect or incomplete.

A large number of indicators and datasets were used to assess how well each country performs with respect to the enabling factors, which are then weighted according to their importance for each technology/material. For example, two indicators – the system average interruption duration index and the system average interruption frequency index – are used to assess the reliability of electricity supply as an enabling factor. In some cases, different indicators are relevant for assessing the enabling conditions of the various commodities or technologies. For example, the availability of lithium reserves is important for manufacturing batteries but is irrelevant for the production of near-zero emissions ammonia. For other enabling factors, the same indicators can be used across all clean commodities or technologies. This is particularly true for political stability and corruption, and overall ease of doing business, as well as financing costs. Countries that feature prominently with respect to these cross-cutting factors are better placed to attract investment, though the importance of these factors varies across technologies and materials. A comprehensive description of the methodology is detailed in Box 4.1, and a full list of indicators, sources and coverage can be found in the Annex.

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[4] While other chapters present projections for Central and South America, which does not include Mexico (instead included in North America), this chapter focuses on Latin America, which does include Mexico.

Table 4.1 Relative importance of enabling factors for manufacturing selected clean technologies and materials

Category	Enabling factor	Solar PV	Wind	EVs	Batteries	Steel	Ammonia
Business environment	Ease of doing business	◑	◑	◑	◕	◑	◑
	Industrial competitiveness	◕	◔	◕	◕	◑	◑
	Financing cost	◔	◑	◔	◔	◕	◕
Energy and transport infrastructure	Energy infrastructure	◕	◑	◔	●	◑	◑
	Reliability of electricity supply	◕	○	◑	◕	◔	◔
	Access to low-emissions energy	◑	○	○	◑	●	●
	Energy prices	●	◔	◔	◕	●	◕
	Transport infrastructure	●	●	●	◔	●	◕
Resource availability and domestic markets	Resources and material inputs	◔	●	●	●	◕	◔
	Domestic demand	◕	●	◕	◔	◕	●
	Market size of related industries	◑	◔	◕	◑	◑	◕
	Workforce skills / human capital	◑	◕	◑	◕	◔	◑

Notes: The shading of icons indicates the level of importance from relatively low (○) to high (●), which are translated into weights for the enabling factor analysis (see Box 4.1). Relative importance levels have been evaluated based on expert elicitation for each specific technology or material and should not be compared across technologies and materials. A description of the indicators used for each enabling factor is included in the Annex.

Box 4.1 Methodology for assessing enabling conditions for investment in the manufacturing of clean technologies and materials

We have developed a methodology to assess the attractiveness of a country to investors in manufacturing clean energy technologies and near-zero emissions materials based on a number of key enabling factors. The methodology entails the following steps:

Identification of enabling condition indicators: Quantitative indicators were identified to reflect relevant conditions for investment decisions. A total of 63 indicators were identified and grouped within the 12 enabling factors under the three categories of business environment, energy and transport infrastructure, and resources and domestic markets. The indicators were chosen to represent the wide range of considerations for the development of a project. The datasets used for each indicator are drawn from various entities. The ease of doing business enabling factor, for example, is composed of three indicators: the World Bank's *Ease of doing business* and *Political stability* indexes and Transparency Internationals' *Corruption perception indicator.* Most indicators within the categories "Business Environment" and "Energy and Transport Infrastructure" are cross-cutting and are applied across all supply chains, while indicators within the "Resource Availability and Domestic Markets" category are supply-chain specific. In total, the number of indicators that are considered for each supply chain varies between 29 and 39.

Data collection by indicator: Data was collected for each indicator for all countries within the three study regions: Latin America, Africa, and Southeast Asia. Comprehensive and reliable data was not always available. A lack of data was most prevalent among African countries. To make the assessment as comprehensive as possible, data was collected for 2018-2023, with priority given to more recent datasets.

Normalisation of indicator data and aggregation: The data collected for each indicator are normalised across countries to a value range of [0-1]. Advanced economies, including the United States, Japan and Germany, are used to provide the benchmark indicator values. The normalised values of all indicators for an overarching enabling factor are averaged to obtain one value [0-1] per enabling factor and country.

Evaluation of importance of enabling conditions. Each enabling factor is given an importance grade that is unique for each supply chain, with values ranging from 1 (least important) to 5 (most important). Indicators that are not relevant for a specific supply chain were omitted. These gradings were based on expert judgement and on information gathered in industry surveys.

Determination of total opportunity score. For all enabling factors within a supply chain, the averaged normalised enabling factor value is multiplied by the corresponding importance rating. The total opportunity value for each country is calculated for each technology or material by adding the weighted values for all enabling factors together.

The assessment should not be interpreted as a definitive judgement of a region's long-term potential to become a major new manufacturing hub for clean energy technologies. The analysis is based on the selected countries' *current* performance with respect to a number of varied indicators. In particular, effective policy action could address specific barriers to competitiveness and investment, such as labour market measures to reduce shortages of qualified personnel or regulatory reforms to strengthen the reliability of electricity supply, thereby improving a country's attractiveness to investors in the future. The assessment can, therefore, be seen as an indication of the size of the task facing emerging markets in exploiting opportunities for taking a stake in the new clean energy economy.

Business environment

A predictable, stable and effective regulatory and political environment increases the attractiveness of investing in new clean energy supply chain infrastructure in a given country, by boosting investors' confidence in obtaining the required rate of return and providing clarity over future revenues. Political risks can cause delays or postponements in energy investments, and slow down economic development, increasing the probability that the investment will not turn a profit. Perceptions of potential conflict can disrupt investment in clean energy. For example, a large-scale solar PV investment close to the Türkiye-Syria border was halted in 2022 due to the threat of war. Such threats can also increase insurance costs for investors, reduce the overall bankability of projects and cause firms to postpone outlays until the risk is reduced.

Attracting capital to develop new manufacturing infrastructure requires a conducive, positive business environment – the combined outcome of simplified laws, rules, and regulations, a streamlined taxation process, and developed infrastructural facilities such as transportation, law and order, banking and financial systems. A level and equitable playing field for the private sector plays a crucial role. The ease of doing business in a country has an outsize impact on inward foreign direct investment in emerging markets. These considerations are taken into account when assessing the ease of doing business, based on a number of indicators published by the World Bank.

Industrial competitiveness describes a nation's capability to strengthen its position in global and regional markets by developing industrial sectors and activities that generate higher value added and integrate more advanced technology into their economic activities. Estimating a country's industrial competitiveness involves assessing the competitiveness of its labour costs, the complexity of its economic make-up and its current trade activity.

Investments in new clean energy supply chains require substantial upfront capital investments, often balanced out in the long run by reduced operational and fuel costs. While equity is not in short supply in most emerging markets, investors there typically demand higher returns than in advanced economies (IEA, 2021a). Developing new clean energy manufacturing hubs entails a transition towards a capital-intensive investment framework that underscores the importance of maintaining low financing costs for firms.

The overall cost of capital in emerging markets and developing economies (excluding China)[1] is higher compared to advanced economies due to the level of domestic financial system development and a range of country risk factors. Economy-wide financing costs in emerging markets and developing economies (EMDE) as a whole range between 7% to 15% – seven times higher than in the United States and Europe – with rates highest in riskier supply chain segments (IEA, 2021a). Yet financing costs carry an outsized importance in these countries: EMDEs today rely heavily on public sources of finance, but over 70% of clean energy investments cumulatively to 2035 in all three of our scenarios are privately financed. The share of clean energy investment financed through debt is highest in the Net Zero Emissions by 2050 Scenario (NZE Scenario) (IEA, 2024a), yet debt finance is more constrained in the EMDEs as local banking sectors often lack the necessary capabilities and experience to evaluate clean energy projects. This underscores the importance of reducing the hurdles facing domestic and foreign investors in accessing low-cost capital.

There is considerable variation in the scores for each of the components of the business environment for clean energy investments in our assessment. Countries in Southeast Asia generally score high for all business environment enabling factors, while parts of Latin America and Africa stand out in ease of doing business (Argentina, Chile, South Africa) and industrial competitiveness (Brazil, Mexico) (Figure 4.2). Southeast Asia has some of the highest scores for logistics, shares of high technology manufacturing exports and manufacturing and trade volumes. Generally, African countries score lowest for their current industrial competitiveness, but the spread in the region is high – Egypt and South Africa score higher than all but four Latin American countries.

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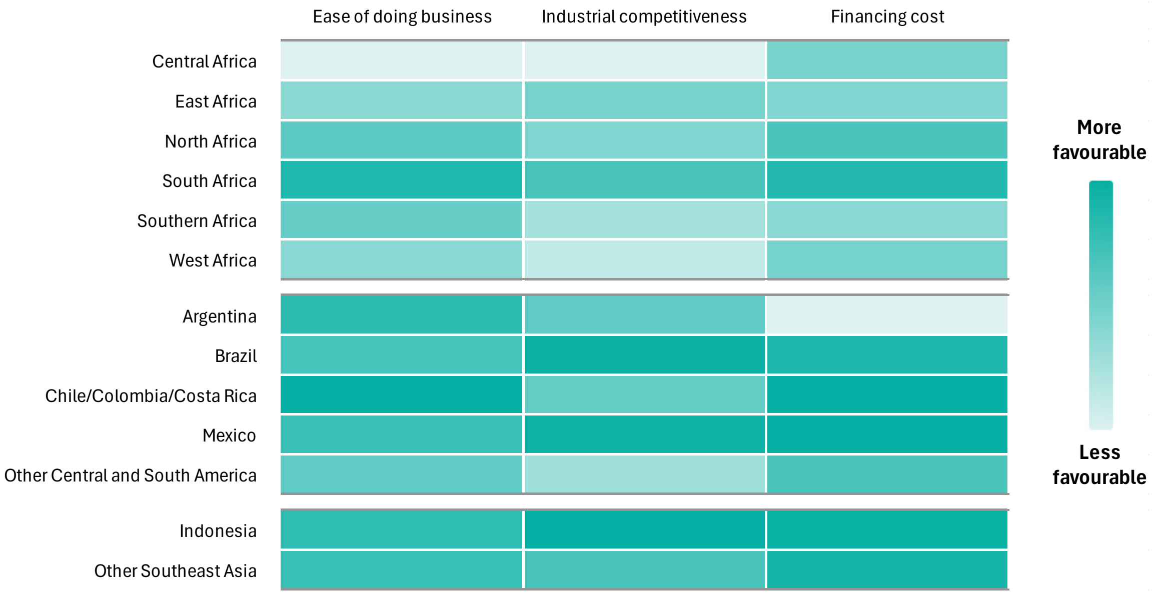
[1] Emerging market and developing economies exclude China in the rest of this chapter unless otherwise stated.

Figure 4.2 Current status of enabling factors for business environment by country/region



IEA. CC BY 4.0.

Note: Indicators for each enabling factor are described in the Annex.

Countries in Southeast Asia score high in all business environment enabling factors, while there is a greater spread of values for Africa and Latin America.

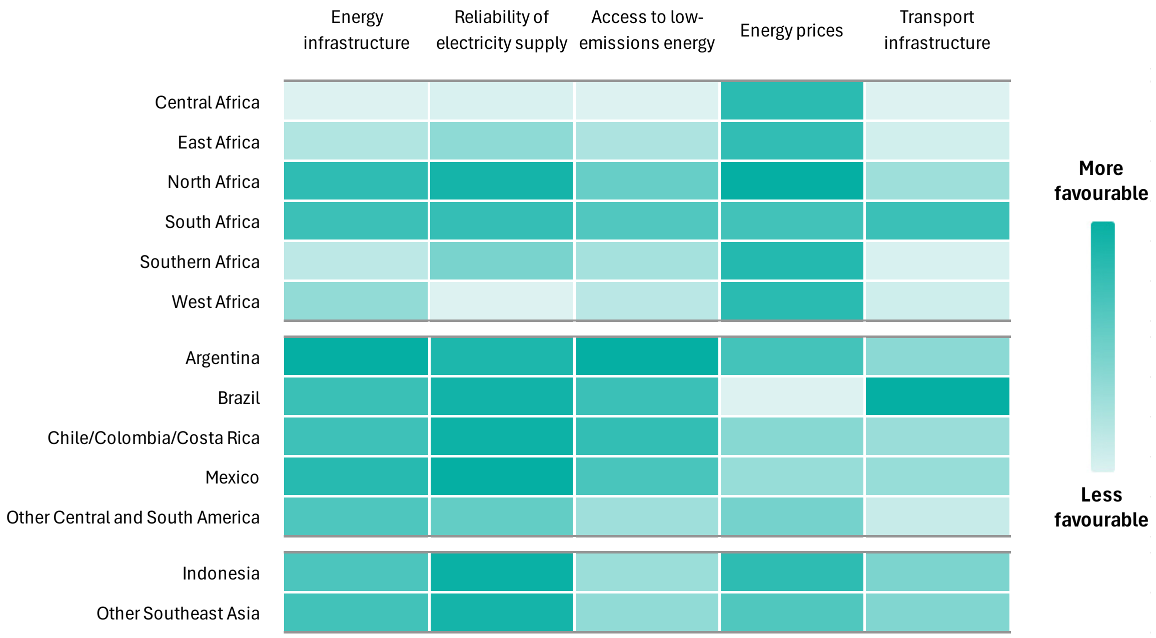
While the economy-wide cost of finance is consistently highest in West and Central Africa, Latin America presents a more varied picture: Ecuador and Argentina have some of the highest financing costs in the world, while the cost of capital in Chile, Peru and Mexico is close to that in advanced economies. Some of these discrepancies are compensated by the "ease of doing business" enabling factor, as it includes the access to (as opposed to simply the cost of) finance – which can be poor in countries with relatively low costs of finance.

Energy and transport infrastructure

Clean technology manufacturing can involve energy-intensive processes, making access to reliable and competitively priced energy supplies a vital consideration for investors. It may also call for a significant expansion of low-emissions power generation and widespread grid reinforcements. Regions that benefit from abundant renewable energy resources and which have existing robust energy infrastructure have a clear competitive advantage, even if a manufacturing site might pursue captive power generation or its own microgrid system. Access to transport infrastructure is another important factor, especially in the case of clean energy technologies and related materials that are destined for export. Having existing, well-connected and efficient transport infrastructure can give countries a leg-up when developing new manufacturing hubs by reducing the need for additional investment and reducing the time needed to bring new supply onstream.

We have compiled data on five enabling factors related to the quality of energy and transport infrastructure: the availability of both types of infrastructure, the reliability of electricity supply, access to low-emissions energy and energy prices (Figure 4.3). Access to reliable energy and transport infrastructure varies greatly among the regions assessed. Several countries, notably in Latin America, have relatively good energy infrastructure, but poor transport infrastructure. In Africa, many countries currently have limited access to electricity and other forms of modern energy compared with the rest of the world. Financing difficulties, poor regulatory frameworks and below-cost tariffs are major barriers to attracting much-needed investment in the electricity sector across the continent.

Figure 4.3 Current status of enabling factors for energy and transport infrastructure by country/region



IEA. CC BY 4.0.

Note: Indicators for each enabling factor are described in the Annex.

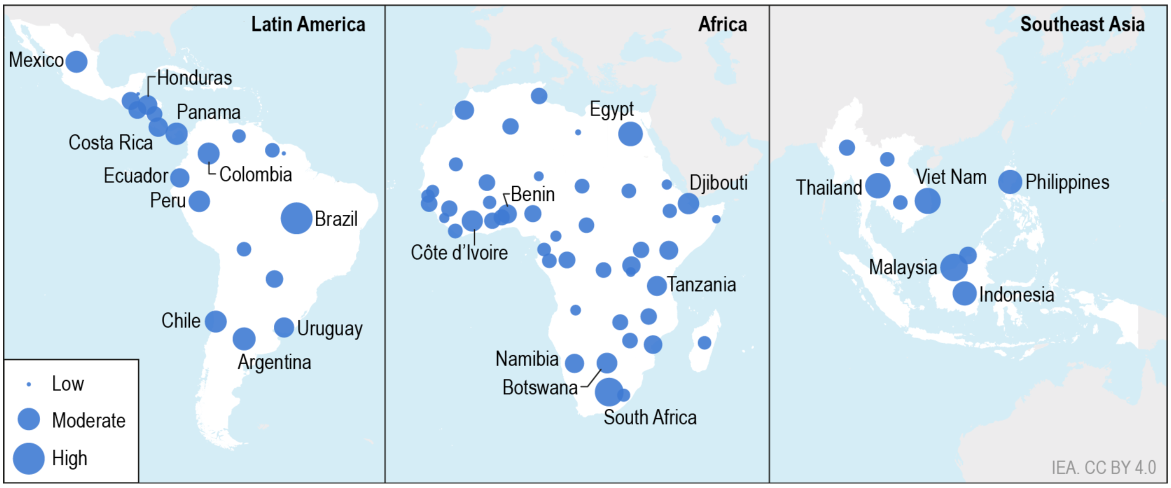
Access to good energy and transport infrastructure varies greatly, with South Africa enjoying favourable conditions across all indicators.

Among the energy and transport factors, energy prices vary largely across regions and countries, reflecting various elements, including the availability of energy resources, subsidy policies and transmission and distribution costs, while the reliability of electricity supply is consistently high for all regions except West and Central Africa. The situation is somewhat better in East African countries, which have been working hard to build a regional electricity pool to connect more customers to the grid and spur industrial and economic growth in the region. They have increased their installed capacity, but delays in building transmission lines have increased the risk of financial losses for generators, due to the inability to trade excess energy.

The availability of renewable and other low-emissions energy resources can indicate which regions have the greatest long-term potential to produce clean materials and technologies. Endowments vary enormously among regions and by resource. Brazil has substantial bioenergy potential and North Africa strong solar generation potential, while Argentina has good onshore and offshore wind resources. In particular, offshore wind could make coastal regions near ports attractive for establishing clean technology and material manufacturing hubs. In addition to solar and wind potential, countries that lie along major tectonic plate boundaries have additional geothermal potential, though it is generally tiny compared with wind and solar. Hydropower is a mature renewable energy resource that has already been widely exploited in many of the countries assessed here. In Paraguay, Brazil, Zambia and Ethiopia, hydropower is still a major source of power generation (IEA, 2021b).

Africa and, to a lesser extent, Latin America, have less access to transport infrastructure than other regions (Figure 4.4). In particular, capacity of dry bulk and port liners is very low compared with the United States and Japan. Brazil and South Africa are the main exceptions, with both being major trade hubs. Brazil's dry bulk port capacity, at 1.5 Gt/yr, is comparable to that of the United States. In many cases, the lack of access is explained by the fact that countries are landlocked, though good road and rail infrastructure, as well as favourable regional agreements, compensates for this in some cases. Good road and rail links can provide an opportunity to explore regional synergies between landlocked countries that have a significant raw material availability, such as Bolivia, and neighbouring countries that have existing port infrastructure.

Figure 4.4 Status of transport infrastructure in Latin America, Africa and Southeast Asia



Notes: This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA analysis based on MDST port container spare capacity assessment MDS Transmodal Ltd. (2024); World Bank's logistics performance index (2023); and Vershuur et al. (2022).

Brazil stands out for its robust transport infrastructure, thanks mainly to its large dry bulk port capacity, which is comparable to that of the United States.

Resource availability and domestic markets

Mineral and other endowments, along with domestic markets, are also important factors in attracting investment in clean technology and materials manufacturing. In contrast to the two other categories of enabling factors, which affect investment decisions across a wide range of economic activities, the relevant resources and domestic markets that serve as enabling factors are very specific to the supply chains of clean energy technologies.

We have identified four enabling factors here: the availability of resources and material inputs, the level of domestic demand, the market size of related industries and workforce skills. Resources, such as iron ore deposits for iron and steel production and lithium for EV batteries, can increase the attractiveness of establishing those industries. Of course, the more easily and cheaply resources can be transported and traded internationally, the less of a requirement domestic availability may be. Similarly, the importance of the size of the domestic market varies according to the type of technology or material and how easy and costly it is to export, while having existing industries with similar characteristics is likely to be more important for some technologies/materials than for others. Likewise, the workforce characteristics desired may also vary based on the industry. While low labour costs can be an advantage for lowering the costs of production, clean technology manufacturing and near-zero emissions material production may require particular skillsets. For example, good availability of technical skills would be considered valuable for the upstream stages of PV and EV manufacturing, but less so for module or vehicle assembly.

Given the specificity of the various indicators for resource availability and domestic markets for different supply chains, we describe the relevant indicators and regional favourability across this category of enabling factors in the following technology-specific sections.

4.2 The prospects for manufacturing

A number of countries in Latin America, Africa and Southeast Asia hold large deposits of the critical minerals needed to support the clean energy transition. Many of them have been seeking to develop mines and expand existing ones to meet rapidly growing demand. For example, Brazil recently announced the launch of the Strategic Minerals Investment Fund, which aims to raise over USD 200 million to promote new mineral ventures that are essential for the energy transition, decarbonisation and sustainable food production (International Trade Administration, US DOC, 2024).

An increasing number of countries are also looking to move further down the supply chain, notably by developing mineral processing facilities and manufacturing technologies and components that require those minerals. Other strategies go beyond mineral resource endowments and look to capitalise on renewable energy resources for the production of clean technologies and near-zero emissions materials as a means to foster economic development and job creation. Some efforts are focused on a specific part of the supply chain of a particular technology, while others aim to develop full supply chains across multiple technologies. Examples of recent efforts to develop clean energy manufacturing include the following:

- Malaysia (Malaysian Investment Development Authority, 2023) and Nigeria (PV-Tech, 2023) are both looking to further vertically integrate their solar PV supply chains, moving beyond just solar PV module and cell manufacturing.
- Chile has signed an agreement with the European Union to encourage investment in the country's supply chains for wind and other clean energy technologies, leveraging lithium resources among other factors (EC, 2023).
- Indonesia is aiming to develop EV and battery supply chains to take advantage of its nickel and other natural resources (Indonesia Central Government, 2019).
- Mauritania is moving from exporting iron ore to producing hot briquetted iron or finalised steel products (CWP Global, 2024).
- Namibia aspires to take advantage of its renewable energy resources to develop low-emissions hydrogen-based products, including ammonia and fertilisers (Ministry of Mines and Energy of Namibia, 2022).

The prospects for emerging markets, individually and collectively, to exploit the opportunities associated with the growing global demand for clean energy technologies and their material inputs depend not only on existing policies and projects, but also on the prevalent enabling conditions discussed above. While geography and geology determine resource endowments, government policies will be central to exploiting the others. Collaboration and partnerships with advanced economies can also play a role in building out clean energy supply chains in EMDEs through the provision of technical, financial and policy support. For example, a recently announced collaborative initiative between the United States and India seeks to cooperate with and support clean energy projects in African countries (The White House, 2024). The growing role of EMDEs in clean energy technology manufacturing across the scenario projections reflects the relative strength of policy action to realise ambitions and unlock opportunities associated with the transition to net zero (Figure 4.5).

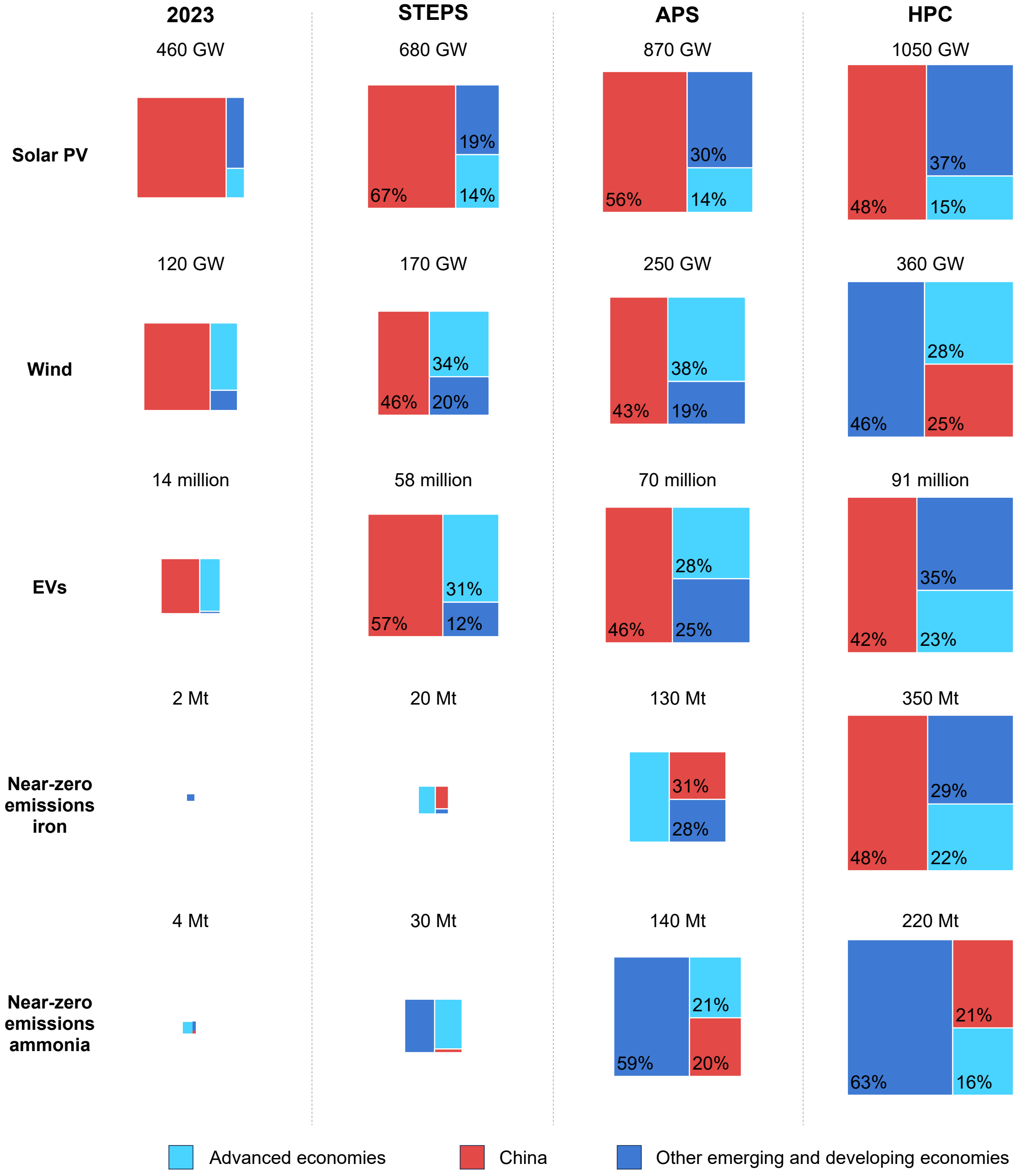
The following sections explore the manufacturing and trade prospects for EMDEs by technology using the APS, which takes account of government energy and climate policy goals, announced manufacturing projects and industrial policies, as well as the enabling conditions in EMDEs more broadly. The results reveal the priority economic opportunities for EMDEs on the basis of policies and enabling conditions as they are in place today.

However, even in the APS many countries remain left behind in reaping the economic benefits of the new energy economy. In the APS, one-fifth of the value generated from the manufacturing of clean energy technologies and near-zero emissions materials in 2035 takes place in EMDEs excluding China, up from less than 5% today. This is partly because the manufacturing pipeline in China and advanced economies is already very large, making it difficult for new market entrants to compete. In addition, many EMDEs currently lack access to finance and adequate institutional frameworks to fully exploit their competitive advantages.

For this reason, the analysis of the APS is complemented by an additional High Potential Case to identify further opportunities for emerging markets to build out their clean energy manufacturing sectors to 2050. In this Case, global demand for clean energy technologies and near-zero emissions materials is assumed to be compatible with the energy sector reaching net zero emissions by 2050, i.e. higher than in the APS. This means that the High Potential Case reflects an upside potential for the manufacturing of these technologies and materials, and that a growing role (and share) of production in emerging markets generally does not require lower production volumes in other regions. The Case further assumes that emerging markets succeed in overcoming barriers to exploiting all their competitive advantages in manufacturing a targeted scope of clean technologies and near-zero emissions materials, tailored to their respective high potential areas and enabled by international support mechanisms.

The results of the High Potential Case are presented alongside the detailed projections for the APS in the following sections on solar PV, wind turbines, EVs and batteries, near-zero emissions iron and ammonia, focusing in each case on the regions where large opportunities have been identified.

Figure 4.5 Regional/country shares in clean technology production in the Stated Policies Scenario, Announced Pledges Scenario and High Potential Case, 2023-2035



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; HPC = High Potential Case; EV = electric vehicle. Solar PV refers to module production; wind refers to nacelle production.

China is a leader in clean energy technology manufacturing today, but the role of other EMDEs could grow beyond that envisaged by today's policy settings.

Solar PV

Technology-specific enabling factors

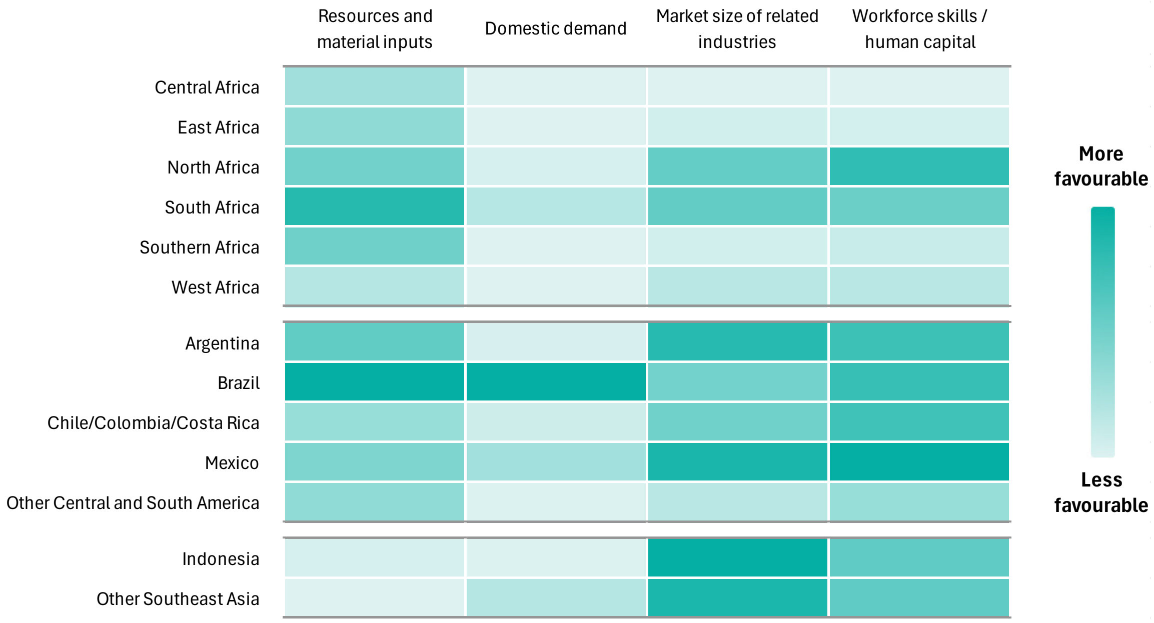
Today, EMDEs, apart from China, make a relatively small contribution to global production of the four key solar PV manufacturing segments – polysilicon, wafers, cells and modules – with most countries concentrating their activities in the two latter stages: cell and module assembly. Half of all cell and module production outside China is in Thailand and Viet Nam, with negligible capacity in other EMDEs. Malaysia is one of the few EMDEs with significant polysilicon production capacity, accounting for around 2% of global production. However, a growing number of EMDEs are in the process of expanding, especially Malaysia, Viet Nam and Indonesia, in Southeast Asia, where additional capacity commitments have reached 17 GW for wafers and 1 GW for polysilicon, in addition to the observed growth in the last couple of years. Nigeria has broken ground on a vertically integrated plant that will eventually have a nameplate capacity of 50 MW for ingots, wafers and cells, and 1 kt of polysilicon (PV-Tech, 2023).

The availability of low-cost, reliable electricity has been the main factor constraining the growth rate of polysilicon and wafer capacity beyond existing markets. The average electricity price for solar PV manufacturers is estimated at USD 90/MWh globally; we estimate that less than a quarter of countries across Latin America, Africa and Southeast Asia currently have lower prices (based on standard industrial rates). They include Algeria, Angola, Ethiopia and Nigeria in Africa; Argentina and Paraguay in Latin America; and Indonesia and Viet Nam in Southeast Asia. Nonetheless, other countries could potentially achieve lower prices in the future by generating renewable electricity onsite (autogeneration): large-scale solar PV plants and wind farms are capable of producing electricity at costs that are well below current industrial retail prices in most countries. Polysilicon and wafer/ingot production typically require a continuous load, so countries with geothermal and hydropower resources are better positioned to autogenerate in these sectors. Elsewhere, storage would be needed in the case of 100% reliance on onsite generation, raising electricity supply costs substantially.

Due to the highly electricity-intensive nature of solar PV manufacturing, there could also be interest in regions with lower carbon intensity to reshore manufacturing. A number of countries, including France and Korea, are introducing the embodied carbon footprint of panels in their competitive tender processes for new large-scale installations, while the European Union is evaluating its policies on embedded intensity for imported renewable energy products. At present, 24 countries in Africa and 17 in Latin America have a lower average grid carbon intensity than today's global average of 452 grammes of carbon dioxide per kilowatt-hour (g CO_2/kWh).

Polysilicon production can leverage its strong synergies with related industries, notably semiconductors and chemicals (Figure 4.6). Countries with a strong base in these industries include Malaysia, the Philippines, Thailand and Morocco. They could co-locate related polysilicon plants with these industries to pool skills and share infrastructure, lowering costs through economies of scale. Co-locating other facilities, such as electrolysis and other manufacturing plants, could further reduce electricity costs by optimising consumption patterns. Wafer production could also benefit from co-location with related industries, notably high-tech goods. Cost- competitiveness is particularly critical for wafer production, as much of the current capacity is concentrated in a few regions that already enjoy long-standing economies of scale, making it hard for new market entrants to compete on cost alone. Several countries in Southeast Asia with existing wafer production plants, including Indonesia, Malaysia and Viet Nam (which are among the global top ten producers), are best-placed to expand capacity.

Figure 4.6 Current status of enabling factors for resource availability and domestic markets for solar PV manufacturing by country/region



IEA. CC BY 4.0.

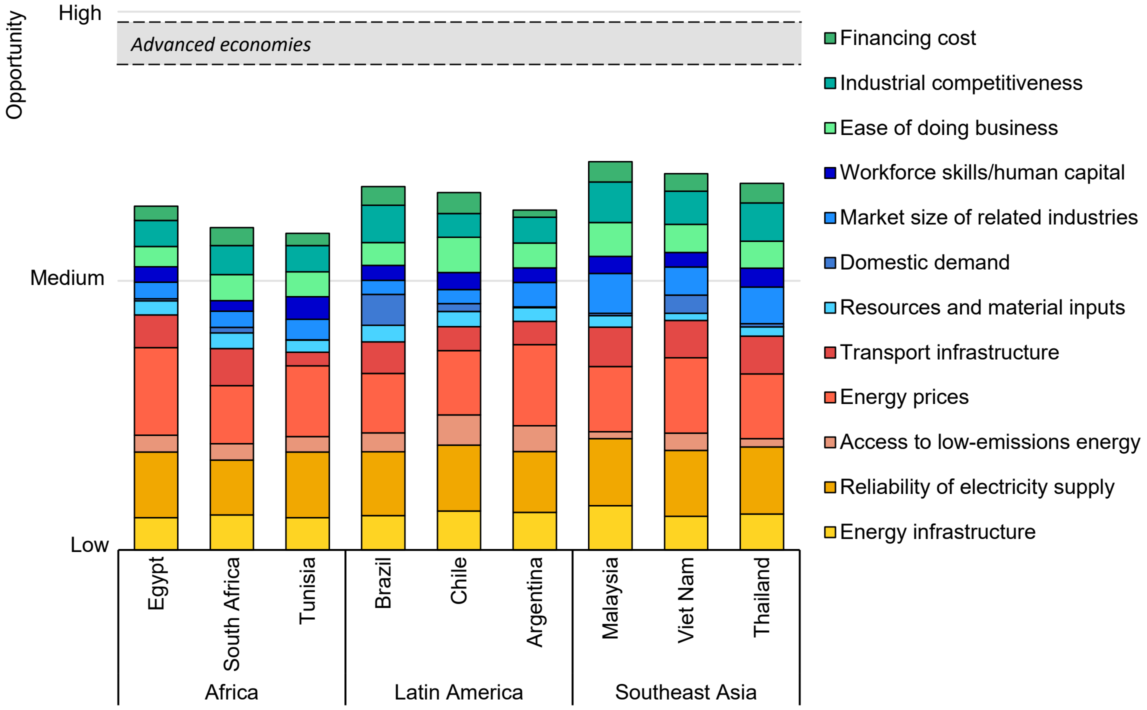
Note: Indicators for each enabling factor are described in the Annex.

Southeast Asia has favourable conditions for PV manufacturing considering synergies with current industrial activities, while Brazil stands out for its domestic demand.

Developing new solar PV manufacturing activities requires a range of workers with different skills, from assemblers to production engineers. Polysilicon and wafer production facilities operate in large batches that require less manual work, and consequently involve fewer jobs. However, these steps require higher technical knowledge. Polysilicon production, in particular, is a complex process based on heavy chemical industrial processes, favouring countries with an established industrial capacity and skilled workforce in the chemical sector.

Unsurprisingly, countries in Southeast Asia have the best overall enabling conditions for solar PV manufacturing (Figure 4.7). Their relatively low energy prices, robust energy and transport infrastructure and industrial competitiveness have already made the countries in the region important manufacturing hubs for exporting products of significant complexity. Malaysia already has significant polysilicon production capacity and scores relatively well in terms of industrial competitiveness and related industry experience. Viet Nam and Thailand also have strong transport infrastructure and relatively low electricity prices. In Latin America, Brazil scores highest thanks to its large domestic demand, while Chile has a relatively large share of low-emissions energy consumption today.

Figure 4.7 Top three scoring countries for enabling factors for solar PV polysilicon and wafer manufacturing in Africa, Latin America and Southeast Asia



Notes: The size of each column segment is proportional to the combination of how well a country scores on a specific enabling factor and the relative importance of the factor. The range for advanced economies is based on the assessment of enabling factors in the United States, Germany and Japan. The results of this enabling factor analysis should not be interpreted as indicating the only countries in these regions with opportunities for manufacturing. A comprehensive description of the methodology is detailed in Box 4.1, and a full list of indicators, sources and coverage can be found in the Annex.

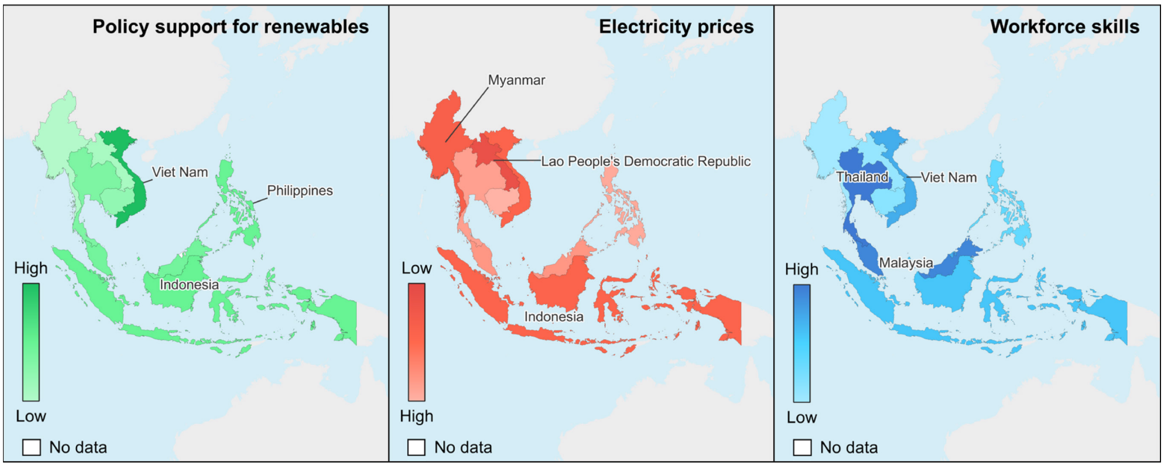
Competitive electricity prices and reliable electricity supply are the main determinants of the potential of countries to attract investment in solar PV manufacturing.

Opportunities for solar PV wafer and polysilicon manufacturing in Southeast Asia

Our analysis suggests that enabling conditions for attracting investment in the solar PV sector are most favourable for wafer and polysilicon manufacturing in Southeast Asia. The region is already a net exporter of some segments of the solar PV supply chain, and accounts for around 10% of global solar PV cell and module supply. Viet Nam (4%), Thailand (2.5%), and Malaysia (1.5%) already have significant manufacturing capacities, most of which were developed by Chinese companies for exports to the United States. However, the region as a whole hosts only around 2% polysilicon capacity (concentrated in Malaysia) and 3% of wafers (centred in Viet Nam and Malaysia). In contrast, total domestic demand for solar PV across the region, at around 3 GW per year, is over 30 and over 20 times lower than its module and cell supply capacities, such that virtually all modules output is exported.

Several countries in the region have strong enabling conditions for manufacturing of solar PV wafers and polysilicon (Figure 4.8). This is particularly the case where there is a skilled workforce, high levels of activity in sectors that have potential synergies with PV production, rapidly growing domestic demand, supportive energy fundamentals, a business environment conducive to clean energy investment, and low costs of debt financing. Southeast Asia has the potential to exploit its favourable conditions and existing capacity in selected PV supply chain segments to build out a vertically integrated supply chain that regionally concentrates upstream wafer and polysilicon manufacturing. It could become one of the cheapest places in the world to produce polysilicon and wafers by 2035, largely due to its low energy prices.

Figure 4.8 Key enabling factors and indicators for PV supply chains in Southeast Asia



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Notes: This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Policy support for renewables refers to the Regulatory Indicators for Sustainable Energy (RISE) indicator set; workforce skills refers to the average of the indicators for the workforce skills/human capital enabling factor.

Sources: IEA analysis based on data from World Bank (2021); IEA (2024b); Global Petrol Prices (2023); WIPO (2024); ILO (2024); and UNESCO (2024).

Several Southeast Asian countries benefit from favourable conditions for developing solar PV supply chains.

In the **STEPS**, the expansion of solar PV manufacturing capacity out to 2035 is lower in Southeast Asia than in other EMDE regions, as policies in place today are insufficient to exploit the potential we have identified. The region remains second to China in manufacturing capacity for modules and cells, ahead of the United States and India. Production drops by more than 40% for modules between 2023 and 2035, but almost doubles for cells and triples on average for wafers and polysilicon (albeit from a low base). In general, policy support in Southeast Asian countries does not target solar PV manufacturing specifically, but takes the form of broader tax incentives, land and labour provisions, or special economic zone arrangements aimed at encouraging manufacturing in general.

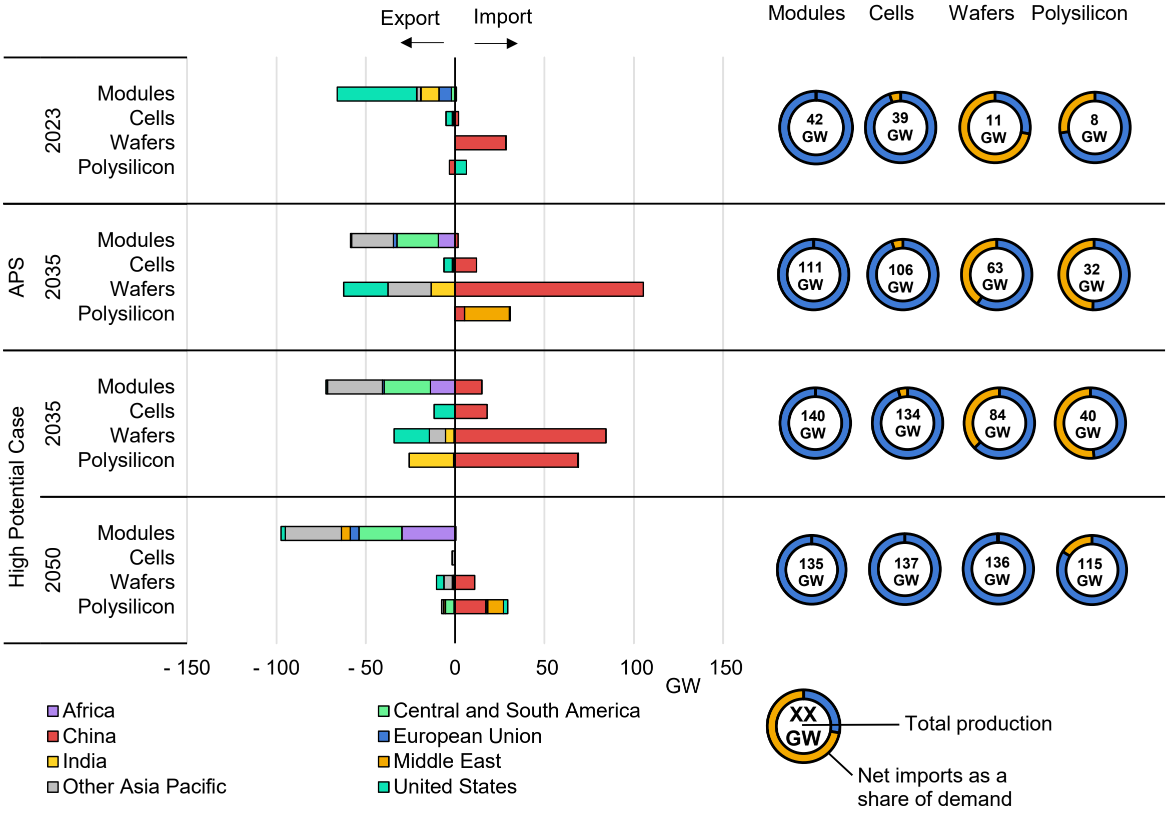
Malaysia offers tax incentives and preferential financing arrangements to promote investment. For example, the Green Technology Financing Scheme provides preferential interest rates and government guarantees for investments in green technology (Malaysian Sustainable Finance Initiative, 2020). Corporate tax breaks are available for new large foreign investors, projects of national importance, and high-technology companies. Indonesia's long-term Electricity Business Plan (RUPTL) directs the country's electricity capacity. According to this plan, solar PV is projected to contribute approximately 5 GW by 2030; it mandated a 20% local content requirement for components in the solar PV value chain, implemented in 2022. The ambitions of neighbouring, land-constrained Singapore also weigh heavily for Indonesia: Singapore’s Energy Market Authority has launched a series of requests for proposals to import 4 GW of low-emissions electricity by 2035 through cross-border trade (Energy Market Authority of Singapore, 2024).

Support for scaling up domestic demand elsewhere in the region is more varied. Viet Nam has a generous feed-in-tariff for solar (USD 51/MWh for ground and USD 65/MWh for floating solar plants, above the unit cost of solar PV in the country). Thailand has ambitious plans to build 2.7 GW of floating solar PV on reservoirs by 2037 – 2 of the 16 facilities planned have been built to date.

In the **APS**, which takes into account policy goals to expand renewable electricity output, solar PV capacity additions across Southeast Asia increase by about 25 times between 2023 and 2035, reaching 45 GW from less than 2 GW in 2023 (Figure 4.9). This anchors growth in the region’s manufacturing capacity in the short-term, vertical integration of PV supply chains in Southeast Asia, which is able to serve fast-growing domestic and export demand. Export of PV modules to the advanced economies and other EMDEs that currently have neither existing manufacturing capacity nor announced additions, and are therefore expected to require imports to meet future domestic demand, reach 6-7% of global demand by 2035. Thereafter, those exports fall as more regions develop domestic capacity to serve their domestic markets, and pick up again following the global demand increase.

Through to 2035, the region retains a competitive advantage, driven by favourable cost fundamentals, and in particular by the development of a robust wafer and polysilicon industry. The share of global polysilicon production hosted by Southeast Asia doubles, while its share of wafers triples, with few countries in other regions entering those sectors. The region achieves a lower cost of production of polysilicon than China by 2035.

Figure 4.9 Market for PV modules and components in Southeast Asia in the Announced Pledges Scenario and High Potential Case, 2035-2050



IEA. CC BY 4.0.

Notes: APS = Announced Pledges Scenario. Demand for components that are not the final product are determined by the production of the subsequent component. Import and export refer to net trade flows between Southeast Asia and each of the regions displayed, while net imports as a share of demand refers to the net imports to Southeast Asia accounting for all regions as a share of domestic demand.

Southeast Asia expands its upstream solar PV capacity in the APS, based on low energy prices, fast-growing domestic demand and a favourable industrial base.

Southeast Asia has the potential to play an even bigger role in solar PV supply chains in the long run than projected in the APS. In the **High Potential Case**, domestic production of modules, cells, wafers and polysilicon is 25-35% higher than in the APS in 2035. In this case, domestic manufacturing of wafers and polysilicon grows a further 60% and 185% in 2050, respectively, compared to in 2035, meeting over 80% of domestic demand. For polysilicon in particular, Southeast Asia's share of global production increases from less than 2% today to over 10% in 2050 in the High Potential Case; for wafers, the share in global production grows more than sixfold. Most of this production remains in the region, supporting the vertically integrated manufacturing of modules, while any polysilicon imports primarily come from China and the Middle East.

Unlocking this potential hinges on a number of factors, notably policy measures to bolster demand for solar PV installations across the region to underpin investments in domestic manufacturing. In Viet Nam, the new National Power Development Plan envisages substantial increases in capacity deployment, but there remain policy gaps that hinder project development (IEA, 2024c). In Thailand, policy support has been limited and so only modest capacity additions are currently anticipated for distributed PV. The Philippines introduced an auction programme in 2022 that is expected to significantly boost utility-scale PV, but grid delays are likely to constrain growth.

Grid capacity would also need to be reinforced, to support both new manufacturing capacity and domestic demand growth. The Philippines and Indonesia have strong renewables policy support schemes, but their electricity grids require upgrading to accommodate new manufacturing hubs, as well as new renewables-based generation. Malaysia is a bright spot: although its grid also needs upgrading, transmission losses today are very low, at less than 7%. Grid interruptions are also infrequent and typically of short duration. Some grid-related constraints that could hinder the expansion of wafer and polysilicon manufacturing in the region could also be addressed quickly. In Indonesia, for example, the duration of grid interruptions has been more than halved between 2020 and 2023, while their frequency has been reduced by 54%.

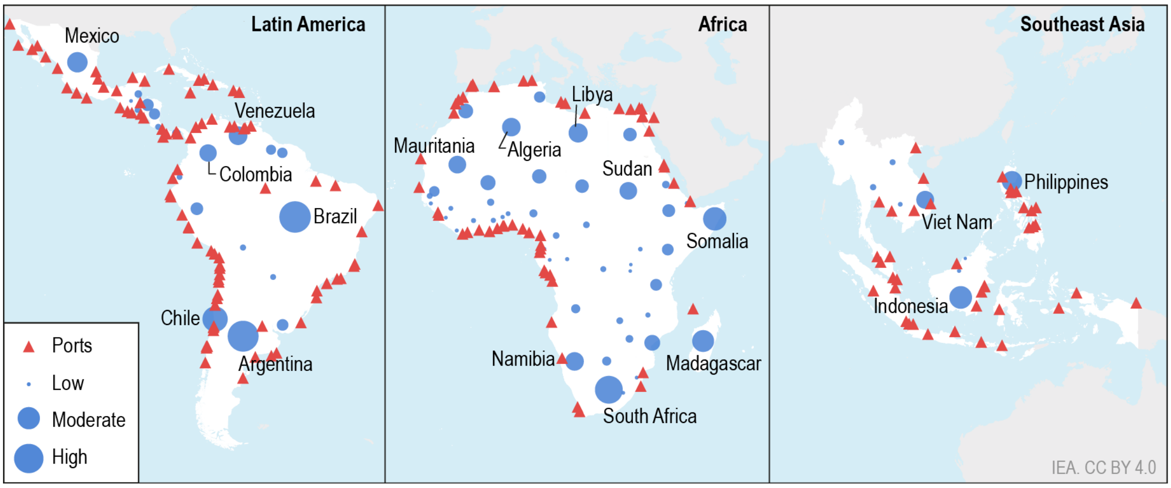
Growth in solar PV manufacturing could also benefit from the development of other clean energy supply chains in the region. Investments in battery manufacturing that are already in the pipeline, based on the region's large nickel and cobalt reserves, could increase momentum for developing skills that are also relevant to solar PV supply chains. Designating zones for clean energy technology manufacturing and setting up arrangements that are conducive to transferring operational skills and competences on the ground could also enhance synergies between those two industries and others such as chemicals.

Wind turbines

Technology-specific enabling factors

As for other clean energy technologies, the enabling factors for wind manufacturing vary across supply chain steps and components, but the availability of raw materials and other inputs has an important influence on the prospects for gaining a foothold in the wind turbine supply chain. Less than 5% of wind nacelle manufacturing capacity and less than 10% of that of blades is located in Latin America, Africa and Southeast Asia today. Our analysis suggests that the most important enabling conditions for expanding the manufacturing of turbines and their components are the level of domestic demand and the suitability of transport infrastructure. Strong wind resources and port infrastructure can point to future potential to manufacture and export wind turbines (Figure 4.10).

Figure 4.10 Existing port infrastructure and wind resource potential in Latin America, Africa and Southeast Asia



Notes: Triangles indicate ports from the World Port Index (Maritime Safety Office, 2024) with a cargo depth of over 11 metres (category J) and where the maximum vessel size is medium or larger (category M or L). This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA analysis based on the World Port Index - Maritime Safety Office (2024); the Copernicus Climate Change Service (n.d.); European Space Agency - GlobCover (2009); Protected Planet World Database on Protected Areas (n.d.); World Wildlife Fund Global Lakes and Wetlands Database (n.d.); and FAO Digital Soil Map of the World (n.d.).

Manufacturing of wind turbines in Latin America, Southern Africa and Southeast Asia has particular potential in areas with good wind resources and port infrastructure for exports.

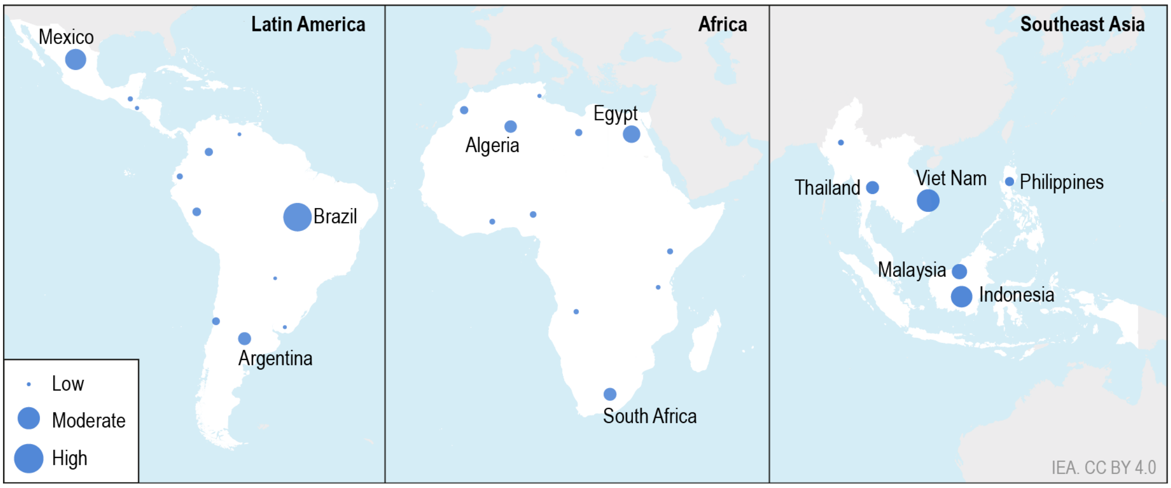
Demand for wind turbines remains small in many emerging markets and so there are only a few manufacturing sites, but rising demand could help to drive investment in turbine manufacturing in those countries in the future. Over the past decade, wind turbine manufacturers have consolidated their manufacturing capacity in a smaller number of sites, as economies of scale at single manufacturing locations are crucial to minimising costs (US ITC, 2021). For this reason, access to robust transport infrastructure, notably ports, is an important enabling factor.

Growth in regional demand is the other key enabler for establishing wind turbine manufacturing in emerging markets. Brazil, Chile and Argentina have the biggest wind resources in Latin America, while South Africa has the biggest in Africa. In Southeast Asia, almost all countries have substantial offshore potential, with

Indonesia having the most offshore wind resources. These countries are well-placed to promote the deployment of wind generation capacity, which could in turn encourage domestic or regional manufacturing.

The availability of material inputs is another factor that could give some countries an edge with respect to manufacturing wind turbine components. For example, access to cheap iron and steel could lower the cost of manufacturing towers (Figure 4.11), while local supplies of carbon fibre could support the manufacturing of blades. Across the three regions, steel production is highest in Brazil, though it represents less than 2% of the global total. Viet Nam and Indonesia together produce similar quantities of crude steel to Germany (a top ten producer globally).

Figure 4.11 Relative magnitude of crude steel production in Latin America , Africa and Southeast Asia, 2023



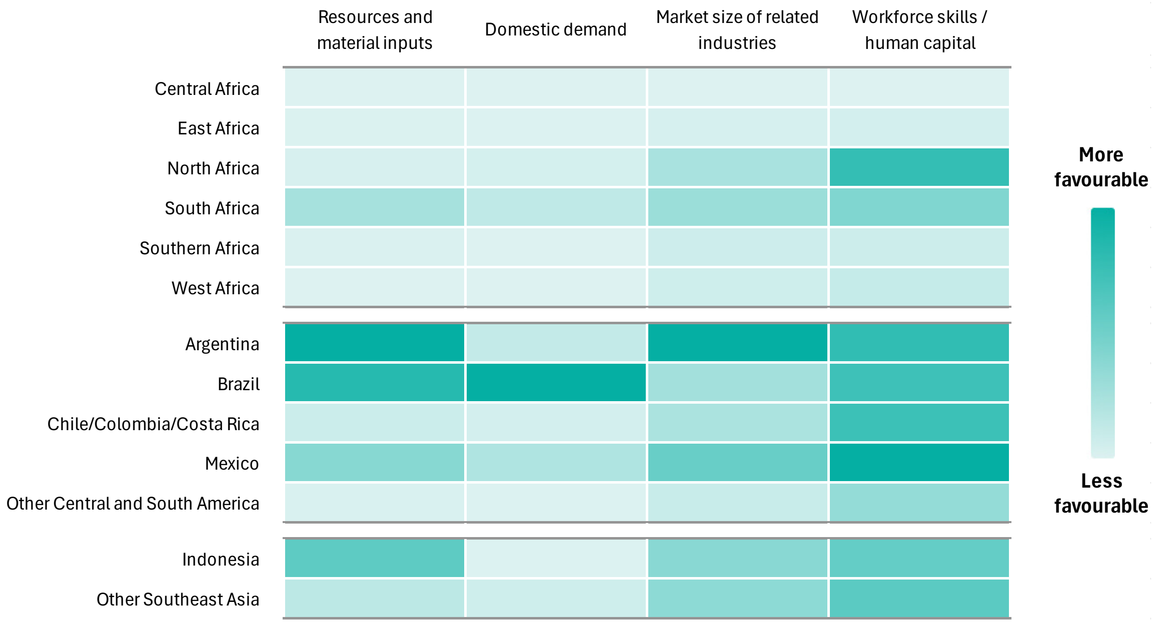
Note: This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Source: IEA based on data from the World Steel Association (2024).

Availability of raw materials – such as iron and steel in countries like Brazil – can be an important enabling factor for wind tower manufacturing.

The existence of a strong manufacturing sector generally can also be an enabling factor for the manufacturing of turbine blades, nacelles and towers. The emerging markets with the greatest share of value added from manufacturing tend to be in Southeast Asia, notably Viet Nam, Thailand and Malaysia. In Latin America, value added in manufacturing is highest in Mexico. In particular, existing industrial experience with electronics, as is the case in Malaysia and Viet Nam, can be an enabling factor for nacelle manufacturing. Access to a workforce with experience in manufacturing fabricated metal parts can also support opportunities for blade and tower manufacturing. This has synergies with mechanical engineering-intensive industries such as automobile manufacturing. Access to relevant workforce skills appears strong across Latin America (Figure 4.12), as well as

Malaysia, Thailand and Viet Nam in Southeast Asia, and Tunisia and Algeria in Africa. Nacelle manufacturing in particular benefits from access to highly skilled technology workers.

Figure 4.12 Current status of enabling factors for resource availability and domestic markets for wind manufacturing by country/region



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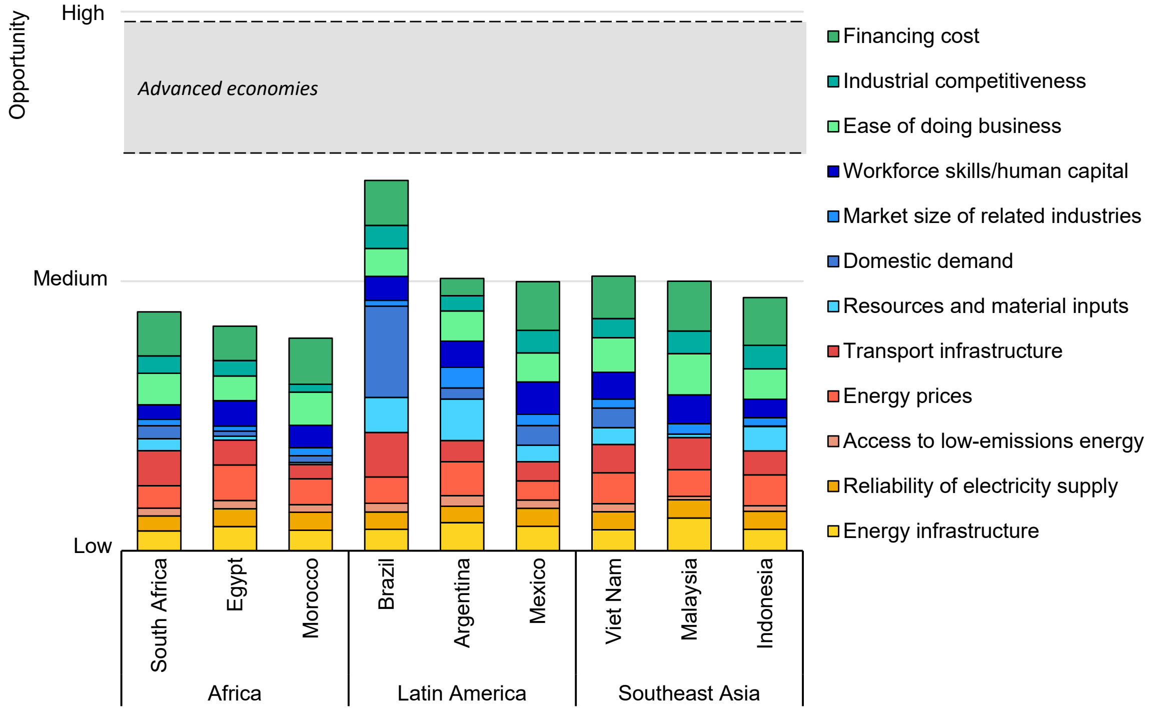
Note: Indicators for each enabling factor are described in the Annex.

Latin America generally has good workforce skills relevant to wind manufacturing, with Brazil enjoying strong domestic demand.

Wind turbine manufacturing is capital-intensive, so access to low-cost financing is an important consideration. In general, the top-ranked countries have relatively low weighted average costs of capital (WACC). Strong transport infrastructure is also important for enabling the export of large wind turbine components.

Among all the countries in the three regions, Brazil scores highest overall for enabling factors for wind turbine manufacturing thanks primarily to its current high domestic demand (Figure 4.13). Argentina is also an attractive location due to its high wind potential, though it currently has a relatively high WACC. Viet Nam scores well across all three categories of enabling factors (business environment, energy and transport infrastructure and resource availability and domestic markets). While Malaysia has no domestic market today, it scores well thanks to its strong energy and transport infrastructure and a generally favourable business environment, particularly low financing costs.

Figure 4.13 Top three scoring countries for enabling factors for wind turbine manufacturing in Africa, Latin America and Southeast Asia



Notes: The size of each column segment is proportional to the combination of how well a country scores on a specific enabling factor and the relative importance of the factor. The range for advanced economies is based on the assessment of enabling factors in the United States, Germany and Japan. The results of this enabling factor analysis should not be interpreted as indicating the only countries in these regions to have current or future opportunities for manufacturing. A comprehensive description of the methodology is detailed in Box 4.1, and a full list of indicators, sources and coverage can be found in the Annex.

Resource availability and low financing costs can help open opportunities for wind blade manufacturing in emerging markets.

Opportunities for wind manufacturing in Latin America

Our analysis shows that Latin America has some of the most favourable enabling conditions for wind turbine manufacturing. Today, Mexico and Brazil are the principal manufacturers of wind components in Latin America, each holding around a 5% share of global production of wind turbine blades. Argentina has several nacelles facilities, but they represent a negligible share of global production.

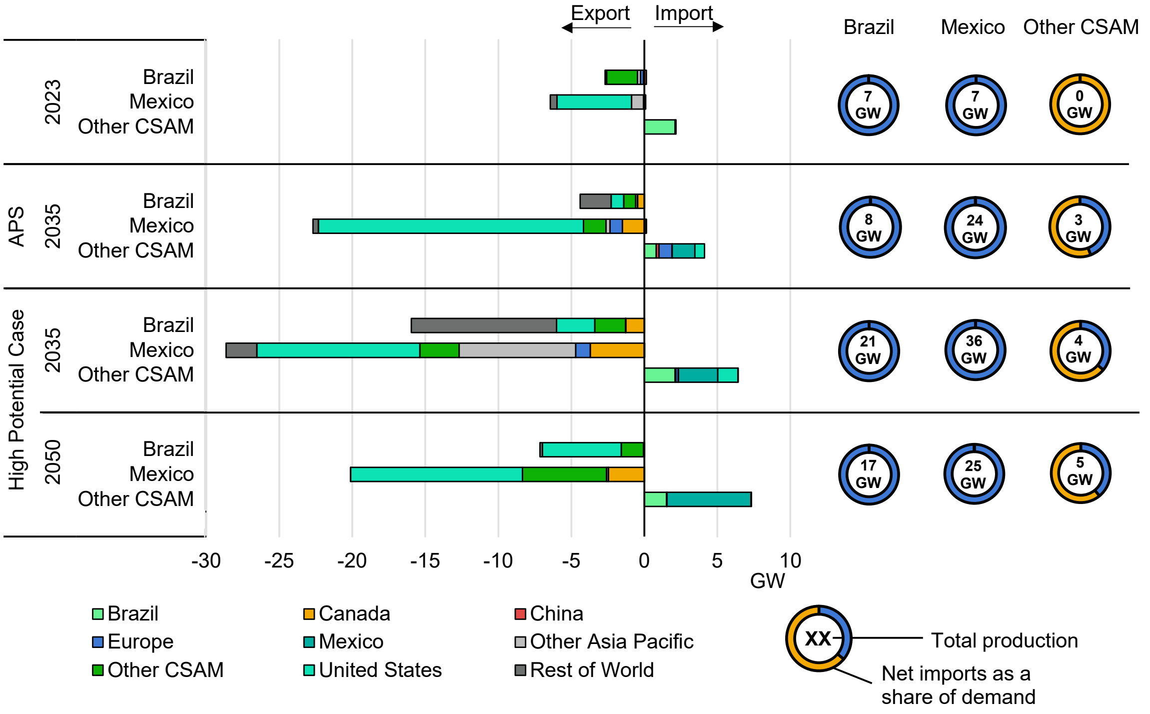
New facilities in Latin America are often established through partnerships between an existing original equipment manufacturer (OEM) based in an advanced economy and a local partner. For example, Vestas, a Danish manufacturer, developed their nacelle assembly line in Argentina in collaboration with Newsan, an Argentinian group that works in manufacturing, marketing and logistics (Energy Watch, 2018). They recently announced new investments in Brazil in nacelle and blade manufacturing (UOL, 2024). Nordex, a German firm, also established nacelle assembly in Argentina with FAdeA, an aeronautical company run by the Argentinian Ministry of Defence (Nordex, 2018). Brazil is home to several local manufactures such as Aeris, which supplies blades for Nordex and Vestas, and WEG, an electrical engineering company that has been active in the wind energy sector since 2013 and produces two types of onshore wind turbines. In 2024 Goldwind opened its first manufacturing base outside of China in Brazil (Goldwind, 2024). Furthermore, it is planning to open a blade facility in co-operation with Sinoma Tech, another Chinese company (Renewablesnow, 2024).

The build-up of wind turbine manufacturing capacities in Brazil and Argentina was driven in part by domestic content requirements. In Brazil, the National Development Bank (BNDES) makes access to concessional finance conditional on those requirements; they differ according to the component but are generally around 60% by value (Flanders Investment and Trade, 2022). While this has supported domestic manufacturing, the focus on downstream components has also resulted in higher production costs, making it difficult for those manufacturers to compete internationally. In Argentina, the second round of the RenovAr programme launched in 2017 had a local content requirement of 37%, but was later discontinued (Energiae Strategica, 2020).

In Chile, as part of the government’s “green hydrogen strategy”, dedicated wind power is expected to be deployed for various hydrogen projects that are due to come online this decade. More broadly, the government has also set the ambitious target that 80% of the country’s electricity will come from renewables by 2030, with wind power expected to contribute significantly to achieving it (Ministerio de Energia de Chile, 2022). While this would increase demand for wind turbine components, there are currently no specific policies to support wind manufacturing in Chile. Wind turbine manufacturer Vestas has shown interest in establishing new projects in the country (La Tercera, 2023), despite there being no wind component manufacturing facilities since the first plant dating from 2011 was discontinued (América Economía, 2011).

Mexico, Brazil, Argentina and Chile are best-placed to expand wind turbine manufacturing capacities in Latin America over the coming decades. However, in the **APS**, Brazil and Mexico are the only countries that see any significant growth in blade exports to 2035. Mexico increases exports, especially to the United States and Canada, thanks to its proximity and trade agreements. In Brazil, where wind blade manufacturing is relatively mature, capacity is projected to flatline to 2035. In the **High Potential Case**, Brazil continues to expand its blades manufacturing capacity, and exports increase sixfold by 2035 compared to current levels, and more than three times higher than in the APS in the same year (Figure 4.14). In Mexico, production capacity of wind blades grows by 40% and exports by 25% in the High Potential Case in 2035 compared to in the APS, with export markets becoming more diversified. Other Latin American countries also expand their capacity to meet increasing domestic demand, in particular Chile, which becomes a net exporter. Offshore wind projects (including floating offshore wind) are a particular opportunity and become a focus for specialisation in manufacturing in the High Potential Case. Most Central and South American countries, however, continue to rely on imports, mainly from other Latin American countries, thereby highlighting the role for regional trade agreements that could support realisation of this High Potential Case.

Figure 4.14 Market for wind blades in Brazil and other Latin American countries in the Announced Pledges Scenario and High Potential Case, 2035-2050



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Notes: APS = Announced Pledges Scenario, CSAM = Central and South America. Rest of World includes Eurasia, Middle East and Africa. Import and export refer to net trade flows between Brazil or other Latin American countries and each of the regions displayed, while net imports as a share of demand refers to the net imports to Brazil or other Latin American countries accounting for all regions as a share of domestic demand.

In 2035, Brazil's wind blade exports are three times higher in the High Potential Case than in the APS.

Making the High Potential Case a reality for wind turbine manufacturing would call for centralising manufacturing close to cities with good road and port links to allow those sites to become hubs to serve local or export markets. In some cases, this would depend on large investments in transport infrastructure. For example, in the southern part of Chile, which benefits from the highest wind speeds, there are currently no large ports that could serve a thriving wind manufacturing industry.

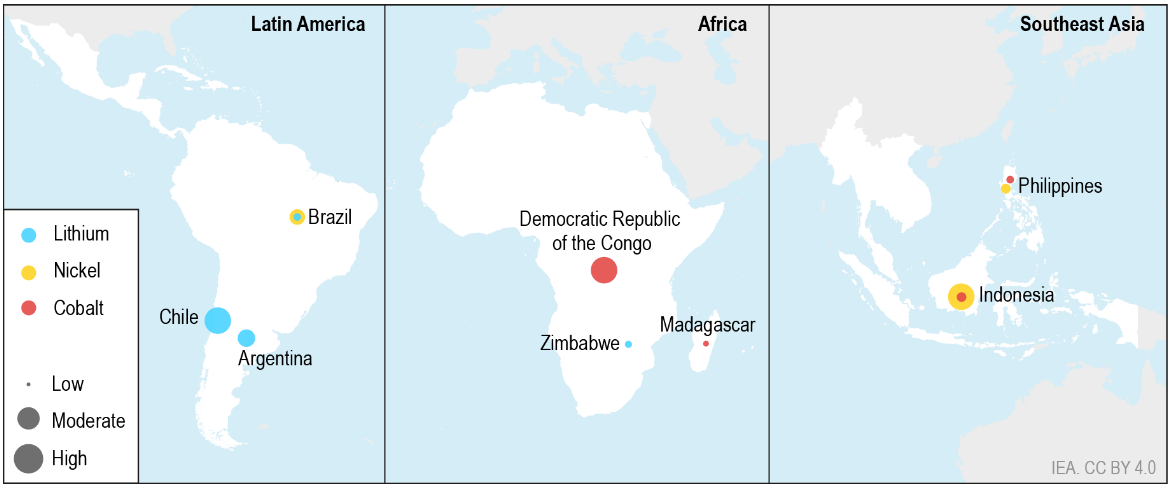
EVs and batteries

Technology-specific enabling factors

Today, critical minerals for making batteries, including lithium, nickel and cobalt, are often mined in one or a few countries and then exported, mainly to China, for refining or for transforming refined minerals into precursors used for battery components production. This is, in part, due to relatively low transport costs, in addition to the significant mineral processing capacity and expertise that has been developed over time in China. Nonetheless, access to domestic resources can form the basis for establishing a refining and processing industry, and potentially manufacturing cathodes and anodes. This strategy has been adopted by Indonesia, for example, where a substantial portion of the nickel mined there is also processed in the country.

Some South American countries, particularly Argentina, Bolivia and Chile, have large lithium resources, with the "lithium triangle" containing over 50% of the world's resources (USGS, 2024a). If they were to build out lithium processing capacity, investment in cathode and EV battery manufacturing could follow. Nickel reserves and mines could be another enabling factor for EV battery manufacturing, as lithium (Li)-ion batteries using high-nickel chemistries, which are dominant in the US and EU markets, contain more nickel by weight than lithium (IEA, 2024d). Together, Indonesia and the Philippines represent over 60% of nickel mining today and up to 45% of estimated reserves, while Brazil holds around 10% of nickel reserves (Figure 4.15). For cobalt, the Democratic Republic of Congo is currently responsible for two-thirds of mining output and home to around 55% of known reserves.

Figure 4.15 Lithium, nickel and cobalt reserves in Latin America , Africa, and Southeast Asia, 2023



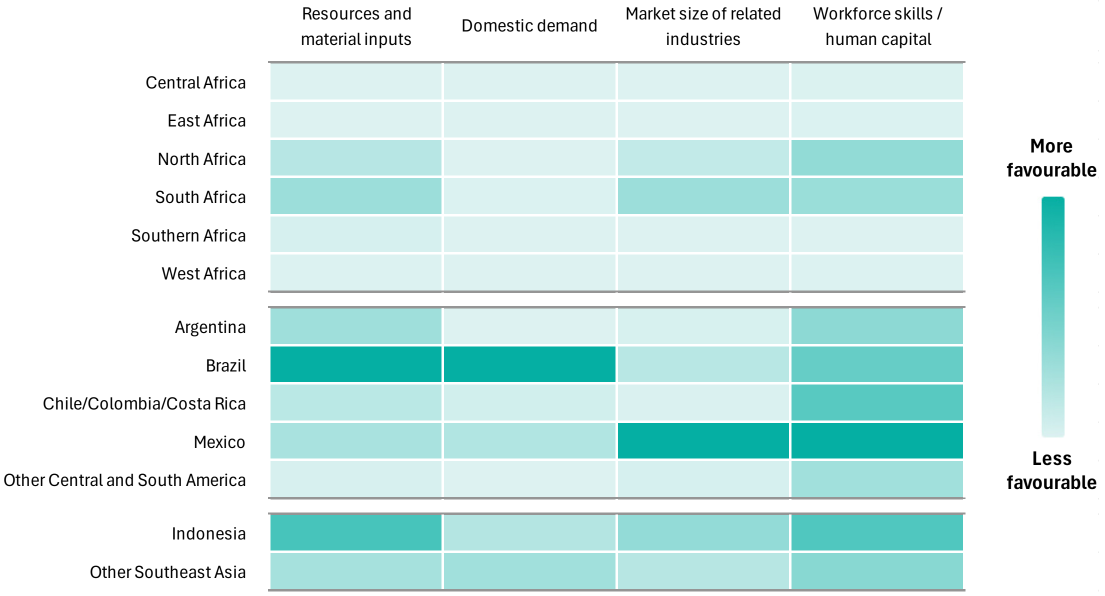
Note: This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Sources: IEA analysis based on data from USGS (2024a); (2024b); (2024c).

Latin America has substantial lithium reserves, as well as nickel reserves, which could drive investment in several downstream steps in battery supply chains.

Interest in developing EV supply chains is likely to be strongest in countries with a potentially large domestic EV market or proximity to such markets. The initial surge in EV and battery production in China was driven by strong domestic demand, underpinned by strong policy support. In the APS, sales of EVs across Latin America, Africa and Southeast Asia in 2035 are highest in Indonesia, reflecting ambitious national targets and the relatively large size of the overall car market, followed by other Southeast Asian countries and Mexico. The attractiveness of Mexico as a manufacturing hub is enhanced by its proximity to the United States, where demand is projected to grow strongly to 2035, creating the world's largest national electric car market after China with over 10 million battery electric car sales in 2035 in the STEPS.

For EV manufacturing, an established internal combustion engine (ICE) vehicle manufacturing sector gives a country a clear competitive edge, as much of the equipment and components needed are the same (e.g. car body, chassis, interiors, electronics, wheels, suspensions, etc), as well as materials used, such as steel and aluminium, and existing assembly plants can be repurposed. Among the emerging markets of the three regions assessed here, Egypt, Morocco, Mexico, Brazil, Argentina, Indonesia, Viet Nam and Thailand have well-established ICE vehicle manufacturing industries. Yet this does not guarantee success in developing a strong EV manufacturing sector: in 2023, Japanese OEMs produced about a third of ICE cars sold worldwide, but less than 5% of EVs. Chinese OEMs, by contrast, produced 10% of ICE cars but over 60% of electric cars.

Figure 4.16 Current status of enabling factors related to resources and domestic markets for EV manufacturing



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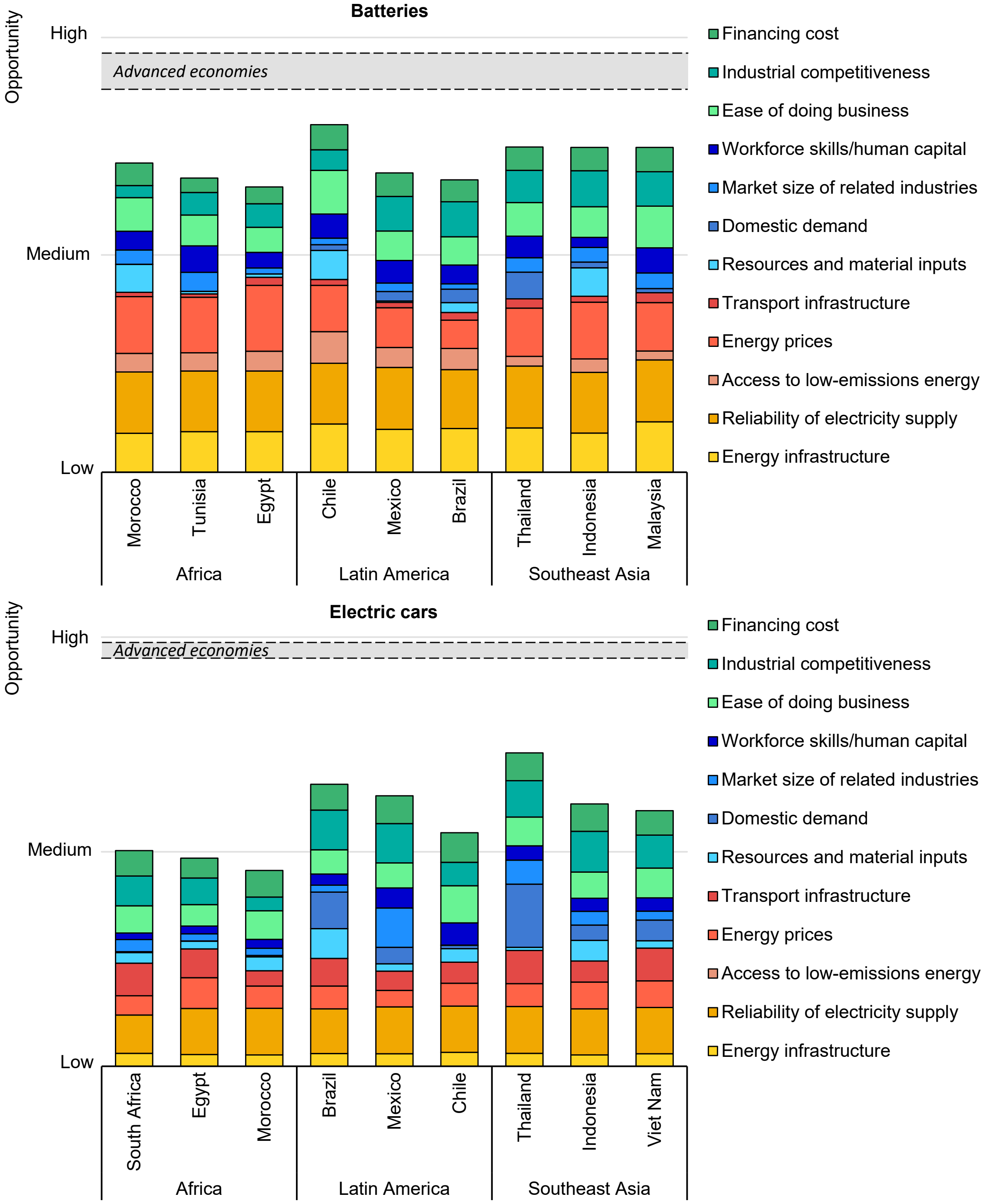
Note: Indicators for each enabling factor are described in the Annex.

Existing automotive manufacturing capacity in Mexico, along with the related skills, make the country an attractive destination for investment in EV manufacturing.

For battery manufacturing, the availability of highly skilled workers is an even more important consideration in emerging markets than in advanced economies, based on the results of the IEA survey on the drivers of investment. Battery manufacturing generally requires more highly skilled workers than EV assembly. In our analysis, Chile and Mexico can most readily benefit from workforce skills related to both EV and battery manufacturing in Latin America, Tunisia and Morocco in Africa, and Indonesia and Thailand in Southeast Asia (Figure 4.17).

Figure 4.17 Top three scoring countries for enabling factors for EV and battery manufacturing in Africa, Latin America and Southeast Asia



Notes: The size of each column segment is proportional to the combination of how well a country scores on a specific enabling factor and the relative importance of the factor. The range for advanced economies is based on the assessment of enabling factors in the United States, Germany and Japan. The results of this enabling factor analysis should not be interpreted as indicating the only countries in these regions to have current or future opportunities for manufacturing. A comprehensive description of the methodology is detailed in Box 4.1, and a full list of indicators, sources and coverage can be found in the Annex.

Several countries with favourable enabling factors for battery manufacturing are also well placed for EV manufacturing, with Chile scoring highest for batteries and Thailand for EVs.

Taking into account all the enabling factors for establishing battery manufacturing, several emerging markets score highly in our analysis, in large part due to low electricity prices and availability of raw materials:

- In Latin America, Chile has strong potential thanks to its large renewable energy resources, low electricity prices and large lithium resources. Brazil also scores well due to its nickel and high-purity lithium production (Energia, 2023). Mexico offers low electricity prices and strong industrial competitiveness due in part to low labour costs.
- In Southeast Asia, Indonesia's access to raw materials – namely nickel – could underpin production of high-nickel Li-ion batteries, which today are the chemistry of choice of both the United States and the European Union (IEA, 2024d). Lithium iron phosphate (LFP) batteries are growing in importance globally as they are cheaper to make, but nickel-containing chemistries are projected to remain important and account for about 50% of EV batteries in 2030 and 2040 thanks to their higher energy density (IEA, 2024e). Thailand, Indonesia, and Malaysia are best-placed to exploit their favourable enabling conditions for battery manufacturing (see below).
- In Africa, Tunisia's strength in related industries – a relatively high share of its GDP comes from value added within the electrical fittings and battery sectors – could provide a basis for battery manufacturing. Egypt could also attract investment in that sector given its relatively low electricity prices. Morocco rates highly for ease of doing business compared with other African countries and its rich phosphate resources, which could help it attract investment in manufacturing batteries.

Many of the same countries also have strong enabling conditions for EV manufacturing, though there is a stronger tilt towards countries with existing automotive manufacturing industries.

- In Latin America, Brazil ranks first overall thanks to its large current demand for EVs and domestic production of materials, especially aluminium. Mexico ranks second, largely due to its existing conventional vehicle manufacturing industry. Chile scores well for ease of doing business and relevant workforce skills.
- In Southeast Asia, Thailand stands out on account of its large domestic EV market, as does Viet Nam, though to a lesser degree. Indonesia scores well on its amount of materials production, including steel and aluminium.
- African countries generally have less favourable business environments and domestic markets for EV manufacturing. South Africa and Egypt have relatively strong energy and transport infrastructure, putting them in a stronger position than other African countries. Morocco also has notable potential thanks to the ease of doing business there and its existing and growing car industry.

Opportunities for EV and battery manufacturing in Southeast Asia

Southeast Asia has some of the strongest potential for establishing EV and battery manufacturing, especially in Viet Nam, Thailand and Indonesia. Demand for electric cars is growing rapidly in these countries, reaching around 15% of total car sales share in Viet Nam, 10% in Thailand and 2% in Indonesia in 2023. Electric car manufacturing is already underway in the region, with a total output of 40 000 units. Several Southeast Asian countries also have plans to expand or develop EV manufacturing, including through local content requirements. Singapore could also become a critical asset for EV manufacturing in the region, leveraging its sizeable and well-connected port and growing domestic market; the country has adopted a wide range of policies to support adoption of EVs, including a ban on new ICE vehicles from 2030 and incentives for expanding charging infrastructure (LTA, 2024). In the APS, sales of electric cars in Southeast Asia are projected to reach 3.7 million by 2035, representing over 60% of new car registrations in the region.

In Viet Nam, domestic electric car manufacturer VinFast was almost fully responsible for the more than 30 000 electric car sales recorded in the country in 2023. The company has ambitious targets for EV sales and plans to expand manufacturing capacity from 300 000 vehicles per year today to 950 000 by the end of 2026 (Vinfast, 2017). Today, Viet Nam has the capacity to manufacture 1 million cars per year, which could be repurposed for EV production. VinES Energy Solution, which is part of VinFast, is building a 5 GWh LFP battery plant in partnership with the Chinese battery producer Gotion for both EVs and stationary storage (Reuters, 2022a). The batteries produced in this plant are primarily meant to serve domestic demand, with VinFast looking to export EVs, including to the United States (Reuters, 2022b).

By contrast, the majority of the 90 000 EVs sold in Thailand in 2023 were manufactured in China by Chinese OEMs. However, like Viet Nam, the country is well-placed to switch from making conventional ICE cars to EVs. It not only has one of the largest overall car markets in Southeast Asia but is also the largest producer, ranking 10th globally, with a total manufacturing capacity of around 3 million vehicles at end-2023. The country produced roughly 1.8 million cars in 2023, more than half of which were exported. Thailand is gaining a lot of interest from Chinese OEMs seeking to invest in EV manufacturing. For example, BYD – the world's largest EV manufacturer – is targeting annual production of 150 000 electric cars in the country (BYD, 2024) and Changan Automobile and SAIC 100 000 each (S&P Global, 2024b), (MG, 2024). In aggregate, the planned capacity additions of Chinese manufacturers, if completed on time, would result in total EV manufacturing capacity of more than 500 000 units by the end of 2024. Thailand currently has battery manufacturing capacity of 1 GWh at a plant owned by Energy Absolute in Chachoengsao. While the company currently mostly supplies batteries to local electric bus manufacturers, this capacity could be used to serve electric cars and other vehicle types in the future. Announced projects are expected to increase capacity to about 4 GWh by 2025, reaching 8 GWh later if preliminary plans also come to fruition (Just Auto, 2023).

Indonesia was the second-largest car producer in Southeast Asia in 2023, with a total manufacturing capacity of more than 2 million vehicles. Most of that capacity is owned by Japan- or Korea-headquartered companies, and there are no locally owned car manufacturers. In March 2022, Korean automaker Hyundai opened its first EV assembly line in the country as part of a new vehicle factory, with an initial annual capacity of 150 000 units (ICE vehicles and EVs), expected to reach 250 000 units following a USD 1.6 billion investment (Hyundai, 2022). Chinese OEMs are also looking to invest in EV manufacturing. BYD and Chery both already have plans to establish or expand manufacturing facilities in Indonesia in the coming years, targeting annual production up to 150 000 (Marklines, 2024a) and 100 000 (Antara, 2024) EVs respectively. Other foreign OEMs have also announced EV manufacturing investments in Indonesia: VinFast, which will invest USD 1.2 billion (Vinfast, 2023), Toyota with USD 1.8 billion (Reuters, 2022c) and GAC Aion with about USD 65 million (CNEVPOST, 2024).

Battery manufacturers are also looking to tap into Indonesia’s nickel resources and growing EV market, supported by domestic refining, with major capacity investments from Chinese companies (Australian Strategic Policy Institute, 2024) following the nickel export ban implemented by the Indonesian government (IEA, 2023a). Nonetheless, most of the refined nickel continues to be exported to China for transforming into nickel sulphate, which is the main precursor used as cathode material for battery production (IEA, 2024e). However, the large nickel resources and production, together with the strengthening of local refining, are attracting major investments in high-nickel cathode active material manufacturing. If all announced projects are built, Indonesia will reach a cathode active material production capacity of over 250 kt, equivalent to over 150 GWh, sufficient to supply around 2 million battery electric cars in 2030.

In just 3 years, Indonesia has signed more than a dozen deals worth over USD 15 billion to invest in production of battery materials and EVs (Reuters, 2023). If all investment announcements come to fruition, Indonesia could become a major EV and battery exporting hub in Southeast Asia. Korea’s LG and Hyundai recently opened their first battery manufacturing plant (FT, 2024), while CATL, the world’s largest battery manufacturer, announced in 2022 that it will partner with local publicly owned groups to build a USD 6 billion mining-to-battery complex (BNEF, 2022).

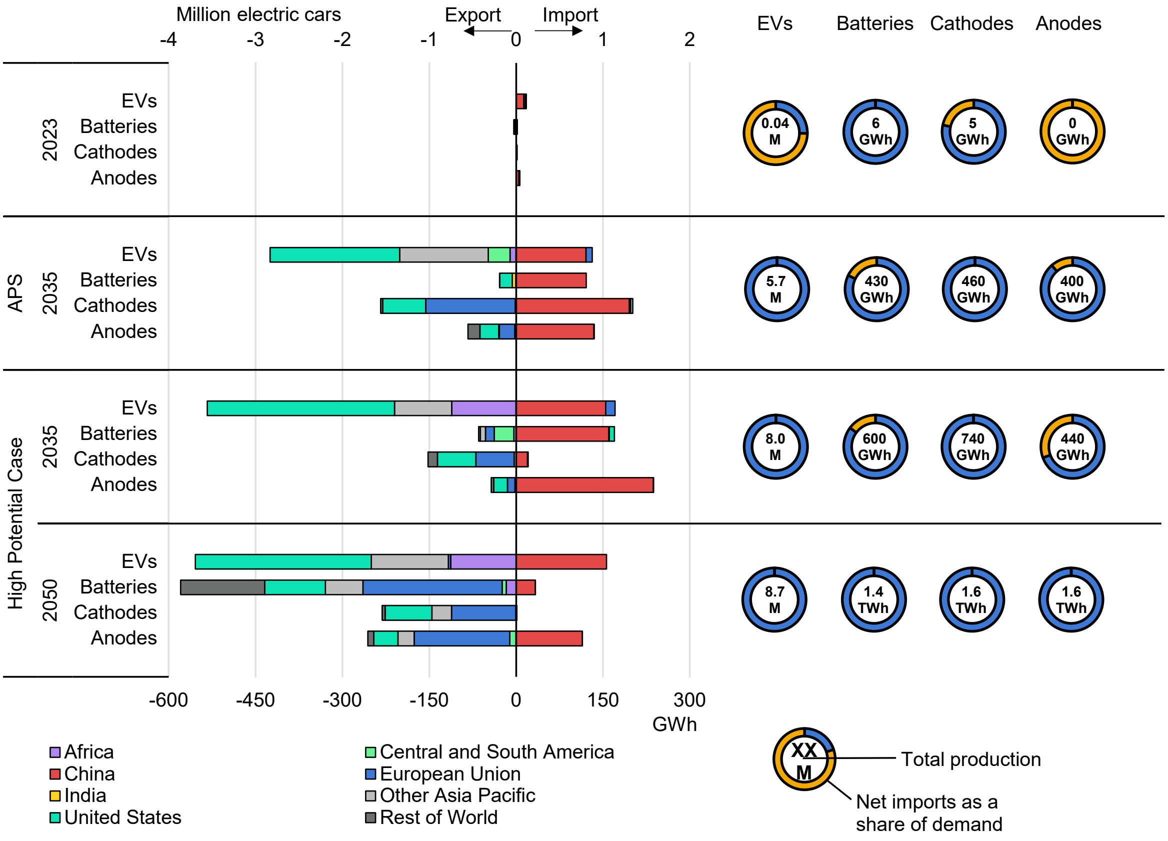
Table 4.2 EV manufacturing policies and goals in selected Southeast Asian countries

Country	Supply-side support policies	Demand-side support policies	Goals
Viet Nam	Companies involved in EV manufacturing benefit from import tax exemption on raw materials and supplies for production.	Exemption of registration fee for buyers and purchase tax reduction. No local content requirements in EV manufacturing to access tax rebate and financial incentives when buying an EV.	Commitment to reach net zero emissions in transport by 2050.
Thailand	Tax breaks and subsidies for OEMs producing two electric cars and motorcycles domestically per vehicle imported by 2026 (three EVs by 2027). Import duty exemptions for equipment and raw materials used in EV manufacturing. Corporate income tax exemption for EV companies.	Direct purchase subsidies up to around USD 3 000 for electric cars priced under about USD 60 000. Import duties for EVs reduced up to 40%. Purchase tax cuts for buyers of electric cars and motorcycles.	EV 3.5 policy: “30@30” goal of reaching a 30% zero-emission vehicle (ZEV) share in locally produced vehicles by 2030. 100% ZEV share in new car registrations by 2035.
Indonesia	Waiver on import duties and luxury sales tax for EV manufacturers committing to produce EVs in Indonesia before 1 January 2026.	VAT reduction to 1% for consumers who purchase an EV that has more than 40% (60% by 2027) of its components produced locally.	Target to produce 600 000 EVs locally by 2030 and reach 140 GWh of battery local production.

Note: All policies and goals are taken into account in the APS.
Sources: EV3.5 Scheme - Thailand Board of Investment (2023); Viettonkin Consulting (2023); and ASEAN Briefing (2024).

Southeast Asia is set to become a large EV, battery and component producer, building on its growing domestic market, strong industrial base, good transport infrastructure and low labour costs. Demand in Southeast Asia grows to 3.7 million electric cars in 2035 in the **APS**, but is outpaced by production, reaching 5.7 million cars, making Southeast Asia a net exporter to other countries in the Asia Pacific region and in North America (Figure 4.18). This is underpinned by strong policies both in place and planned to boost EV deployment and production (Table 4.2). The largest EV manufacturer is Indonesia, which produces about 2.6 million EVs under this scenario, and exports almost 1 million, mostly to the left-hand drive countries Australia and New Zealand. Battery production in Southeast Asia also grows rapidly, reaching over 400 GWh of production in 2035, sufficient to cover more than three-quarters of demand and export about 30 GWh, mostly to the United States.

Figure 4.18 Southeast Asian market and import-export balance for EVs, batteries and components in the Announced Pledges Scenario and High Potential Case, 2035-2050



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Notes: APS = Announced Pledges Scenario; M = million; EVs = electric vehicles, specifically passenger cars and pick-up trucks. Battery demand, production, and trade include all EV types and stationary storage. It is assumed that all countries and regions produce the global average chemistry share for both batteries and components. Cathode and anode refer to cathode and anode active materials. Demand for components that are not the final product are determined by the production of the subsequent component. EV data is reported in million units (top axis), and battery cell, cathode, and anode active materials in GWh (bottom axis). Import and export refer to net trade flows between Southeast Asia and each of the regions displayed, while net imports as a share of demand refers to the net imports to Southeast Asia accounting for all regions as a share of domestic demand.

Southeast Asia can become an important electric car manufacturer, serving not only the growing regional market but also exports, notably to the United States.

Production of EVs across the region reaches 8 million units in 2035 in the **High Potential Case**, 40% more than in the APS. In this case, Southeast Asia battery and cathode production grows 40% and 60% compared to the APS, making the region a major global battery producer and a net exporter of cathode active material, capitalising on its nickel resources. The potential for expanding production, particularly for batteries and components, is even greater in the long term. In 2050 in the High Potential Case, Southeast Asia reaches an EV output of over 8.5 million, exporting almost 600 GWh of batteries and 250 GWh of cathodes, more than half of which go to the United States and the European Union combined.

To fully tap into this potential, the region would need to forge stronger relationships with existing EV manufacturers from across the region and beyond, in order to access their expertise and replicate their low-cost manufacturing know-how. Second, and over the longer term, the priority is on establishing domestic battery and EV supply chains to both meet domestic EV demand and open up the possibility of exporting to major EV markets, including through trade agreements. The level of financing and attention brought to VinFast (Reuters, 2023a) is a good example of how local manufacturers can grow rapidly while targeting both the domestic and export market (IEA, 2024d).

Opportunities for EV and battery manufacturing in North Africa

North Africa benefits from several enabling conditions that could make it a global player in the EV industry. Morocco, in particular, is attracting interest from investors in EV and battery manufacturing, due to its geographical proximity to the large EU market, low labour costs, large phosphate reserves and potentially cheap renewable electricity thanks to abundant solar resources. Similarly, Tunisia benefits from experience in car manufacturing, with more than 260 automotive component companies accounting for about 90 000 direct jobs (US DOC, 2022). The country also has phosphate resources suited to the production of LFP batteries and recently introduced policy support to kickstart the local EV market, with purchase incentives of up to USD 3 200 per car (AGBI, 2023). In addition, the Egyptian automotive industry, with annual production capacity of more than 200 000 vehicles, is starting to attract Chinese investment in EV manufacturing (Afrik21, 2024). The emergence of a wide network of battery and battery components suppliers is enhancing the availability of a skilled workforce, which should make it easier to scale up EV manufacturing capacity in the future.

Morocco benefits from existing manufacturing capacity for 650 000 cars per year, which is generally owned by European automakers (in particular Renault and Stellantis) that have established manufacturing facilities in the country to benefit from low labour and energy costs. Proximity to Europe and strong transport links also gives Morocco an advantage as a trade partner: the Tanger-Med port, one of the largest in the Mediterranean Sea, facilitates easy and efficient shipping, reducing logistics costs and delivery times.

Morocco’s automotive exports, largely to the European Union, overtook those of the phosphate mining sector in monetary value in 2023 (Morocco World News, 2024). Yet the country’s phosphate resources are attracting significant investments from overseas battery-related companies for the establishment of LFP battery manufacturing facilities, reaching USD 15.3 billion in 2022 – equal to that of the previous 5 years combined (Bloomberg, 2023). In September 2023, China’s CNGR Advanced Material Company announced a USD 2 billion project to produce enough LFP batteries to equip 1 million EVs a year. More recently, Chinese battery-maker Gotion announced about USD 6.5 billion investment in a 100 GWh manufacturing capacity plant (Bloomberg, 2023), which is larger than the biggest battery manufacturing plant operating in the European Union today (the 86 GWh LG plant in Poland).

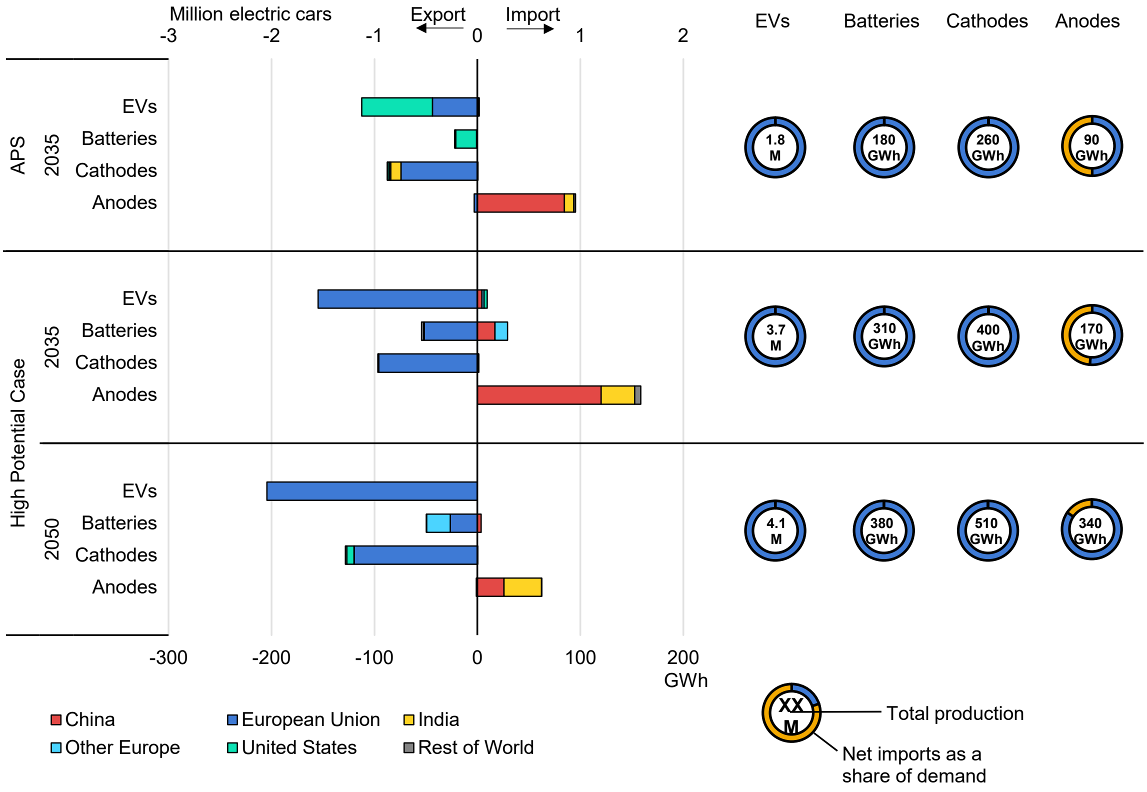
Morocco also benefits from free trade agreements with more than 60 countries, including the European Union and United States, which could open the door to exports of EVs and batteries. EVs manufactured with minerals sourced from Morocco are eligible for tax rebates in the United States. In September 2023, Korea's LM Chem and Youyshan, a subsidiary of Huayou Group of China, announced plans to make Morocco their global base for making LFP batteries, citing the US Inflation Reduction Act (IRA) mineral requirements as a key motivator (Argus Direct, 2024). Mass production is planned for 2026.

In 2035 in the **APS**, EV production in North Africa reaches 1.8 million units, of which about 70% are exported, almost exclusively to the United States and Europe (Figure 4.19). Investments in battery and cathode active material manufacturing mean that North Africa becomes a net exporter of batteries, primarily to the United States, and of cathode active materials, mainly to the European Union. Most of these investments, particularly in Morocco, come from Chinese producers. In turn, this means that the forthcoming new manufacturing facilities in North Africa will benefit from the extensive technical experience that Chinese companies have acquired in low-cost manufacturing of battery cells and components. As a result, by 2035 in the APS, North Africa is expected to locally produce about half of its demand for anode active materials, with much of the remaining supply imported from China.

Over the longer term, EV and battery manufacturing could become key pillars of economic development in North Africa. In the **High Potential Case**, EV production reaches close to 3.7 million as soon as 2035, with exports being over 30% higher than in the APS, and 4.1 million in 2050, with almost half earmarked for exports to Europe. North Africa becomes a strategic supplier of batteries and cathodes for Europe, with exports accounting for 5% of European batteries demand and nearly 20% of cathode demand in 2050. In this scenario, North Africa also reduces its dependence on Chinese anodes, satisfying 85% of its demand domestically in 2050.

To fully tap into this potential, Morocco would need to continue to attract investments from OEMs in a broad range of countries to diversify its production base. The surge of investments in recent years creates an opportunity to build a skilled local workforce, which could benefit other countries in North Africa that are well-positioned to develop EV and battery supply chains, such as Egypt and Tunisia.

Figure 4.19 North African market and import-export balance for EVs, batteries and components in the Announced Pledges Scenario and High Potential Case, 2035-2050



Note: APS = Announced Pledges Scenario; M = million; EVs = electric vehicles, specifically passenger cars and pick-up trucks. Battery demand, production, and trade include all EV types and stationary storage. It is assumed that all countries and regions produce the global average chemistry share for both batteries and components. Cathode and anode refer to cathode and anode active materials. Demand for components that are not the final product are determined by the production of the subsequent component. EV data is reported in million units (top axis), while battery cell, cathode, and anode active materials in GWh (bottom axis). Import and export refer to net trade flows between North Africa and each of the regions displayed, while net imports as a share of demand refers to the net imports to North Africa accounting for all regions as a share of domestic demand.

North Africa, led by Morocco, has the potential to scale up EV and battery production in the long term, mainly for export.

Opportunities for battery manufacturing in Latin America

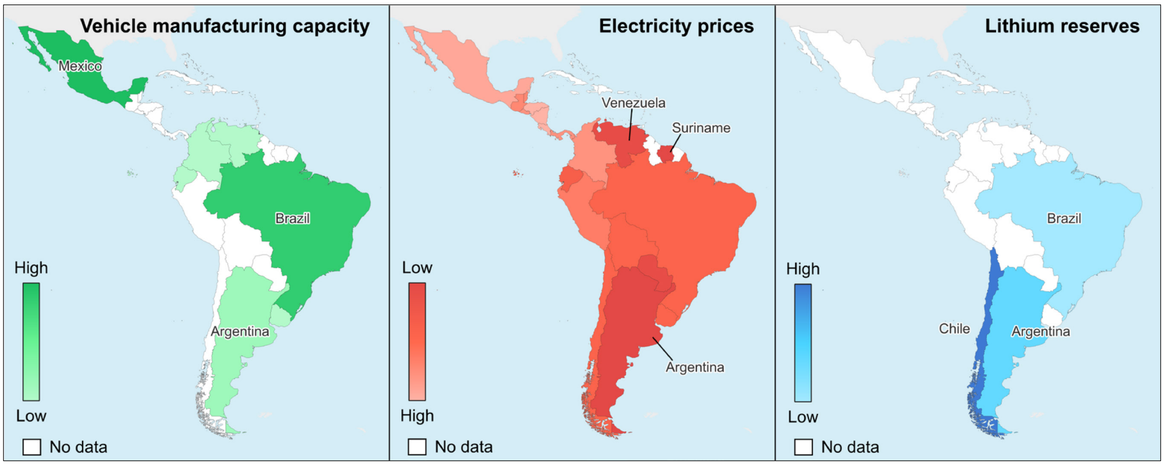
Thanks to access to large lithium resources, expertise in the car industries, and abundant renewable energy, Latin America is one of the regions with the biggest potential for building an integrated EV and battery supply chain (Figure 4.20). The market for batteries is already growing rapidly in the region, thanks to rising demand for EVs (Reuters, 2024a). For example, BYD plans to invest more than USD 600 million in building an EV plant in Brazil, aimed at supplying the local market (The Rio Times, 2024). BYD also plans to produce LFP cathodes in Brazil, though a planned project in Chile has been put on hold. Brazil's new decarbonisation policy, which passed into law in 2024, also incentivises EVs through tax credits for new R&D and production projects (Government of Brazil, 2024).

Mexico is also set to become a large EV producer thanks to growing domestic demand and exports to the United States. Under the United States-Mexico-Canada Agreement (USMCA) free trade agreement, cars produced in Mexico are eligible for financial support through the IRA (see Chapter 3). Tesla has announced that it plans to build a new plant in Mexico with a capacity of 2 million units, starting production in 2027 (InsideEVs, 2024). Audi has also announced the construction of an EV plant in Mexico, valued at USD 1 billion (Reuters, 2024b).

The rise of EV manufacturing in Mexico and Brazil could create new openings for Latin American countries with large lithium resources, including Argentina, Chile and Bolivia. Latin America, thanks to Chile, is today the world's second-largest extractor of lithium after Australia, and the second-largest refiner after China. Based on planned mining projects to 2030, Latin America is set to retain its position in refining but drop to third place in mining behind China (IEA, 2024e). In 2023, Chile supplied one-quarter of all lithium produced globally. In total, about 55 kt, or 30% of global output, came from Latin America in 2023. The second-largest producer in the region is Argentina, which produced 9 kt in 2023 and it is targeting a rapid expansion of lithium production (Bloomberg, 2024a). By 2025, Argentina's supply is projected to be almost three times higher, compared with growth of just 16% in Chile (IEA, 2024e). Almost half of the projected production of lithium in Latin America in 2030 is set to come from Argentina, with the remainder coming from Chile.

The development of lithium extraction and refining capacity in Chile is generating increasing interest from international partners. For example, the free trade agreement (FTA) between Chile and the United States, which came into force at the beginning of 2024, could accelerate the development of Chile's domestic EV and battery supply chains (Office of the US Trade Representative, 2024). It means that EVs made with batteries or components using Chilean lithium are eligible for tax breaks in the United States, which is expected to foster bilateral trade (Reuters, 2024c). Similarly, Chile is an important trade partner for the European Union (EC, 2024a), which is currently seeking to diversify its sources for lithium.

Figure 4.20 Enabling factors for battery and EV supply chains in Latin America



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Note: This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

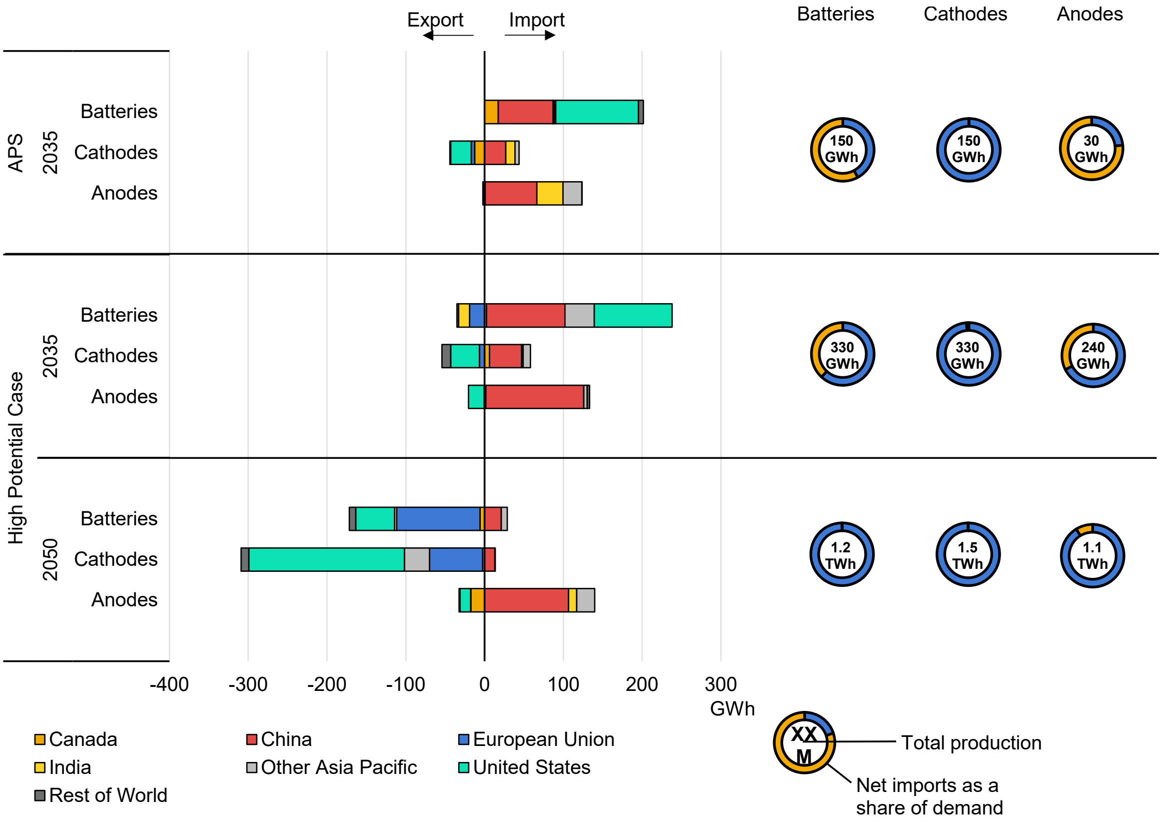
Sources: IEA analysis based on data from USGS (2024a); IEA (2024b); Global Petrol Prices (2023); and Marklines (2024b).

There are opportunities across Latin America to capitalise on enabling conditions in different countries to support the establishment of regional EV and battery supply chains.

In the **APS**, Mexico and Brazil become large EV producers, with total production reaching about 3.5 million in 2035, increasing battery demand. This provides a basis for the construction of large battery industries in Chile, Argentina, Brazil and Mexico, with production rising from virtually zero in 2023 to 150 GWh in 2035 – more than twice EU production levels in 2023 (Figure 4.21). Domestic production satisfies around 45% of the region's total battery demand, with most of the rest imported from the United States and China. Thanks to large lithium resources in South America, domestic production of cathode active materials reaches 150 GWh in 2035, on par with demand. However, around a third of regional production is in fact exported, predominantly to North America, while around a third of the demand is met with imports, most of which are from China and India. When it comes to anode active materials, production is not on par with demand in 2035, and the region is reliant on imports, mainly from Asia.

The potential for Latin America to expand its battery industry is much greater than that projected in the APS. In the **High Potential Case**, battery cell and cathode active materials production more than doubles in 2035 compared to the APS. Anode production grows over seven-fold, satisfying nearly 70% of regional demand. Latin America becomes one of the largest battery production regions in 2050 in this Case, reaching close to 1.2 TWh batteries produced, of which the majority serve the domestic EV and stationary storage markets, and nearly 200 GWh is exported to the European Union and the United States. Cathode production grows even more, to 1.5 TWh, with over 300 GWh of materials exported, mostly to North America.

Figure 4.21 Latin America market and import-export balance for batteries and components in the Announced Pledges Scenario and High Potential Case, 2035-2050



Notes: APS = Announced Pledges Scenario. Battery demand, production, and trade include all EV types and stationary storage. It is assumed that all countries and regions produce the global average chemistry share for both batteries and components. Cathode and anode refer to cathode and anode active materials. Demand for components that are not the final product are determined by the production of the subsequent component. Import and export refer to net trade flows between Latin America and each of the regions displayed, while net imports as a share of demand refers to the net imports to Latin America accounting for all regions as a share of domestic demand.

Latin America has significant untapped potential for battery manufacturing, based on its large critical mineral reserves and growing domestic EV market.

Realising the full potential to boost battery manufacturing would require strong regional collaboration and strategic partnerships. Chile and Argentina are well-placed to provide lithium and cathode active material to the entire region and beyond, thanks to their large reserves and previous experience in lithium mining and refining. Combined with the strong experience in car manufacturing, notably in Brazil and Mexico, this could catalyse the development of the regional EV and battery industry, creating a fully integrated supply chain within Latin America and maximising the economic and social benefits for the entire region.

Box 4.2 Synergies between air conditioners and heat pumps in EMDEs with large cooling demand

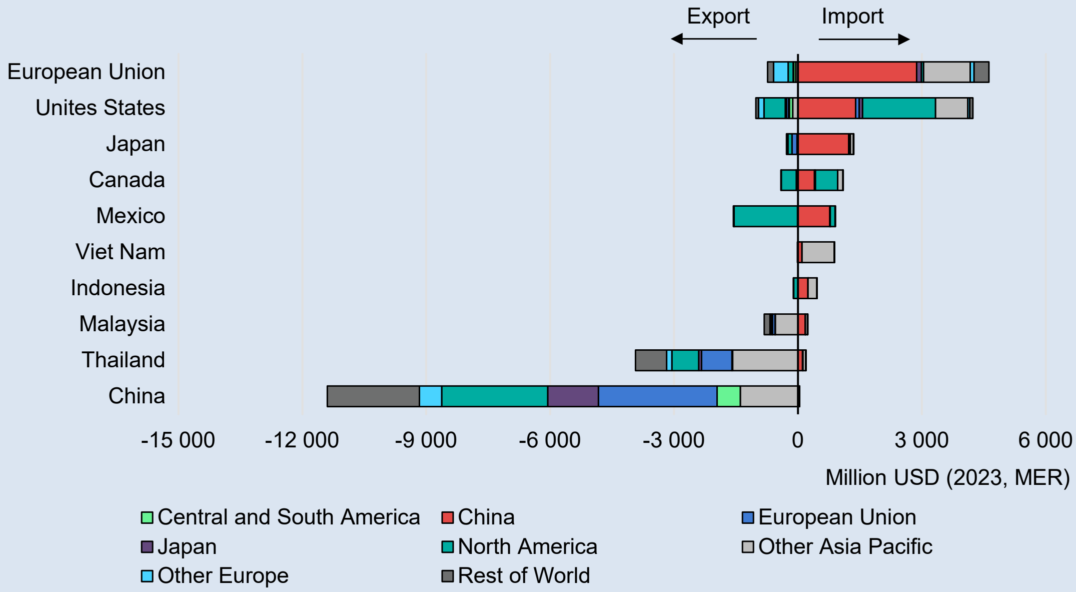
Most EMDEs are not heating markets, which means that little growth is expected in heating equipment sales, including heat pumps. However, some EMDEs are major air conditioner markets and produce high-quality products, including for export. Given similarities in the assembly processes, there could be an opportunity for these EMDEs to manufacture and export heat pumps, especially for air-to-air units, but also for air-to-water ones.

Air conditioning systems based on vapour compression refrigeration, including reversible air-to-air heat pumps, have been manufactured, installed and traded on a large scale for decades. China is the largest producer, exporter and domestic market for air conditioners, with nearly 170 million units produced, 70 million exported and 100 million sold domestically in 2023 (ChinaIOL, 2024). Advanced economies such as the United States, the European Union and Japan are also major producers, with tens of millions of units produced and sold each year. According to the UN Comtrade Database, China's exports accounted for over USD 10 billion in 2022, while the European Union and the United States imported air conditioning units for a value of more than USD 4 billion each (Figure 4.22). Most EU imports are smaller window-type air conditioners, primarily from China and Southeast Asia, while the United States mostly imports larger units, with strong trade volumes from Mexico. The volume of global production, sales and trade of heat pumps mainly used for heating is relatively small compared to the entire air conditioning market. Heat pump sales in each of the three largest markets (China, the European Union and the United States) were between 3 and 6 million units in 2023.

There are large similarities between the assembly processes for air conditioners and heat pumps, which simplifies the conversion of air conditioner assembly lines to heat pumps and vice versa. In addition, main components, such as compressors or heat exchangers, are common to both, although they may have different specifications. Incumbent air conditioner manufacturers may therefore have a competitive advantage in expanding horizontally into the heat pump market, as they could benefit from economies of scale, cheaper sourcing of components, use of existing workforce, and expansion or repurposing of existing production lines or facilities. This is already the case for manufacturers in economies such as Japan, China, the United States and the European Union, where many major air conditioner manufacturers also manufacture heat pumps.

This could represent an opportunity for certain EMDEs: Thailand and, to a lesser extent, Malaysia, are major players in the global air conditioner market, with combined air conditioner exports of over USD 4.5 billion in 2022, mostly to the European Union, North America and other Asia Pacific countries. They also play a significant role in the manufacture and export of components used in air conditioning systems. Globally, Thailand is the seventh largest exporter of compressors used in refrigerating equipment (HS code 841430), reaching almost USD 1 billion in 2022. Malaysia was in 2022 among the 20 largest exporters of heat exchangers (HS code 841950), with exports totalling around USD 250 million.

Figure 4.22 Import and export value of air conditioners in selected cooling markets, 2022



IEA. CC BY 4.0.

Notes: Import and export trade volumes correspond to the Harmonized System (HS) codes 841510, 841581 and 841582.

Source: IEA analysis based on UN Comtrade Database (2024).

However, this opportunity is not yet being fully exploited. Heat pumps that are mainly for heating (HS code 841861) which are manufactured and exported in these two markets remain a fraction of those manufactured for air conditioning, with negligible domestic demand due to low heating needs in the region. There are promising trends in Malaysia, where exports of heat pumps mainly for heating totalled USD 80 million in 2023, which is still less than 10% of the air conditioners volume, but entails an eightfold increase compared to the average exports in the previous 5 years. Moreover, some heat pump manufacturers are expanding their operations in Thailand, such as Stiebel Eltron, which announced an investment of over USD 15 million at the end of 2023 to build a new heat pump factory aimed at the export market (Bangkok Post, 2023).

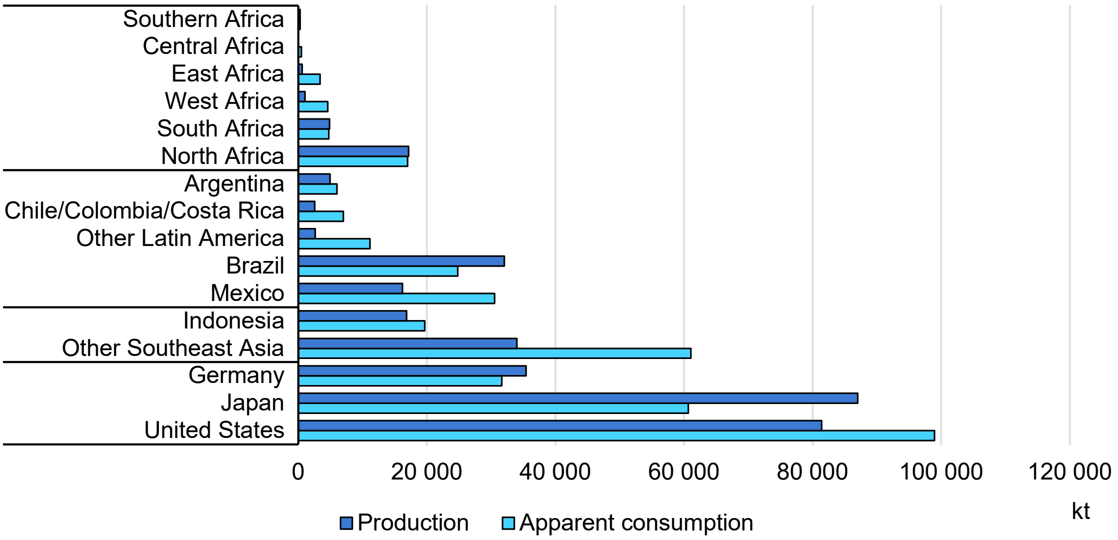
Air conditioners and heat pumps manufactured in emerging markets such as Thailand, Viet Nam, Malaysia and the Philippines benefit from lower production costs but can still offer high efficiency specifications. Many leading Japanese, Korean and Chinese air conditioner manufacturers have already established factories in these countries, so units produced there can benefit from know-how, logistics and economies of scale, and can achieve high efficiency levels for export to markets such as the European Union, the United States or Japan.

Iron and steel

Technology-specific enabling factors

Demand for steel is today concentrated in China, which accounts for half of global consumption, followed by advanced economies with 25%. Demand has been growing in EMDEs in recent years and this trend is set to continue with population growth and economic development. Crude steel production in emerging markets for clean energy technologies is concentrated in Southeast Asia, Mexico, Brazil and North Africa, where demand for the commodity is already high (Figure 4.23).

Figure 4.23 Regional production and apparent consumption of crude steel, 2023



IEA. CC BY 4.0.

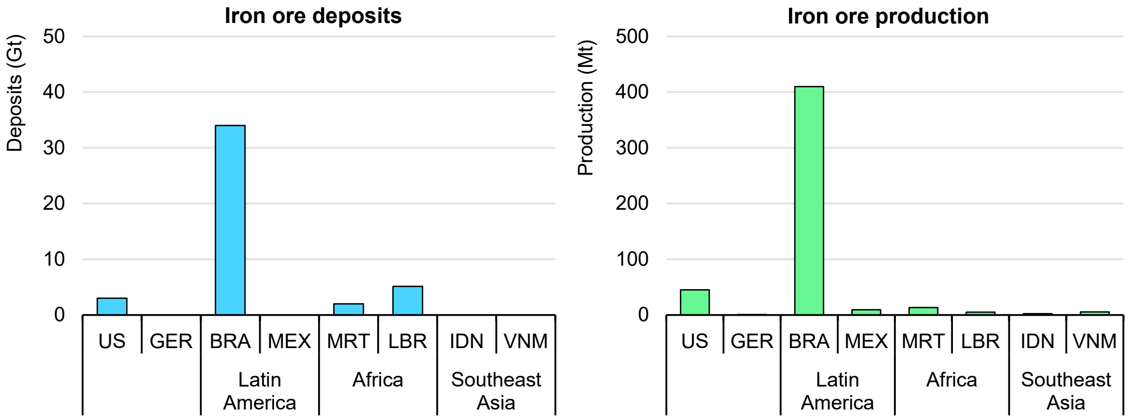
Note: Apparent consumption considers the sum of production and imports minus exports.
Source: IEA analysis based on data from the World Steel Association (2024).

Steel demand in Germany, Japan and the United States alone is roughly the same as in all emerging markets combined.

Emerging markets for clean energy technologies typically export raw minerals with minimal processing today (IEA, 2024e). Brazil stands out among emerging markets as the world's second-largest exporter of iron ore after Australia (Asociación Latinoamericana del Acero, 2022), exporting most of its iron ore production, predominantly to China (almost 70% of exports). Moving down the iron and steel supply chain presents an opportunity for emerging markets with iron ore resources to capture more of the value chain (Figure 4.24). Moreover, this could potentially lower the cost of supplying steel to domestic markets, including to clean energy technology manufacturers that would otherwise depend on imports.

The key enabling factors that determine opportunities to develop iron and steel supply chains, including those based on near-zero emissions technologies, are access to cheap and reliable sources of energy and materials. In the past, steel plants were usually sited close to coal mines, but, to the extent that these emerging technologies depend on electricity, proximity to cheap renewable energy will play a crucial role. Low-cost supplies of iron ore will also remain an important enabler. At present, the cost of fuel and raw materials accounts for around 60-80% of the steel production cost, and the shift to cleaner steel production will depend on reliable low-cost energy supplies. However, significant mineral deposits of iron ore are found in regions where access to energy infrastructure is currently poor, for example in West and Central Africa, which have a total of about 22 billion tonnes of proven iron ore deposits, but are not particularly well-endowed with renewable energy resources, nor with good energy infrastructure, such as reliable electricity grids. In addition, any increase in electricity output will need to be used to contribute to providing universal household access as a first priority. In countries where the lack of infrastructure can be a barrier, many project developers are looking to use captive renewables (i.e. that are solely dedicated to supplying electricity to the project). Access to energy infrastructure is a major hurdle for many emerging markets, due to difficulties in securing the financing needed for investments in the electricity sector.

Figure 4.24 Raw material availability for steel production in selected countries, 2022



IEA. CC BY 4.0.

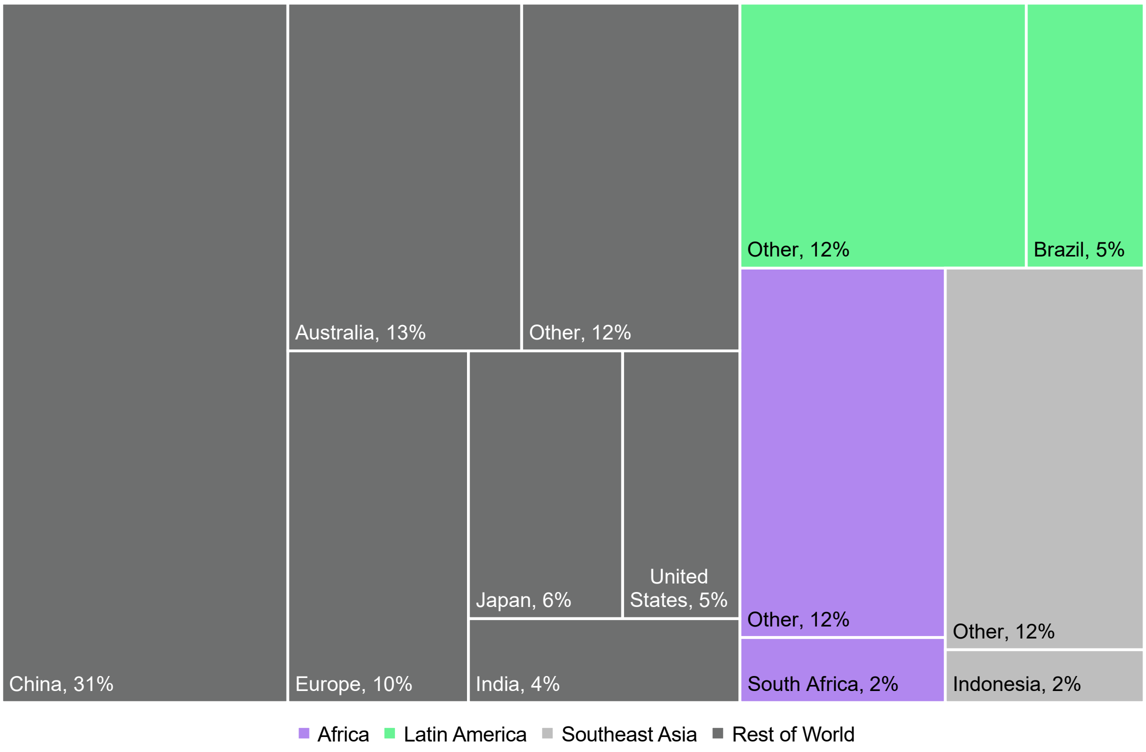
Notes: US = United States; GER = Germany; BRA = Brazil; MEX = Mexico; MRT = Mauritania; LBR = Liberia; IDN = Indonesia; VNM = Viet Nam.

Sources: IEA analysis based on data from USGS (2023); S&P Global (2024a); and World Steel Association (2024).

Brazil is a big steel producer thanks to its large deposits of iron ore, though a lack of domestic resources has not precluded the establishment of a steel industry elsewhere.

However, iron ore is widely traded and easily shipped at relatively low cost, so the existence of good transport infrastructure, including ports, can compensate to some degree a lack of domestic resources. In addition, steel is so commonly traded at the global level that all countries, including major and emerging markets, even if they are net exporters of steel, rely to some degree on imports to meet domestic demand for the wide variety of steel products and qualities. Port and transport infrastructure is therefore another key enabler, whether for importing iron ore (when not domestically available), or for trading iron and/or steel. Africa, Latin America and Southeast Asia together currently account for only 20% of global port throughput of dry bulk carriers, with more than 40% of this share coming from just three major mineral exporters: Brazil, South Africa and Indonesia (Figure 4.25). Most of the other countries in those regions would need to improve their port infrastructure in order to develop a domestic steel supply chain. In doing so, adapting the depth of ports to accommodate ships with larger carrying capacity can be crucial.

Figure 4.25 Global port throughput of dry bulk carriers, 2023



Source: IEA analysis based on data from J. Vershuur (2022).

Port infrastructure is of critical importance for the development of iron and steel supply chains, but very few emerging markets have the necessary capacities today.

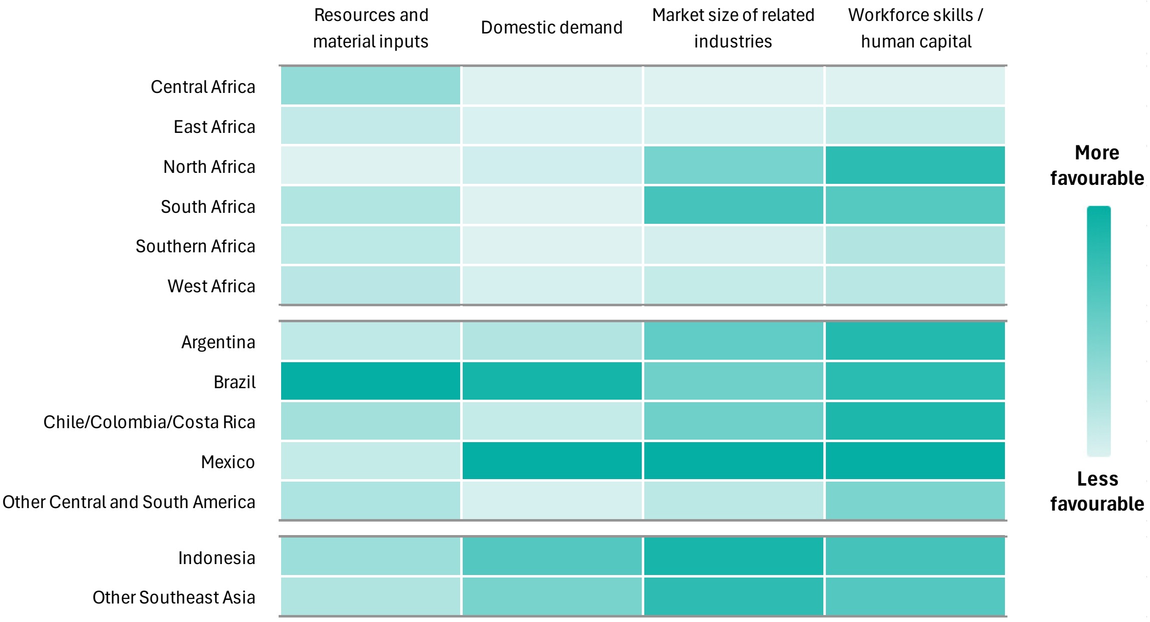
Historically, a lack of domestic resources has not precluded the establishment of a steel industry and today a number of major steel-producing countries, including Germany and Japan, rely on imports of ore, energy and coking coal for steel production. Steel-producing countries tend to be major manufacturing centres that use steel products – another key enabling factor for the development of production capacity. The majority of the major markets for clean energy technologies produce steel, but only a few – notably Australia and the United States – have significant iron ore reserves. Steel-producing countries without reserves have taken advantage of globalisation, advanced technology, a specialised workforce and strong transport infrastructure to make it financially viable to produce steel from imported raw materials, though reliance on imports carries the risk of supply chain bottlenecks in the event of a major disruption along trade routes. Increasing reliance on scrap steel, often sourced domestically, also reduces the importance of domestic production of ore. However, many emerging markets have limited availability of scrap, but abundant renewable resources, which can open the door to local production of hydrogen-based direct reduced iron (DRI), which relies on electricity.

Box 4.3 Water consumption in near-zero emissions steelmaking

Steel production requires substantial quantities of water for various primary production processes, including cooling, descaling and dust scrubbing. Water consumption in the steelmaking process averages around 30 cubic metres (m^3) per tonne of steel produced, depending on the production route. The majority (about 90%) of the water can be recycled or returned to the water source, while the remaining 10% is lost, mostly due to evaporation (World Steel Association, 2015). With the uptake of hydrogen as an energy carrier to replace coal, the demand for water onsite increases substantially. Water demand for electrolysis amounts to anywhere between 30 to 70 m^3 per tonne of hydrogen produced, depending on the cooling technology and on the ambient conditions, of which 10 m^3 of water is direct feedstock (IEA, 2024f). This shift would increase total water consumption in steel production by up to 200%. However, the water produced by the DRI process could be then recycled and used for hydrogen production through water electrolysis. For every tonne of iron produced in the DRI process using hydrogen, approximately 0.5 tonnes of water is produced as a by-product. The potential for water conservation adds another layer of sustainability to the clean iron production process, beyond just reducing carbon emissions. Desalination of sea water can provide an alternative source of supply, but additional treatment processes are needed to minimise the impact on the ecosystem and to ensure that desalination is sustainable. This favours regions with low water stress. If desalination is used as a water supply option, it can also improve access to clean water for the population in water-stressed regions.

Countries with an existing iron and steel industry have the advantage that any new production facilities can benefit from existing infrastructure and logistics. An established manufacturing sector and mineral extraction activities also favour the development of steel production, due to the existence of a workforce with complementary skills. Among emerging markets for clean energy technologies, the iron and steel, manufacturing and mining sectors are concentrated in Southeast Asia and in a few countries in Latin America and Africa (Figure 4.26). Indonesia has particularly high value added in all these sectors, though iron is not among the main minerals mined in the country.

Figure 4.26 Current status of enabling factors for iron and steel production by country/region



IEA. CC BY 4.0.

Note: Indicators for each enabling factor are described in the Annex.

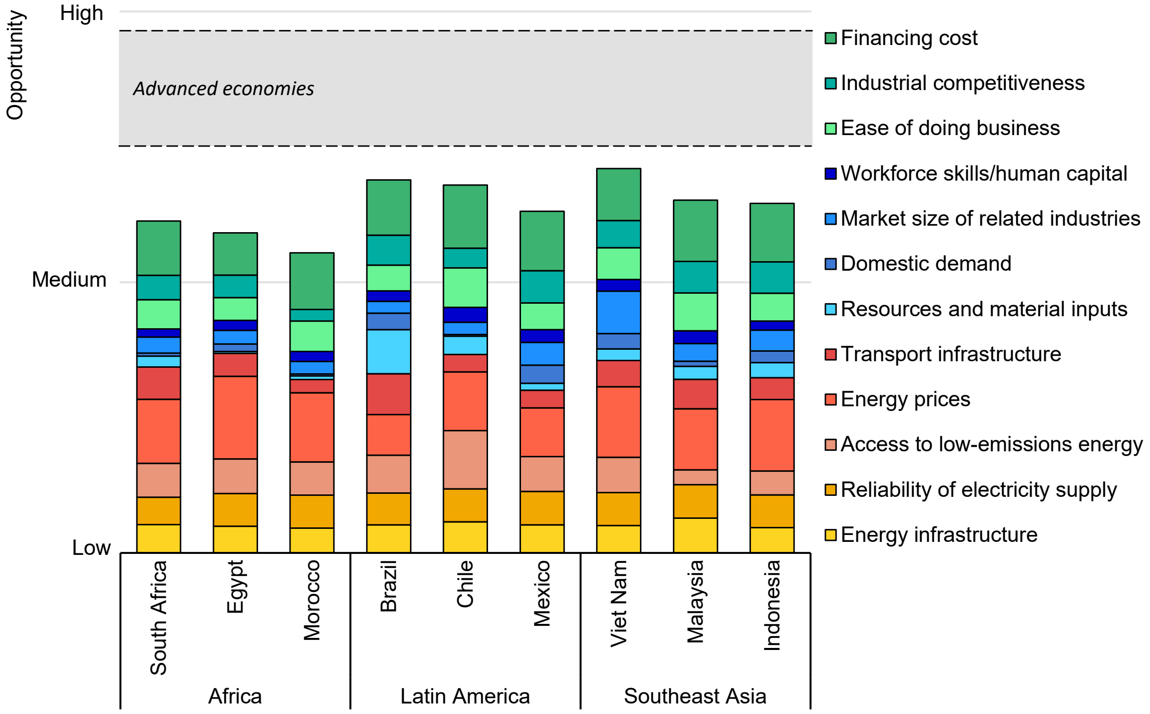
Across the African continent, South Africa and countries in North Africa stand out for their industries related to iron and steel production, as well as relevant workforce skills.

In our analysis of enabling factors, the scores differ markedly among those countries with the strongest potential to develop their iron and steel supply chains (Figure 4.27). In Latin America, Brazil already has a competitive iron and steel industry, thanks to the availability of raw materials including iron, scrap steel, and water (Box 4.3). Chile has lower energy prices and great access to low-emissions energy, as well as a favourable business environment, as does Mexico, but in both cases, the lack of raw material inputs reduces their potential for steel production.

In Southeast Asia, Viet Nam, Malaysia and Indonesia all score well thanks to their low energy prices, welcoming business environments and established markets in related industries, particularly in the case of Viet Nam. However, the lack of iron ore production in the region might hamper the development of new production capacity.

In Africa, South Africa and Egypt already have well-established iron and steel sectors thanks to cheap energy sources (coal in South Africa and natural gas in Egypt), existing domestic demand, or proximity to large markets such as Europe. In addition, both countries have robust transport infrastructure. Even without a highly developed iron and steel sector today, Morocco has comparable potential to South Africa and Egypt, on account of its high renewable energy potential (from solar PV), robust energy sector, and favourable business environment relative to other African countries.

Figure 4.27 Top three scoring countries for enabling factors for iron and steel production in Africa, Latin America and Southeast Asia



Notes: The size of the column segment is proportional to the combination of how well a country scores on a specific enabling factor and the relative importance of the factor. The range for advanced economies is based on the assessment of enabling factors in the United States, Germany and Japan. The results of this enabling factor analysis should not be interpreted as indicating the only countries in these regions to have current or future opportunities for iron and steel production. A comprehensive description of the methodology is detailed in Box 4.1, and a full list of indicators, sources and coverage can be found in the Annex.

Low-cost energy and iron ore supplies, large domestic markets and favourable business environments boost the potential for iron and steel investment in Viet Nam and Brazil.

Opportunities for direct reduced iron (DRI) production in Africa

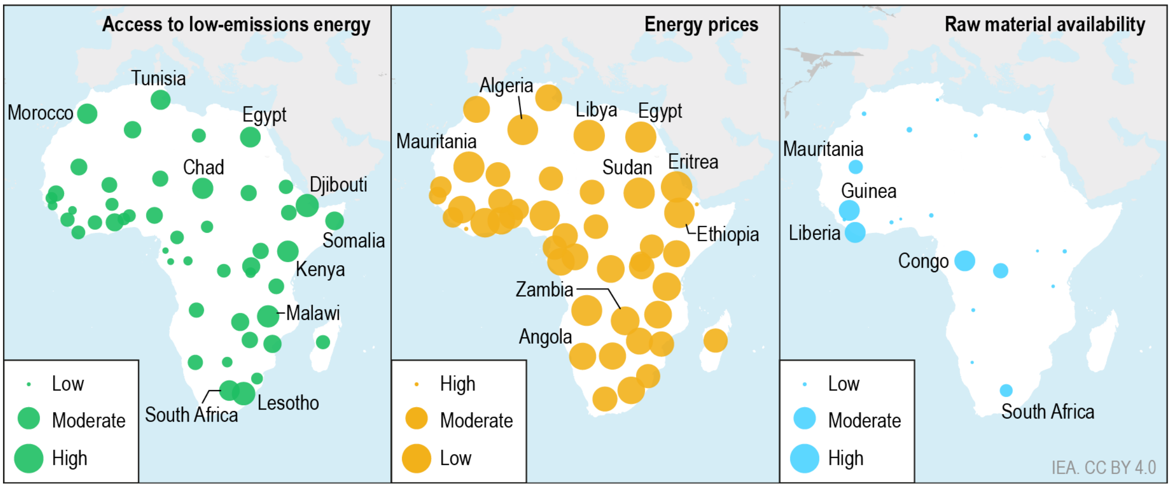
DRI production opportunities in Africa are spread across the continent. Western, Central and Southern Africa all have significant iron ore reserves, which offer an opportunity to move up the supply chain and export intermediate or final products that can bring more added value to their economies. In West Africa, reserves are spread between Guinea, Liberia, Mauritania, Nigeria, Sierra Leone and Togo, with Guinea having the most volume, though the deposits are low-grade (Britannica, 2024). Significant deposits can also be found on Central Africa's west coast (Gabon and Republic of Congo), as well as in South Africa, and to a lesser extent Zimbabwe and Namibia. It is important to mention that, with the available technologies today, the development of DRI production capacities requires the use of high-grade iron ore, but there are already projects developing technologies for the use of iron ores with lower grade (Fortescue, 2024). However, the location of these reserves and the lack of good infrastructure to deliver them to industrial centres can also make bringing the reserves to market difficult. In the case of North Africa, where these raw materials are not available (in the past, Morocco and Tunisia had significant reserves that today have been largely depleted), the opportunities lie more in their abundant renewable resources, their proximity to a large demand centre (Europe) and the presence of good trade infrastructure that can facilitate the competitive delivery of these raw materials (which are today globally traded) or intermediate products (like direct reduced iron) and then export the final products.

In 2022, Africa exported 53 Mt of iron ore on a net basis, the majority originating from South Africa, the world's third-largest exporter. Overall, the continent produced about 76 Mt of iron ore, 6% down on 2021, and over 11 Mt of DRI, 19% up on 2021. This downstream move increases the potential to profit from higher revenues: prices for iron produced conventionally can be almost four times higher than for raw iron ore (about USD 400/t compared with about USD 105/t); the price of near-zero emissions iron production could be even higher.

The increasing output of DRI and the need to reduce emissions through the use of alternative reducing agents like low-emissions hydrogen mean that there are increasing incentives to separate iron and steel production, which today are typically carried out in integrated facilities. This would allow for iron production to be located where low-emissions hydrogen can be produced cheaply, which would create an opportunity for emerging markets, provided that the critical trade infrastructure (particularly ports) to handle DRI is available.

The differing enabling factors in countries across Africa mean that there is potential to expand the DRI supply chain in several countries across the continent. DRI production hubs can be formed in areas where certain factors like raw material availability, stable energy infrastructure, and sufficient water resources are present (Figure 4.28). Within West Africa, for example, Guinea and Mauritania could benefit from neighbouring Senegal's robust electricity infrastructure and low water stress to process their abundant iron ore reserves. This type of regional co-operation can mimic other successful examples from the past, such as the European Coal and Steel Community (the precursor of what is now the European Union), established by Belgium, France, Italy, Luxembourg, the Netherlands and West Germany in 1951 with the objective of strengthening coal and steel industries in the region. This facilitated the development of a strong steel industry in the region, leveraging cheap coal resources (in Germany), access to iron ore reserves (in France) and a large demand in all the countries in the region, which were rebuilding their economies after World War II.

Figure 4.28 Enabling factors for the iron and steel supply chain in Africa



Notes: Raw material availability includes iron ore deposits and production, and scrap steel availability. Energy prices refers to electricity and natural gas prices. This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA analysis based on data from the World Bureau of Metal Statistics (2022); USGS (2023); S&P Capital IQ Pro: Commodity Profile database (2024a); World Bank (2024); and World Resources Institute (2023).

Countries with abundant iron ore resources in West and Central Africa could benefit from their proximity to low-emissions and low-cost energy in neighbouring countries.

Namibia, Mauritania and South Africa are already looking to take advantage of their favourable renewable energy potential to move down the iron and steel supply chain, with projects that combine onsite low-emissions hydrogen production with DRI and steel production being planned. The HyIron project in Namibia, for example, will take advantage of the country's high renewable energy potential to produce low-emissions hydrogen for DRI, as an alternative to the traditional production process that uses natural gas (HyIron, 2023). The project aims to produce about 15 kt per year of DRI in an initial phase, avoiding around 27 kt of CO_2 emissions per year.

Mauritania is in the process of reshaping its energy matrix and aims to increase the share of renewables in its electricity mix to 50% by 2030 (Ministère de l'Environnement et du Développement Durable, 2021). The government published a hydrogen roadmap in 2023 (Ministère du Pétrole des Mines et de l'Energie, 2022), and there are already a series of projects at various stages of development, a couple of which aim to produce low-emissions hydrogen for the iron and steel supply chain. Project Aman (CWP Global, 2022) for example, aims to produce about 1.7 Mt of low-emissions hydrogen. Project partners are exploring the possibility of developing a DRI production plant powered by this hydrogen. Steelmaker ArcelorMittal and SNIM, a state-backed iron ore mining company, are also exploring the possibility of establishing a pelletisation and DRI production plant in the country (ArcelorMittal, 2022). In South Africa, Sasol and ArcelorMittal – the country's biggest CO_2 emitters – are exploring the use of hydrogen for a DRI production hub at the Freeport Saldanha Industrial Development Zone hub (Argus Direct, 2022).

The potential for African countries to take a step up the value chain with respect to iron ore exports and near-zero emissions technologies for iron production is also gaining attention in the policy sphere. The African Union's Agenda 2063 commodities strategy includes the aim of moving up the value chain from being a raw materials supplier for the rest of the world, enabling countries to add value and extract higher rents from commodities, contributing to the Agenda's overarching goals of inclusive growth and sustainable development (African Union, n.d.). In South Africa, the Just Energy Transition Investment Partnership plan highlights "green" iron and steel as a key opportunity, helping to tackle the challenges of poverty, inequality and unemployment (Presidential Climate Commission, 2022). Kenya's Vision 2030 also highlights the goal of developing integrated iron and mini steel mills (Kenya Vision 2030, n.d.). The potential opportunity is also gaining attention outside the continent, as seen in a speech by the President of the European Commission emphasising that Mauritania's potential to produce and export low-emissions hydrogen and near-zero emissions steel means it is well-placed to supply demand in Europe (EC, 2024b).

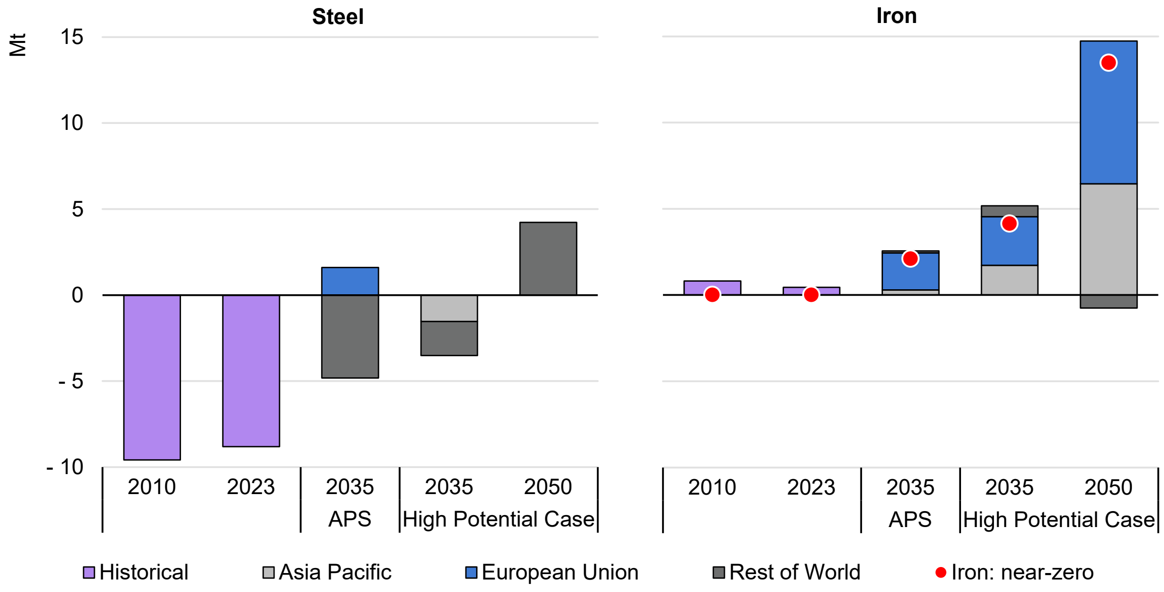
In the **APS**, total demand for steel in Africa grows rapidly. While global output grows less than 10% due to material efficiency gains, Africa's output increases by nearly 70% to 2035, driven by domestic demand and low production costs relative to the rest of the world. Emissions rise much less, by only 30% (9 Mt CO_2, or around 0.3% of global steel sector emissions today) compared with 60% in the STEPS, as a result of the deployment of near-zero emissions technologies, notably hydrogen-based DRI. Domestic demand also increases, driven up by the build out of housing, infrastructure and the vehicle stock, but not as fast as output. As a result, Africa would shift from being a net importer of steel to a net exporter in the long run (Figure 4.29).

An even bigger opportunity exists to boost the production of iron – the most energy-intensive step in steel production – in the long term. In the **High Potential Case**, iron production doubles to 30 Mt in 2035, driving a rise in exports to 5 Mt, with production reaching 55 Mt in 2050 and exports growing to almost 15 Mt.

Demand for exports is primarily a result of the cost advantages and favourable conditions offered by several countries in Africa. Most exports in 2050 in the High Potential Case are iron produced with near-zero emissions technologies, notably hydrogen-based DRI, destined primarily for Europe (around 60%) and Japan (around 35%). These countries all have established steel industries, but face relatively high costs for producing steel, especially based on near-zero emissions technologies. By retaining the steelmaking step (albeit a somewhat declining volume) locally, these importers could retain the flexibility that the proximity to their customers affords, as well as a portion of the value added and jobs that play an important role in their economies today.

For Africa, the opportunity represents a move up the value chain, from exporting iron ore to hydrogen-based DRI, which is likely to command a much higher price. At prices equivalent to the estimated costs of producing this iron in Europe in 2050, the almost 15 Mt of exports in the High Potential Case could be worth around USD 6 billion a year – more than four times the value of the same tonnage of iron ore exports at today's prices.

Figure 4.29 Iron and steel net trade in Africa, historical and in the Announced Pledges Scenario and High Potential Case, 2010-2050



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Notes: APS = Announced Pledges Scenario. Net trade shown for each commodity/technology and each region, which results in different quantities for net imports and exports in each case.

Several African countries could become key players in global exports of iron produced with near-zero emissions technologies by 2050 in the High Potential Case.

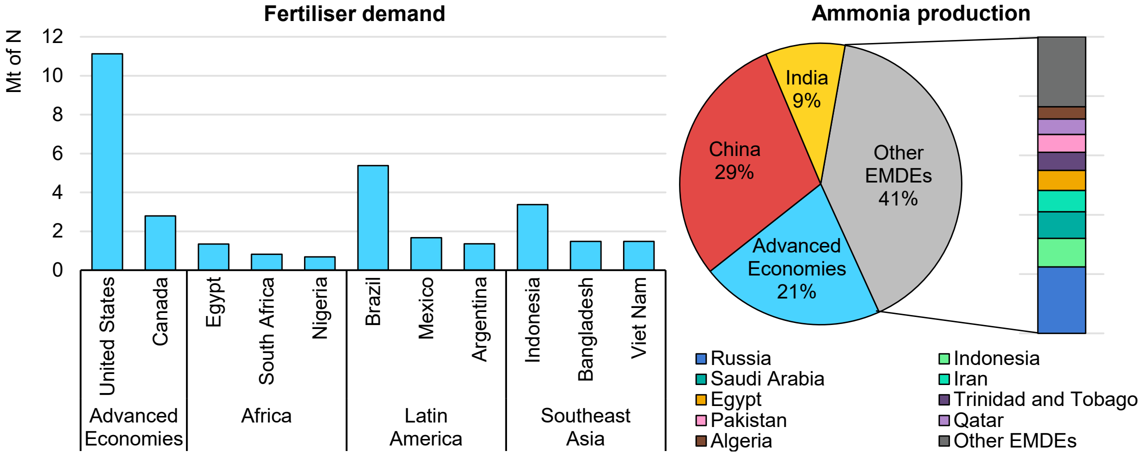
Ammonia

Technology-specific enabling factors

The principal enabling factors for the development of ammonia production in the emerging markets for clean energy technologies are access to low-emissions energy sources, existing domestic demand and production capacity, and the presence of a skilled workforce. In addition, water availability can be an important enabler since it is a major input to produce ammonia from renewable electricity. This is particularly true in countries with strong demand for fertilisers. Near-zero emissions ammonia production capacity will be needed both to replace existing capacity, which is based mainly on natural gas and coal, and to supply fuel for new emerging applications, such as shipping, power generation, seasonal energy storage, or its use as hydrogen carrier. In the near term, a large fraction of near-zero production capacity is expected to replace existing capacity where demand for ammonia is already available, as end-use technologies in new applications are not yet commercialised on a large scale. Overall, global demand for ammonia in existing applications is not expected to increase as strongly as demand for clean energy technologies such as solar PV, wind turbines and EVs, given that fertiliser production will remain the primary use.

Some Latin American countries score highest with respect to the size of the existing market, with the region today accounting for around 10% of global fertiliser demand and Brazil alone accounting for close to 5%. Southeast Asia is the next biggest of the markets studied, accounting for 7% of global fertiliser demand, and Indonesia alone for more than 3% (Figure 4.30).

Figure 4.30 Largest users of fertilisers in Africa, Latin America and Southeast Asia and in selected major markets, and global ammonia production by country, 2023



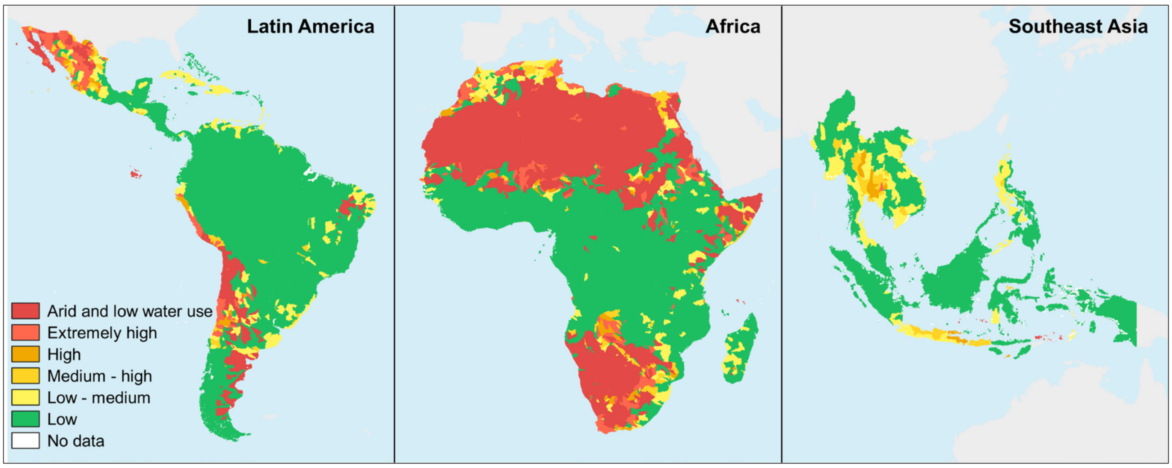
IEA. CC BY 4.0.

Notes: Mt of N = million tonnes of nitrogen; EMDEs = emerging markets and developing economies.
Source: IEA analysis based on data from IFA (2023).

Latin American countries account for the most fertiliser demand among the markets under consideration, while Africa and Southeast Asia account for most of the production.

Two main near-zero emissions production methods are emerging: electrolysis, and fossil-based routes with carbon capture and storage. This should favour emerging markets with access to abundant, low-cost renewable energy resources, as well as gas and coal producers that count on good underground CO_2 storage capacity. However, beyond the energy source, there are other key material inputs for ammonia production, and the availability of these inputs is also an important enabler for the development of new supply chains. The production of near-zero emissions ammonia from renewable energy requires only two material inputs: nitrogen (separated from air, therefore globally available, but requiring electricity) and hydrogen, produced from water electrolysis. This means that countries with large freshwater resources will be best-placed to build large production capacities.

Figure 4.31 Water stress levels in Latin America, Africa and Southeast Asia, 2023



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Notes: The water stress level is a measure of the ratio of total water demand to available renewable surface and groundwater supplies. This document, as well as any data and map included herein, are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

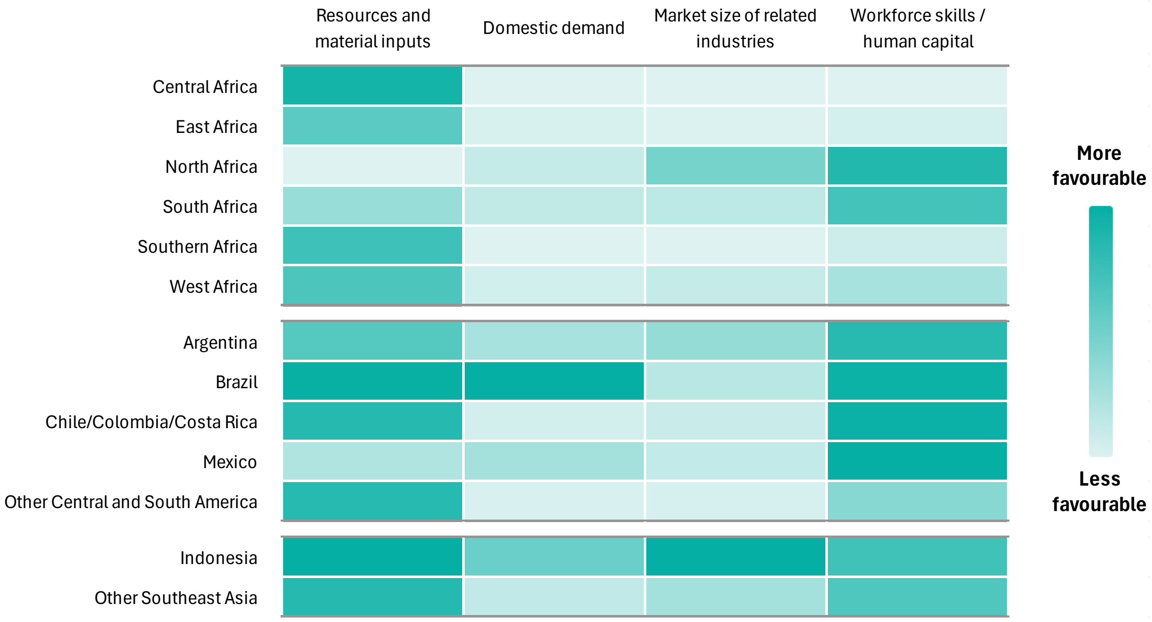
Source: IEA analysis based on data from the World Resources Institute (2023).

Water stress is a big problem in parts of Latin America, Southeast Asia, and particularly Africa, and is often co-located with abundant renewable resources for ammonia production.

Water stress can be a major barrier to the development of near-zero emissions ammonia production based on electrolysis in many emerging markets. Fresh water is particularly scarce across much of Africa and some parts of Southeast Asia and Latin America, especially Chile, Peru and Mexico (Figure 4.31). Some countries in Latin America and Southeast Asia also suffer long periods of drought. One way of overcoming this hurdle is desalination of sea water or treatment of wastewater, and several large projects in areas with significant water stress are under development with the idea of using desalinated water, such as the NEOM project in Saudi Arabia, or a project that ACWA power is developing is Tunisia (IEA, 2024f). However, this can increase the overall cost of ammonia production up to 3%. This might seem small, but could reduce the competitiveness of a project, unless it can be compensated by very low-cost energy.

The presence of a skilled workforce is also a fundamental requirement for the development of new near-zero emissions ammonia production facilities. The processes involved in ammonia production are similar to those for other basic chemicals, and the presence of a large workforce in the chemical industry, and strong science and technology vocational education, are good indicators of the readiness of countries to develop new ammonia plants. Latin American countries score highest for these indicators among emerging markets for clean energy technologies, followed by some countries in Southeast Asia, particularly Thailand (Figure 4.32). Countries with a business environment that favours innovation are most likely to be successful in implementing projects using nascent near-zero emissions technologies.

Figure 4.32 Current status of enabling factors for near-zero emissions ammonia production by country/region



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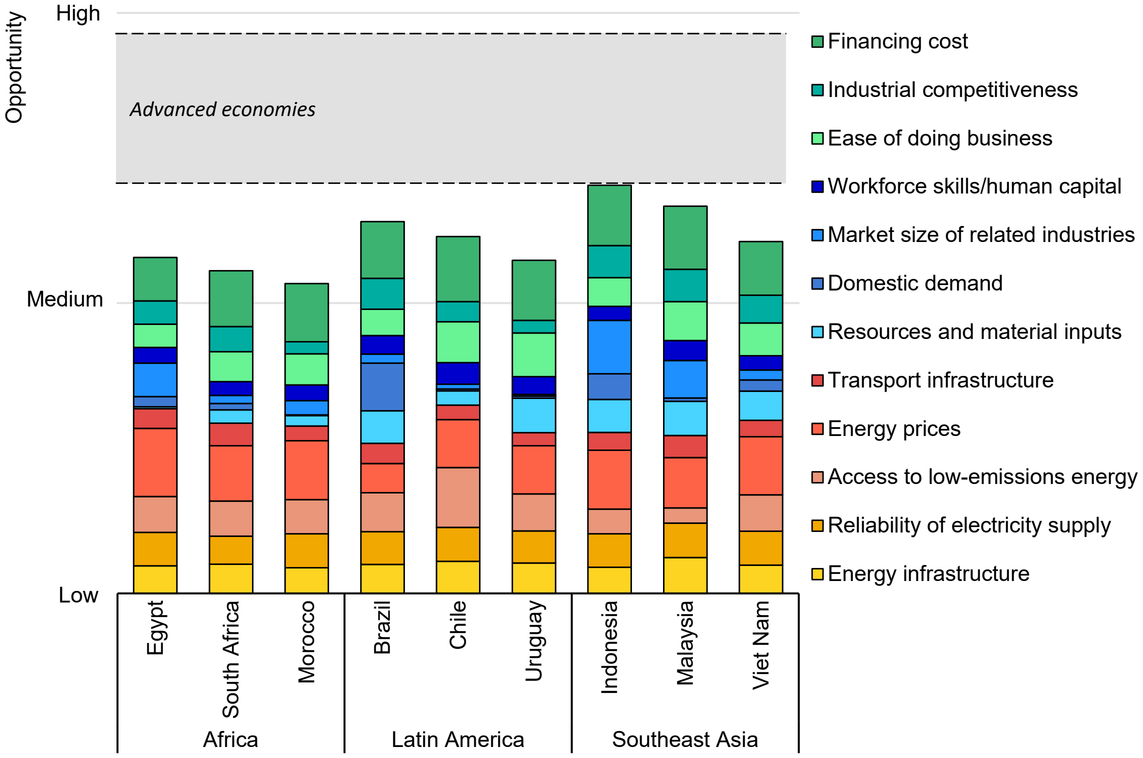
Note: Indicators for each enabling factor are described in the Annex.

Many countries in Latin America, Africa and Southeast Asia could exploit their renewable energy resources to make near-zero emissions ammonia.

Considering all the enabling conditions for establishing near-zero emissions fertilisers and ammonia supply chains (business environment, energy and infrastructure, and resources and domestic markets), the countries that present the best potential for the development of new supply chains are Indonesia, Malaysia and Viet Nam in Southeast Asia; Brazil, Chile and Uruguay in Latin America; and Egypt, South Africa and Morocco in Africa (Figure 4.33).

Figure 4.33 Top three scoring countries for enabling factors for ammonia production in Africa, Latin America and Southeast Asia



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Notes: The size of each column segment is proportional to the combination of how well a country scores on a specific enabling factor and the relative importance of the factor. The range for advanced economies is based on the assessment of enabling factors in the United States, Germany and Japan. The results of this enabling factor analysis should not be interpreted as indicating the only countries in these regions with opportunities for ammonia production. A comprehensive description of the methodology is detailed in Box 4.1, and a full list of indicators, sources and coverage can be found in the Annex.

Enabling conditions for near-zero emissions ammonia production are as favourable in Indonesia as in some advanced economies.

Most emerging markets that have a large number of enabling factors have in common low energy prices, a welcoming business environment and relatively low financing costs. However, other factors are behind significant differences among emerging markets.

For example, Southeast Asian countries share the advantage of very low water stress. Indonesia counts on the largest existing production capacity for ammonia, whereas Malaysia, despite low existing production capacity, already has a large chemical industry that could facilitate workforce development.

In Latin America, Brazil has low water stress and is also the largest existing market for fertilisers (and therefore the largest ammonia demand) across all emerging markets for clean energy technologies. These factors outweigh weaknesses in its existing ammonia production capacity – Brazil is the second-largest importer of ammonia-derived products in the world after India. Among overall top scorers, Chile benefits from the largest renewable energy potential and the lowest financing cost across emerging markets, and also has a strong environment for business development, although it currently has very little demand for ammonia, all of which is met through imports, with no domestic production capacity available.

In Africa, Egypt, South Africa and Morocco present challenges with water scarcity and small existing fertiliser demand, with a large fraction of production being exported today. However, Egypt is the second-largest existing ammonia producer of all emerging markets considered here, South Africa can count on good transport infrastructure and industrial competitiveness, and Morocco on its low energy prices and environment for business development.

Opportunities for ammonia production in Africa

Africa currently produces around 11 Mt of ammonia, and around 7 Mt of nitrogen fertilisers (in nitrogen content 'N' terms) per year. In 2023, the continent imported around 0.5 Mt of ammonia and exported around 2.5 Mt N of nitrogen fertilisers on a net basis.

Ammonia production and imports are mostly used for fertiliser production, with some countries being notable exporters – Egypt, for example, is the fifth largest urea exporter in the world, mostly to Europe.

Ammonia production is concentrated in just a handful of African countries, with Egypt, Algeria and Nigeria accounting for more than 90% of all production. In the rest of the continent, production is very low or almost non-existent, even in countries which today are large producers of fertiliser. For example, Morocco is a large exporter of fertilisers and the world's third-largest importer of ammonia today, and meets all its ammonia demand for fertiliser production with imports.

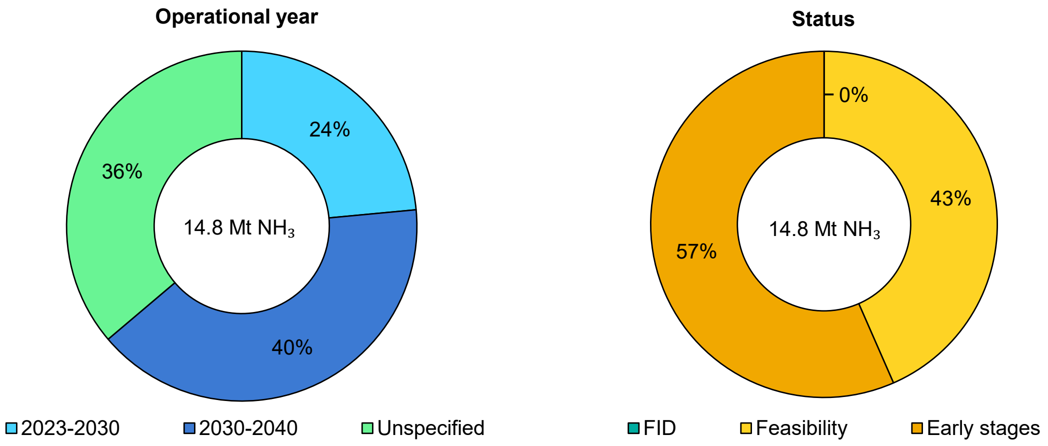
However, the strong potential of these countries to develop supply chains for near-zero emissions ammonia production from renewable energy has already caught the attention of the private sector, which has announced a significant number of projects.

There are multiple drivers behind this trend, with both policy makers and the private sector announcing ambitions to reduce reliance on imports and strengthen local value chains, in particular for the agricultural sector and food industries, which are important in many African countries. The risks of dependency on imported natural gas have recently come to light with some companies in Egypt halting ammonia production due to a gas shortage. Some have since announced plans to switch to hydrogen-based production instead (Cedigaz, 2024).

Elsewhere, in 2023, OCP, a Moroccan state-owned enterprise, announced a USD 7 billion (Atalayar, 2023) investment in the development of renewable ammonia production plants, with the objective of producing 1 Mt by 2027 and up to 3 Mt in 2032. This is part of its USD 12 billion 2023-2027 Green Investment Programme, which specifically mentions the objective to strengthen local value chains and create 25 000 jobs (OCP Group, 2023). In Namibia, the Hyphen Hydrogen Energy Project, with a targeted annual ammonia production of 2 Mt by 2030, expects to create 3 000 permanent jobs, to supply water from the desalination plant to local communities and to reduce Namibia's electricity imports by feeding surplus electricity from the project into the grid (Windhoek Observer, 2024).

Countries that have announced intentions to support the development of local production capacities for renewable ammonia include Kenya (Ministry of Energy and Petroleum of Kenya, 2023), Tunisia (Ministère de l'Industrie des mines et de l'Energie de Tunisie, 2024) and South Africa (Industrial Development Corporation, 2023). Kenya's hydrogen strategy includes a target to produce 300-400 kt of nitrogen fertilisers by 2032, with the aim of developing a local "green" fertiliser industry to decrease dependency on imported fertilisers and of reducing the impact of price volatility for the agricultural sector, the largest sector in Kenya's economy.

Figure 4.34 Near-zero emissions ammonia trade by operational date and status based on announced export-oriented projects in Africa, 2023



Notes: FID = final investment decision. "Unspecified" includes projects that have not announced a target date to start operating.
Source: IEA analysis based on multiple sources, including company announcements.

Announced export-oriented projects in Africa could lead to around 15 Mt of near-zero emissions ammonia exports, but more than half are at very early stages of development.

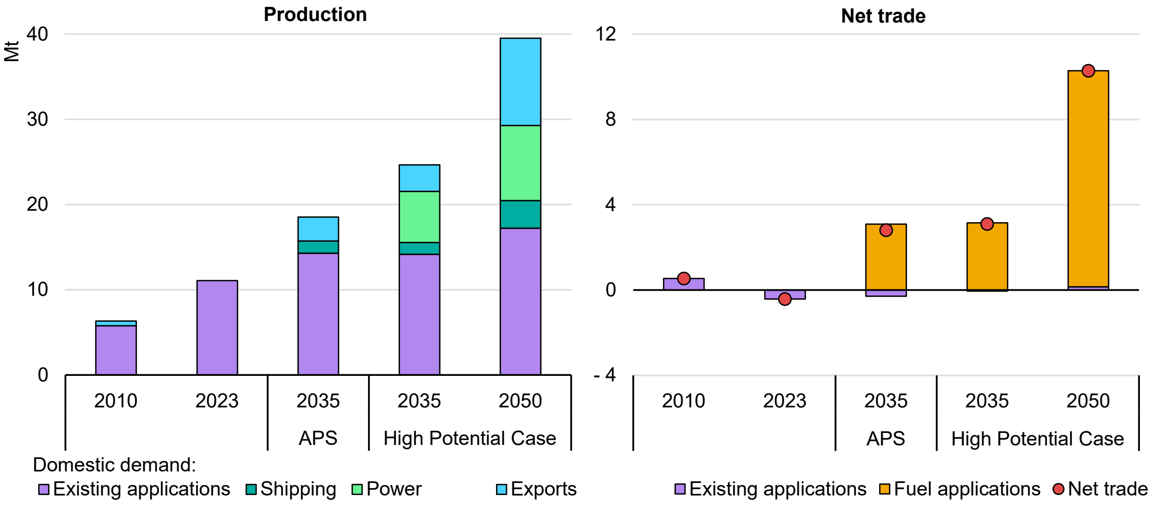
More broadly, many countries and companies want to capture opportunities in a potential global emerging market for low-emissions hydrogen and hydrogen-based fuels (IEA, 2024f). For example, Namibia (Ministry of Mines and Energy of Namibia, 2022) and Algeria (Hydrogen Insight, 2023) have developed export-oriented hydrogen strategies, and a large number of projects for the trade of ammonia (both for fuel and chemical applications) have been announced on the continent (Figure 4.34). While these trade-oriented projects may be seen as a threat to the development of projects oriented to domestic demand, they can also serve the domestic market and help build experience that can lay the groundwork for the development of projects targeting domestic applications.

A potential challenge to the development of large renewable ammonia projects is the large investment they require, especially in the context of the high cost of capital common to most African countries today. Successful development will therefore strongly depend on making them more attractive to investors. One key enabler that can help de-risk these projects is to find dependable off-takers for a large share of the potential production output (see Chapter 6). Counting on large international off-takers with robust resources is more likely to de-risk the project than counting on smaller local companies.

Some projects in Africa, such as the one developed by Hyphen Hydrogen Energy, have already signed preliminary off-take agreements with companies from Europe (RWE, 2022) and Korea (Hyphen Hydrogen Energy, 2023). Moreover, in July 2024, Hintco GmbH (the implementing entity of the H2Global instrument, a double-auction mechanism for the development of projects to export renewable hydrogen-based fuels to Europe) announced that Fertiglobe, with its Egypt Green Hydrogen project, was the winner of the first H2Global pilot auction for renewable ammonia (H2Global, 2024).

In the **APS**, ammonia production in Africa grows from 11 Mt today to 19 Mt in 2035 (Figure 4.35). In addition, near-zero emissions ammonia production grows from nearly nothing today (there is only one small project with a production capacity of around 10 kt of ammonia in Egypt) to reach 7 Mt in 2035. Although unabated fossil fuel-based ammonia production for existing agricultural and industrial uses also grows slightly, to reach 12 Mt by 2035, the faster growth in near-zero emissions ammonia production helps the continent to reduce ammonia imports.

Figure 4.35 Ammonia production and net trade in Africa, historical and in the Announced Pledges Scenario and High Potential Case, 2010-2050



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Note: APS = Announced Pledges Scenario.

Ammonia production in Africa could potentially reach 40 Mt in 2050, helping the continent to reduce dependency on imports and opening up opportunities to export.

However, a larger share of the near-zero emissions ammonia produced in the continent goes to new applications, namely shipping, where demand reaches 1.5 Mt by 2035, or is exported to other regions (3 Mt by 2035). The surge in ammonia exports does not impact food security. In the APS, Africa also sees its nitrogen fertiliser production increase by 25% by 2035, maintaining its net export position after meeting domestic demand.

In a **High Potential Case** with more favourable conditions, ammonia production grows faster and could reach 25 Mt in 2035 and close to 40 Mt in 2050, largely thanks to deployment of near-zero emissions ammonia production, which could reach 15 Mt by 2035 and 35 Mt in 2050. In this Case, the continent could completely eliminate ammonia imports for fertiliser production by 2050.

Export opportunities for ammonia for fuel applications also grow considerably to reach more than 10 Mt by 2050, responding to growing demands, mostly from Europe, where it is either converted back into hydrogen or directly used as a fuel for decarbonisation purposes. At today's prices, these 10 Mt of exports could be worth close to USD 5 billion per year (more than the entire GDP of several African countries), and even higher if fuel markets offer higher premiums.

In this scenario, the geographical distribution of ammonia production becomes more varied as more countries expand their facilities. In 2050, North Africa still leads on production of ammonia for its use in existing applications (70%), but its share of total ammonia production decreases below 50% (down from almost 80% today). South Africa increases its share of ammonia production to around 25%, with a focus on energy applications, particularly in power generation. At the same time, countries in regions like West and Southern Africa exploit their abundant renewable resources to produce ammonia and export it, and to become producers of ammonia for use in international shipping.

Opportunities for ammonia production in Latin America

Latin America and the Caribbean currently accounts for around one-tenth of global fertiliser demand, far more than the other regions considered in this chapter. Around 80% of this is highly concentrated in Brazil, Mexico and Argentina, with Brazil alone accounting for more than 50% of the demand in the region.

The region is a net importer of ammonia and of nitrogen-based fertilisers (if excluding Trinidad and Tobago),[2] with more than 20 countries in the region (accounting for 10% of regional fertiliser demand) satisfying 100% of their demand with imports. Brazil currently imports more than 80% of its fertiliser demand. This has a strong economic impact in the region, which had an annual net trade deficit for fertiliser of USD 3.9-4.5 billion during the 2018-2020 period, which increased to USD 7.1 billion in 2021 and as much as USD 9.1 billion in 2022, as a consequence of the global rise in natural gas prices triggered by Russia's invasion of Ukraine. Brazil alone had an annual fertiliser trade deficit of USD 4.4-7.2 billion in the last 3 years, representing around two-thirds of the deficit for the entire region.

The development of new ammonia supply chains based on the vast renewable resources of the region provides an opportunity to decrease the dependence on imports, improve food security and improve the economies of countries in which agriculture represents a significant share of domestic GDP. Agriculture accounted for 17% of Nicaragua's GDP in 2023, more than 10% of GDP in Bolivia, Guyana, Honduras and Paraguay; and between 5% and 10% for Argentina, Belize, Brazil, Colombia, Ecuador, Guatemala, Peru, Uruguay and Venezuela (World Bank, 2024).[3]

In light of this potential, some governments are already targeting a reduced dependency on fertiliser imports. For example, in 2022 Brazil published a national fertiliser plan for 2050, with the aim of reducing imports by 50% by 2040 (Secretaria Especial de Assuntos Estratégicos, 2022).

Countries in Latin America are also exploring the possibility of using their renewable resources to export renewable ammonia for fuel purposes to regions that are expected to become large importers, mostly in European and Asia Pacific markets. Chile has been particularly active in this respect, setting the target of becoming the global leading exporter of renewable hydrogen and derivatives by

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[2] The region overall is an exporter of ammonia, but this is a consequence of the large ammonia production in Trinidad and Tobago, which exports most of its production and represents almost two-thirds of ammonia production in the region.

[3] These shares include agriculture, forestry and fishing.

2030 (Ministerio de Energía de Chile, 2020). In addition, the Chilean government has signed several export-oriented co-operation agreements and memoranda of understanding with Germany (Ministerio de Energía de Chile, 2021), Korea (The Korea Herald, 2021) and the Netherlands (Ministerio de Energía de Chile, 2023), among others. In addition, Chile is home to a large number of announced projects for the production of low-emissions hydrogen and its derivatives, some at GW-scale. Close to 60 projects have been announced, with 15 of them being export-oriented ammonia projects. If all these projects come to fruition, they could produce close to 10 Mt of near-zero emissions ammonia to export to international markets.

In Brazil, companies have also explored the possibility of developing international supply chains for hydrogen-based fuels. For example, several initiatives have been announced in the states of Ceará and Piaui for the development of this type of project, largely targeting Europe as a potential export market. This activity is primarily being driven by private developers, rather than being stimulated by government policy, which is more focused on developing hydrogen hubs for domestic applications.

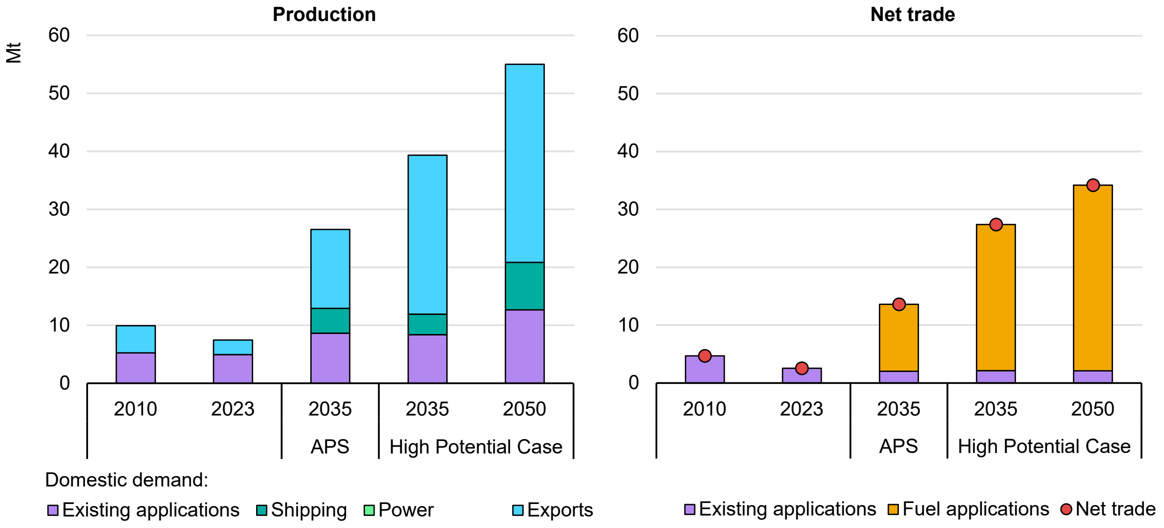
In the **APS**, ammonia production in Latin America grows more than threefold by 2035 (Figure 4.36). This outstanding growth is primarily stimulated by the development of export-oriented supply chains.

This also helps to reduce dependency on imports to meet nitrogen fertiliser demand. In 2023, the region imported 6 Mt of nitrogen in fertilisers (meeting 65% of its demand). In the APS, imports decrease to 5 Mt in 2035 (45% of regional demand).

To achieve this goal, the production of ammonia for fertiliser and industrial applications in the region increases from 7 Mt today to 11 Mt by 2035, with a growing contribution from near-zero emissions production routes. In the APS, production of near-zero emissions ammonia for existing applications grows to reach close to 4 Mt by 2035, up from almost nothing today, accounting for one-third of ammonia production for these use cases. For new applications, more than 4 Mt are produced in Latin America in 2035 for its use as a shipping fuel.

In Brazil, the region's largest user and importer of ammonia derivatives, ammonia production for existing applications in the country expands massively in the APS, reaching more than 4 Mt by 2035, with 80% of this production based on near-zero emissions technologies. Although ammonia imports for existing applications increase slightly compared with today's level, the increase in domestic production allows the country to reduce its net imports of fertilisers from 4 Mt of nitrogen today to 2.5 Mt in 2035, and exports of ammonia for fuel applications reach nearly 2 Mt (around USD 1 billion per year at today's ammonia prices).

Figure 4.36 Ammonia production and trade in Latin America, historical and in the Announced Pledges Scenario and High Potential Case, 2010-2050



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Notes: APS = Announced Pledges Scenario.

Ammonia production in Latin America rises steeply to 2035 in the APS, reducing reliance on fertiliser imports and allowing the region to become an exporter for fuel applications.

In a **High Potential Case**, ammonia production in Latin America could grow to 40 Mt in 2035 and 55 Mt in 2050, with 85% of this production based on near-zero emission routes by 2035 and 95% by 2050. The region could become one of the largest exporters of near-zero emissions ammonia in the world, just behind the Middle East. Latin America could export close to 35 Mt of near-zero emissions ammonia by 2050, mostly to Japan and Europe. This is equivalent to almost twice global ammonia trade today, and based on current ammonia prices, would be worth more than USD 15 billion per year.

The lion's share of these exports is concentrated in Chile, which today has a very small demand for ammonia or nitrogen fertilisers (0.2% of global demand), and this does not change significantly. However, the country makes use of its large renewable potential to develop new supply chains for near-zero emissions ammonia for export to international markets.

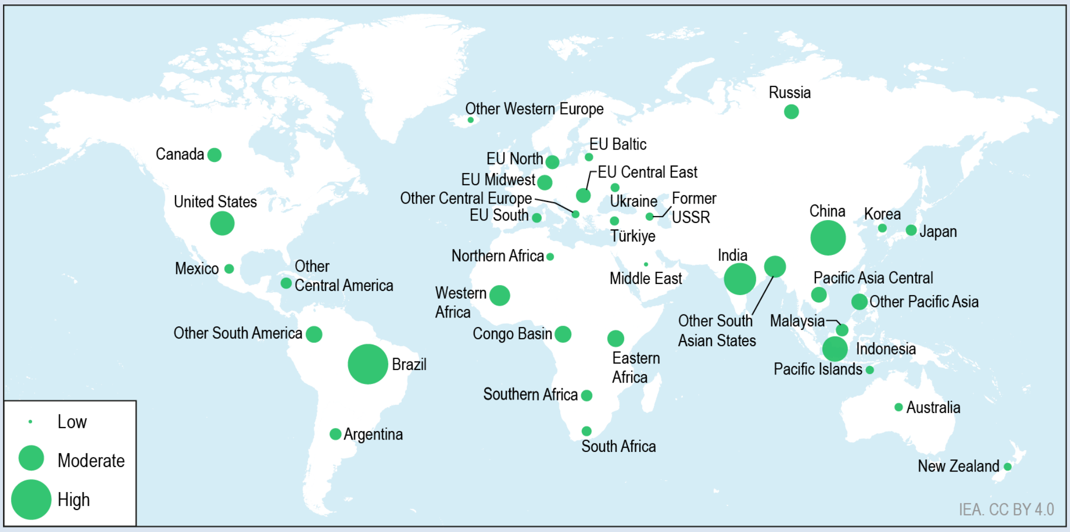
In addition, the spectacular growth of near-zero emissions ammonia production in the High Potential Case – which could account for 85% of total ammonia production for use in existing fertiliser and industrial applications in 2050 – allows Latin America to reduce its import dependence for fertilisers, with only 25% of regional demand met by imports (3 Mt) by 2050. For example, this would allow Brazil to meet its target to reduce import dependency by 50% in 2040 and reduces the total amount of imported fertiliser to just 1 Mt by 2050.

Box 4.4 Opportunities for low-emissions fuel production in emerging markets

Low-emissions drop-in fuels, such as some biofuels and synthetic fuels, can be an important opportunity for decarbonising transport in line with reaching net zero emissions by 2050. They have a particularly important role in long-distance heavy transport modes such as shipping and aviation, which are more difficult to electrify and for which the typically long lifetimes of shipping vessels (20-35 years) and aircraft (25-60 years) mean that drop-in fuels can support emissions reductions in existing assets. They can also play a role in reducing emissions from the existing fleet of road vehicles: even in the NZE Scenario, which sees all new conventional car sales ceasing in 2035, over 80 million conventional vehicles (ICE or hybrid electric vehicles) are still on the road in 2050, representing around 5% of the total car stock. Drop-in fuels are also able to make use of existing storage, transport and fuelling infrastructure, moderating investment costs for new fuel distribution infrastructure.

Biofuels are cheaper to produce than synthetic fuels and are already produced in significant quantities today. There are significant opportunities for emerging markets to produce and export biofuels. For example, Brazil is currently the second-largest biofuel producer worldwide after the United States, producing over 900 PJ of liquid biofuels in 2023 with an estimated market size of over USD 30 billion. Estimates of Brazil's biomass production potential show it has the highest potential among EMDEs (Deng, Koper, Haigh, & Dornburg, 2015). Southeast Asia and West, Central and East Africa also have relatively high bioenergy supply potential (Figure 4.37). In the NZE Scenario, EMDEs make us of their bioenergy potential and produce 8 EJ of biofuels in 2050, about 70% of the global total.

Figure 4.37 Bioenergy supply potential



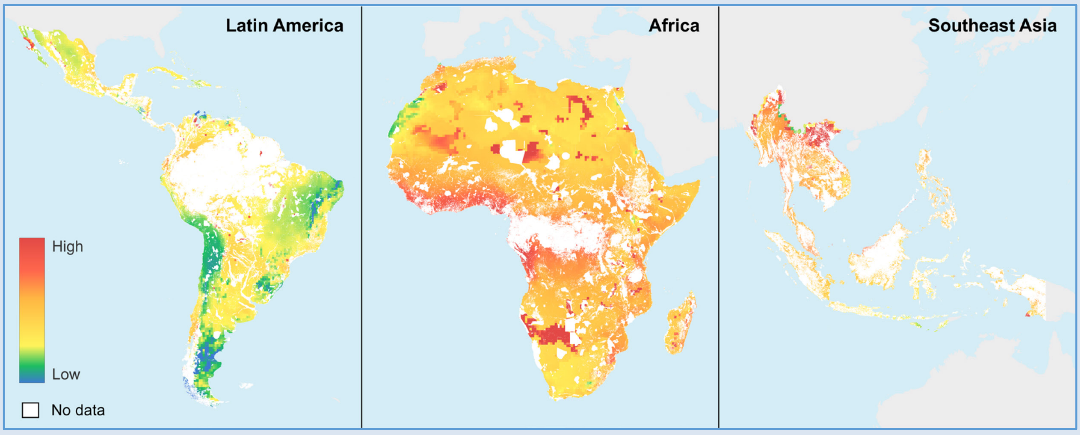
IEA. CC BY 4.0

Notes: IEA analysis based on sustainable bioenergy supply constrained to 100 EJ globally. Regional groupings are based on the International Institute for Applied Systems Analysis (IIASA) GLOBIOM model.

There are, however, limits to sustainable biomass production, with vast uncertainty associated with the impacts of land use change. This renders the use biofuels as a primary means of transport decarbonisation unlikely and requires some form of prioritisation; in the NZE Scenario, the available sustainable bioenergy potential is around 100 EJ. As discussed in a recent IEA study in support of Brazil's G20 presidency, sound regulatory frameworks based on transparent, science-based carbon intensity calculations will be required to attract the investments needed to scale up biofuel production (IEA 2024f).

Low-emissions synthetic fuels can be produced for example using atmospheric CO_2 from direct air capture and electrolytic hydrogen produced from renewables. As such, there is an opportunity for regions with high solar or wind potential and land availability – especially non-arable and bare land availability – to produce these low-emissions fuels. Chile, Brazil and Argentina show the potential to produce relatively low-cost synthetic fuels (Figure 4.38). Some coastal areas in North Africa have high solar generation potential and sufficient land availability, which could be leveraged to produce relatively low-cost synthetic fuels. Southeast Asia is limited in the amount of available land, due to forest coverage and a terrain slope unsuitable for renewable deployment.

Figure 4.38 Relative cost of synthetic fuels production based on solar and wind resources in the Net Zero Emissions by 2050 Scenario, 2030



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Source: IEA analysis based on Jülich Systems Analysis using the ETHOS model suite (Forschungszentrum Jülich, 2024).

Across countries in Latin America, Africa and Southeast Asia, there is the theoretical potential to produce up to 75 EJ of synthetic fuels from solar PV alone.* For comparison, around 7 EJ of synthetic fuels are consumed for transport in 2050 globally in the NZE Scenario, predominantly in aviation and shipping. The production of synthetic fuels for these hard-to-decarbonise transport modes also results in the availability of some by-product synthetic gasoline that could be leveraged to decarbonise the conventional road vehicle stock (IEA, 2023c).

As with other clean technologies, partnerships between countries can play an important role in leveraging different strengths to build out new supply chains. One example is a recent initiative spearheaded by Japan and Brazil to expand the use of sustainable fuels for mobility, combining their expertise on vehicle technologies and low-emissions fuels, respectively (Ministry of Foreign Affairs of Japan, 2024).

* Assuming all the solar PV potential is used for synthetic fuel production (excluding competing uses).

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Chapter 5: International shipping

Highlights

- Shipping is the backbone of international trade, supporting more than 80% of all trade by mass. Global maritime trade has increased threefold in mass terms and tenfold in value over the last four decades. Fossil fuels and other inputs to heavy industry today account for nearly two-thirds of shipping activity, mostly using dry bulk carriers and oil tankers. Fossil fuels alone account for 40% of the total seaborne mass traded, and iron ore and bauxite for making steel and aluminium for 20%.
- Shipping activity today is highly concentrated within the Asia Pacific region, with China at its centre: it is home to the busiest container ports and is the main importer of goods carried by tanker and as dry bulk. Imports to and exports from China account for over 40% of global shipping activity related to the needs of heavy industry and fossil fuels.
- Around 60% of global seaborne trade passes through one or more maritime chokepoints. One-third of all fossil fuel trade passes through the Strait of Malacca, and 20% through the Strait of Hormuz, while two-thirds of maritime trade in clean energy technologies passes at least one chokepoint and over half through Malacca alone. In the Stated Policies Scenario (STEPS), clean technology shipments through Malacca increase substantially and its share in total maritime trade approaches 60% by 2035.
- Clean energy transitions will shift global trade routes and slow shipping activity growth, despite increasing trade in clean energy technologies. In the Announced Pledges Scenario (APS), declining use of fossil fuels and increased recycling reduce shipping activity by 10% compared with in the STEPS by 2035 and 15% by 2050. Emissions from international shipping decline by almost 60% by 2035 and by more than 90% by 2050 in the APS, driven by a switch to biofuels and near-zero emissions ammonia and methanol, though uncertainties remain about future uptake. Those fuels account for more than 80% of shipping energy use by 2050.
- Shipping and other transport costs account for less than 10% of the total cost of supplying low-emissions fuels to ports for refuelling, but they are nonetheless more costly to ship than oil-based fuels. Production costs are lower in regions that are not necessarily bunkering hubs today. This creates an opportunity for ports to become pioneers in low-emissions fuel supply, especially in areas like the Middle East and Australia, where renewable resources are abundant and there is considerable maritime traffic. Ports in other regions with strong renewable resources could also export ammonia to the main existing shipping hubs.

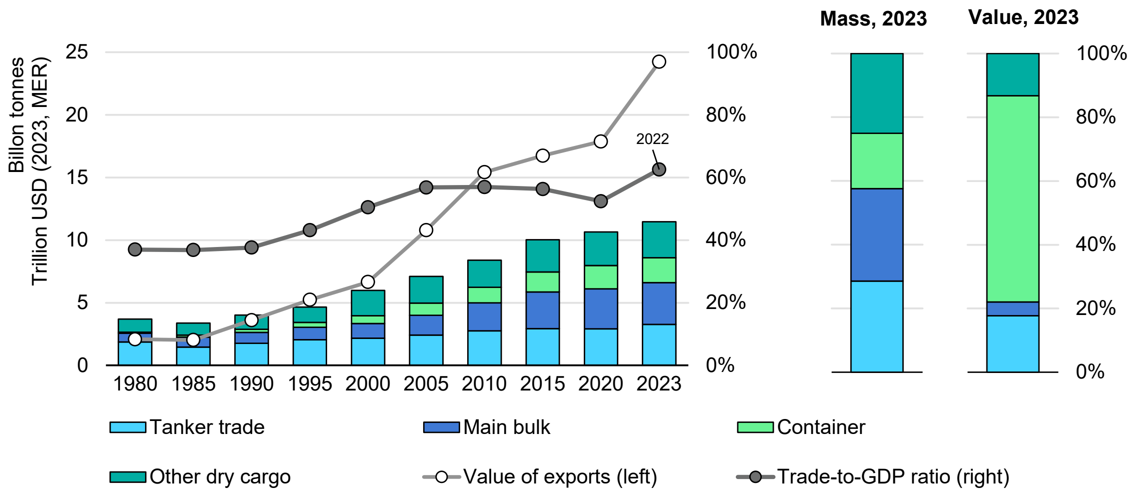
The majority of international trade in fossil fuels, manufactured clean energy technologies and the bulk materials used to make them is transported by sea. The clean energy transition is already starting to have a profound impact on both the scale of international shipping, the types of goods being shipped and maritime routes. This chapter looks at the role of shipping in international trade today, how it could evolve in the different scenarios according to the pace of the energy transition and the prospects for decarbonising shipping operations themselves in contributing to that transition.

5.1 Role of shipping today

Evolution of the shipping industry

Shipping is at the heart of global supply chains, as 80% of all inter-regional trade in mass terms is transported via ships. The mass and value of global maritime trade have both expanded considerably over the last four decades. Between 1985 and 2023, total cargo mass increased threefold and the value of goods shipped increased more than tenfold (Figure 5.1).

Figure 5.1 Global maritime trade in value and in mass, 1980-2023, and shares by cargo type, 2023



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Notes: In the left-hand chart, mass is shown as bars, and value as lines. Definition of categories follows United Nations Trade and Development (UNCTAD) definitions: 1980–2005 figures for main bulk include iron ore, grain, coal, bauxite/alumina, and phosphate; starting in 2006, it includes iron ore, grain and coal only. Data for bauxite/alumina and phosphate are included under other dry cargo. Tanker trade includes crude oil, refined petroleum products, gas and chemicals. The latest data point for trade-to-GDP ratio corresponds to 2022.

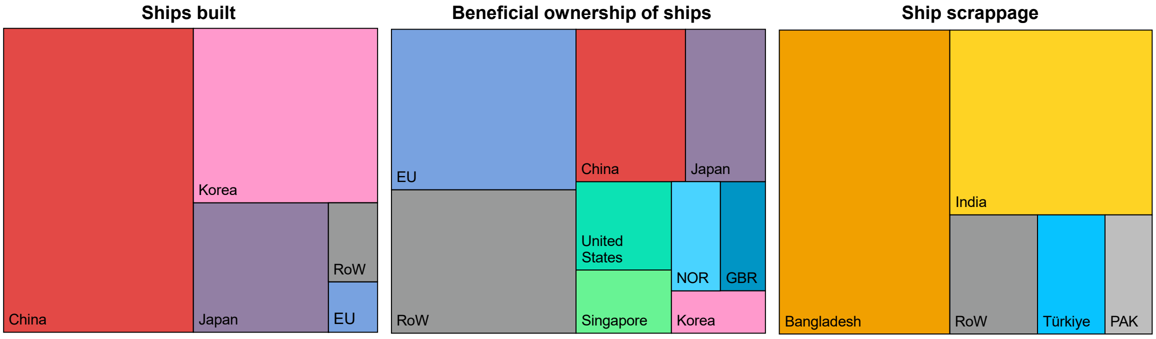
Sources: IEA based on various data sources. Traded mass until 2020: UNCTAD (2021). Total value of world exports: UNCTAD (2024e); and Trade (imports plus exports) to GDP ratio: World Bank (2022).

The mass and value of maritime trade has risen rapidly since the 1990s, with containerised trade increasing fastest.

The expansion in trade was driven mainly by growth in global economic activity and globalisation, with the ratio of trade to global GDP increasing to over 60%. Shipping is the most efficient and cost-effective way of transporting bulky goods. Transporting one tonne of goods over 1 000 km by ship currently costs roughly USD 4 at sea (van der Meulen, et al., 2023), compared with USD 2 000 by air, USD 300 by road and USD 80 by rail (Bureau of Transportation Statistics, 2024). The cost of shipping is an important contributor to the total cost of supplying goods, especially low-value bulk materials, and increases in shipping costs were a major contributor to global inflationary pressures that built up in the wake of the Covid-19 pandemic (Isaacson and Rubinton, 2023).

The structure of global shipping has changed markedly since the 1980s. Oil tanker trade dominated shipping in 1980, accounting for well over half of total traded mass; that share has fallen to around one-quarter today, as trade in bulk materials, containerised freight and other dry goods have all grown more quickly. Bulk shipping is now the leading category, accounting for about 30% of current total mass – up from under 20% in 1980. The share of containerised shipping has, nonetheless, risen faster in percentage terms and dominates global trade in terms of value today: it accounts for 17% of global maritime trade in terms of mass (up from just 2% in 1980), but 65% in value terms. Goods transported in containers, such as intermediate and final products, are usually of much higher value per tonne than bulk goods, such as iron ore, grain and oil. As trade has shifted from commodities to manufactured goods, especially with the rise of global value chains and China as the world's manufacturing powerhouse, the value of traded goods has increased more rapidly than their quantity (see Chapter 1).

Figure 5.2 Country shares of shipbuilding, ownership and scrappage, 2023



IEA. CC BY 4.0.

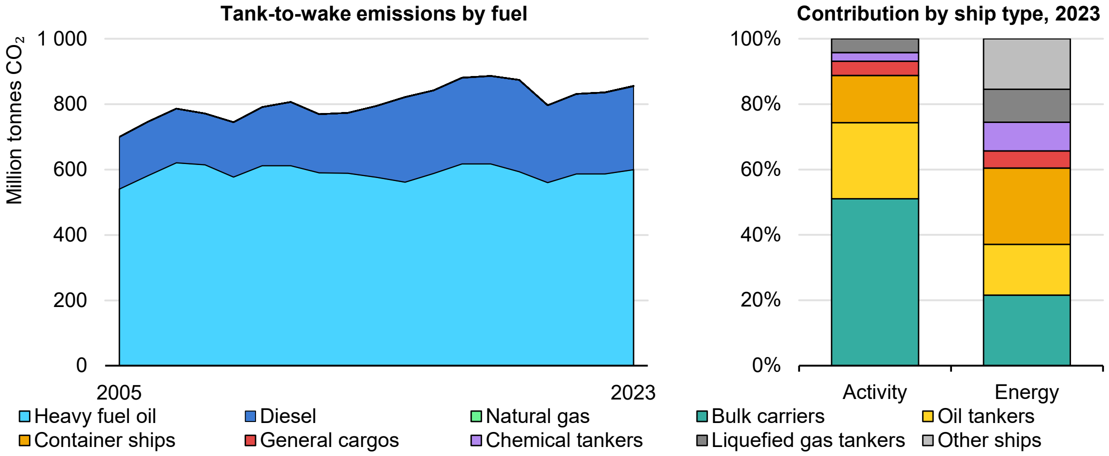
Notes: Shares are weighted by gross deadweight tonnage. RoW = Rest of World, EU = European Union, NOR = Norway, GBR = United Kingdom, PAK = Pakistan.
Sources: IEA based on UNCTAD (2024b), (2024c), and (2024d).

Asia dominates the shipbuilding industry, with China alone accounting for half of the world's production capacity, Korea for 28% and Japan for 15%.

Asia dominates the shipbuilding industry. China alone built more than half of all the gross shipping tonnage in the world in 2023, Korea 28% and Japan 15% (Figure 5.2). Most of these ships were sold to companies known as beneficial owners, located in other countries. Ship ownership is diverse with no single country accounting for more than 15%. EU member states collectively account for about one-quarter, as many liner companies are headquartered there.

The picture for scrappage is very different, with companies in Bangladesh and India recycling almost 80% of the ships that went out of service globally in 2023. Ship scrappage is a labour-intensive activity with potentially harmful environmental effects. Scrappage occurs mostly in South Asia because of low labour costs as well as less stringent regulation, which allows shipbreaking to occur directly on beaches rather than in drydocks. Scrap metal is also in high demand in those regions (Gourdon, 2019). Scrapping practices are expected to improve from 2025 when the Hong Kong convention for the safe and environmentally sound recycling of ship is due to enter into force, after having been ratified by a quorum of countries, including Bangladesh and India, in 2023 (IMO, 2023c).

Figure 5.3 Global energy-related CO_2 emissions in shipping, 2005-2023, and energy use and international activity by ship type, 2023



IEA. CC BY 4.0.

Notes: IEA historical emission estimates are based on country data on energy consumption. These top-down estimates differ from the bottom-up estimates by the International Maritime Organization (IMO), as described in the Fourth IMO GHG Study 2020 (IMO, 2020) and by (UNCTAD, 2023b) which rely on the Automatic Identification System for ships whose coverage has changed over time. Emissions and energy values are for international and domestic shipping. Activity, measured in tkm (tonne-kilometres), is for international shipping only. Other ships include passenger and service vessels for which activity is not measured in tkm and is thus not shown on the graph. Energy use and emissions in ports, as well as at sea, are included.

Source: IEA analysis based on UNCTAD (2022).

Shipping emissions have risen by only about 10% since 2008 compared with an almost 50% increase in shipping activity, thanks to improvements in fuel efficiency.

International maritime shipping currently accounts for about 2% of global energy-related CO_2 emissions. Oil in the form of heavy fuel oil and diesel accounts for almost all energy use by ships. Heavy fuel oil is the preferred fuel for large ocean-going vessels, but the introduction in 2020 of the International Maritime Organisation (IMO) standard limiting the sulphur content of fuel to 0.5% (from 3.5% previously) (MARPOL, 2016) has spurred the penetration of very low sulphur fuel oil, marine gas oil and, to a lesser extent, natural gas. Emissions have risen by about 10% since 2008 – a far smaller increase than that in shipping activity (measured in tonne-kilometres), which increased by almost 50%. This is due to major improvements in the energy efficiency of ships, resulting from a combination of regulatory pressures and economic constraints, contributing roughly equally (MMMCZCS, 2023). Container ships contribute proportionately more to CO_2 emissions, accounting for approximately 25%, than to shipping activity (around 17%), as they need to travel faster than bulk carriers and oil tankers, with a typical speed about 30% higher for a similar sized vessel (Figure 5.3).

Global port infrastructure and shipping network

The global shipping network depends on the co-ordination of vessels and port infrastructure. Singapore is the world's leading port in terms of the value of trade, followed by Rotterdam in the Netherlands, which serves as a logistical hub for European markets, and Shanghai in China, which is the busiest container port in the world, serving as a hub between Asia and the rest of the world. China's other main ports are Shenzhen and Guangzhou in the Guangdong province and Ningbo, in Zhejiang province, which is the busiest port by handled mass in the world. Other important Asian ports are Hong Kong and Busan in Korea. The main ports in the United States are Los Angeles/Long Beach and the Port of New York and New Jersey.

Port infrastructure comprises docks, breakwaters, navigation channels, buildings, cranes and storage facilities (Notteboom, Pallis, & Rodrigue, 2022). The most important entities at each port are the port authorities, port operators and ship operators. Port operations can be governed and managed by private and/or public companies (Dappe & Suárez-Alemán, 2016). At one extreme – the public sector model – ownership and operations of the port are delegated to the port authority, while at the other end of the spectrum – fully private ports – there is no public sector involvement. However, the most common port operation model is a blend of public and private operation, known as the "landlord" model. Landlord ports feature a blend of public and private involvement, with the port authority acting as regulatory body and landlord, while private companies manage the port operations. The infrastructure is leased to the private operators, who provide and maintain their own superstructure and cargo-handling equipment. Rotterdam and Singapore, as well as most ports in other advanced economies and China, operate under this model.

Port operators are in charge of the management of the superstructure and the day-to-day services and operations required by ships, such as loading and unloading cargo, and providing port-related services. They play a critical role in the global shipping and logistics network. Key players in container port operations include PSA International, Cosco Shipping Ports, China Merchants Ports, and APM Terminals (Table 5.1). They manage multiple ports worldwide, ensuring the efficient handling of cargo and providing essential infrastructure for maritime trade.

Table 5.1 Major port operators, 2022

Port operator	Container volumes (MTEU)	Headquarters	Share of world total container volume
PSA International	61.0	Singapore	7.2%
Cosco Shipping Ports	52.9	China	7.0%
China Merchants Ports	50.6	China	6.0%
APM Terminals	48.8	Netherlands	5.7%
DP World	46.5	United Arab Emirates	5.5%
Hutchinson Ports	45.1	China	5.3%
MSC	27.5	Switzerland	3.2%
ICTSI	11.7	Philippines	1.4%
Terminal Investment Limited	10.8	Switzerland	1.2%
CMA CGM	9.4	France	1.1%

Notes: MTEU = million twenty-foot equivalent units, used to determine cargo capacity for container ships and terminals.
Source: Lloyd's List (2023b).

Ship operators can operate either as a liner, transporting cargoes through regular routes, stopping at regular ports and following a fixed schedule, or on a charter or tramp basis. Liner shipping is carried out using container ships, bulk carriers, tankers and specialist ships. Liner shipping is dominated by a handful of players, including those that make up the Ocean Alliance (CMA CGM, COSCO Shipping, Evergreen Line and OOCL), which alone accounts for roughly 30% of container shipping market share, as well as Maersk Line and MSC (previously 2M Alliance). Charter vessels are typically hired to transport cargo over a certain route and for a specified period, with the charterer selecting the route and ports and paying port charges and the cost of the fuel consumed by the ship. Tramp ships do not follow a regular schedule and are hired on the spot market. While most of container shipping is carried out by regular liner vessels, dry bulk and tankers are nearly always operated on a charter or tramp basis.

There are five main categories of goods shipped by sea: dry bulk, wet bulk, containers, breakbulk and Ro-Ro (roll-on/roll-off). Dry bulk goods are mainly raw materials that are shipped in large unpackaged parcels, consisting mainly of unprocessed commodities that are destined to be used in the global manufacturing and production process. Examples include grain, metal ores and coal. Wet bulk refers to liquid substances such as oil, liquefied natural gas (LNG), chemicals and fertilisers that are usually shipped in special tankers. Containers are used to store products such as consumer goods during shipping in dedicated ships. Several clean energy technologies, including solar PV modules and heat pumps, as well as their components, are usually shipped in containers. Breakbulk is the system of transporting goods in pieces separately in individual units, such as the components of wind turbines, typically in general cargo vessels. Ro-Ro shipping involves vessels designed to transport road vehicles and other wheeled cargo.

The goods shipped through ports vary according to local economic factors (Figure 5.4). For dry bulk, Australian ports typically handle large amounts of exports of raw minerals and fossil fuels, North American and Brazilian ports grain, and other Latin American ports minerals. Wet bulk ports are usually located near oil and gas fields such as in the Middle East and the US Gulf Coast or near major industrial areas, where there is strong demand for oil and chemical products. Container ports are usually located near major urban centres, manufacturing hubs and strategic maritime routes. Rotterdam, Antwerp, and Hamburg are the leading container ports in Europe; Los Angeles/Long Beach and the Port of New York and New Jersey in North America; and Colón and Santos in Latin America, while Tanger Med, Port Said and Durban are the biggest container ports in Africa. Shanghai and Singapore are the biggest container ports in Asia.

Trans-shipment hubs are major ports that serve as pivotal points in the global shipping network. They have high capacity and strong linkages to other ports for moving containers or goods to an intermediate destination before transportation over shorter distances to the final destination, by unloading the ships and transferring goods onto smaller ships. They are important because they facilitate the transfer of goods between multiple sources and destinations by providing logistical functions required by shippers. Trans-shipment is required when direct routes between the origin and destination are not efficient or not available. Trans-shipment or transit ports connect smaller ports within a country to the global shipping network and, unlike importer or exporter ports,[1] receive, sort and then ship most of the goods to other smaller ports.

The world’s largest trans-shipment port is in Singapore. Ports in China such as Shanghai also have a large share of trans-shipment. In Europe, the main hubs are the port of Rotterdam as well as ports located on the Gibraltar straits. The port of Colombo serves as a hub for the Indian ocean, while in the Caribbean region, the ports at the Panama Canal and Kingston serve as hubs. North American ports do not act as hubs, but mostly as direct importers and exporters.

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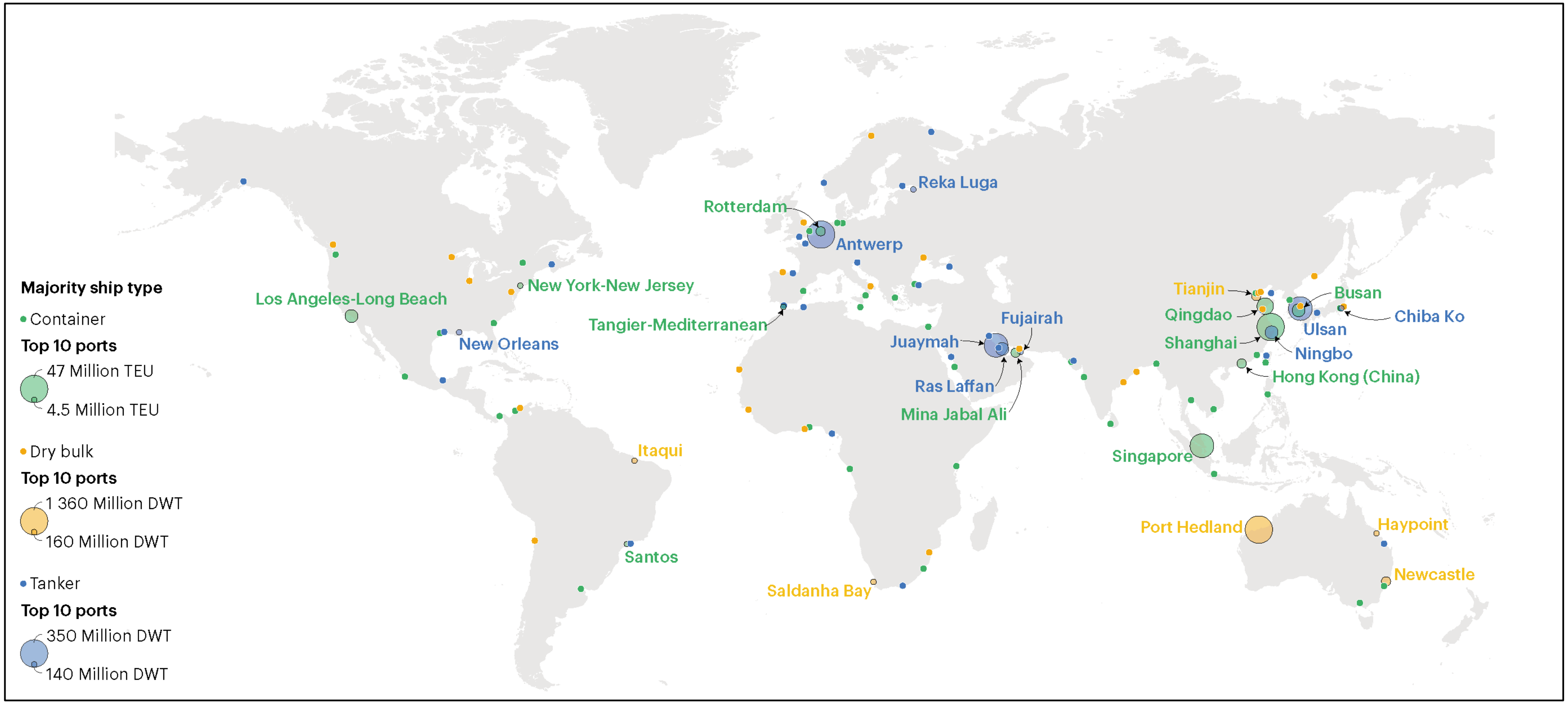
[1] The terms importer and exporter here refer to the handling of inward and outward shipments through a port and not to whether the goods shipped are destined for domestic or overseas markets.

Figure 5.4 Main ports by cargo type and throughput, 2023



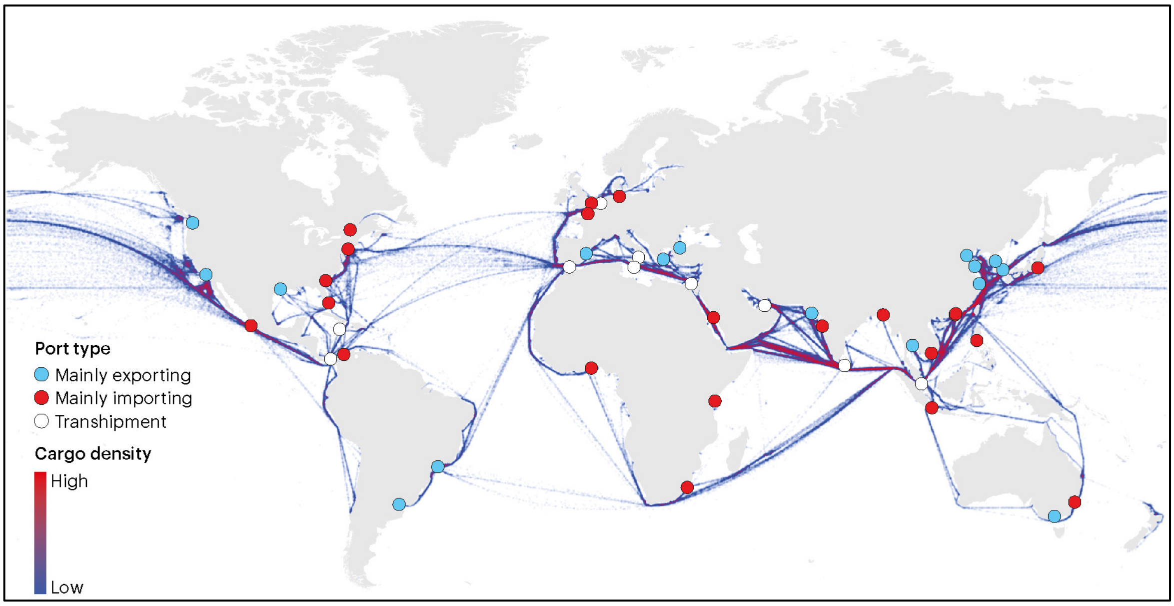
Notes: Map displays 100 ports around the world. Ports have been categorised as container, dry bulk and tanker according to their main activity. For each category, the throughput of major ports is shown. For tankers and dry bulk, port capacity is estimated using Automatic Identification System (AIS) data. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA based on Lloyd's List (2023a) and Verschuur (2022).

Goods shipped through ports vary according to local economic factors, with container ports usually located near major urban centres, manufacturing hubs and strategic routes, and bulk and tanker ports near resource-rich areas.

Trade flows vary markedly between container, tanker and dry bulk shipping, according to differences in the location of centres of production and demand for the goods they transport. Container shipping is concentrated on the east-west axis, in both directions, which accounts for around 40% of total container shipping value (Figure 5.5). The majority of this shipping moves east to west, mainly from China and the rest of Asia to the United States. On the north-south axis, the busiest trade route is from China to South America. Australia is a net importer of container cargoes from China and Japan. Container trade is highly concentrated, with the United States, the European Union and China accounting for roughly half of imports and exports combined (excluding exports to other Asian countries).

Figure 5.5 Major container shipping routes, 2022



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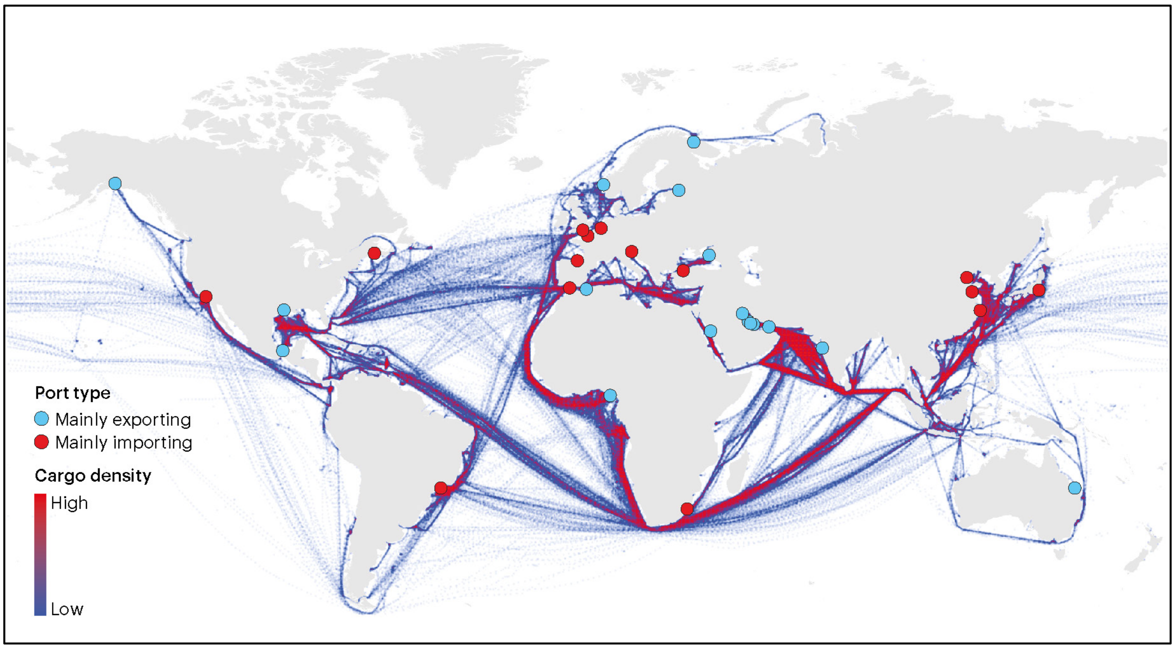
Notes: Cargo density is estimated based on deadweight tonnage and load factor of ships as per Automatic Identification System data in 2022. The red colour indicates more cargo shipped along the route This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA based on United Nations Global Platform (2024) and Verschuur (2022)..

Container trade is highly concentrated, with the United States, the European Union and China accounting for roughly half of imports and exports combined.

Exports of Chinese containerised goods mostly go to Europe, the United States, Indonesia and other Association of Southeast Asian Nations (ASEAN) countries, which together account for about 45% of the country's total exports by value. The trade between China and the rest of Asia accounts for another 10% of global container trade. Exports from Asia to the European Union account for 6% of global trade value, while the share of trade the other way is 4%. China is also the biggest exporter to the United States, making up a third of US imports. Trade from Asia to the United States represents 17% of global trade value, while trade flows in the opposite direction make up just 2%.

Figure 5.6 Major tanker shipping routes, 2022



Note: Cargo density is estimated based on deadweight tonnage and load factor of ships as per Automatic Identification System data in 2022. The red colour indicates more cargo shipped along the route. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA based on United Nations Global Platform (2024) and Verschuur (2022)..

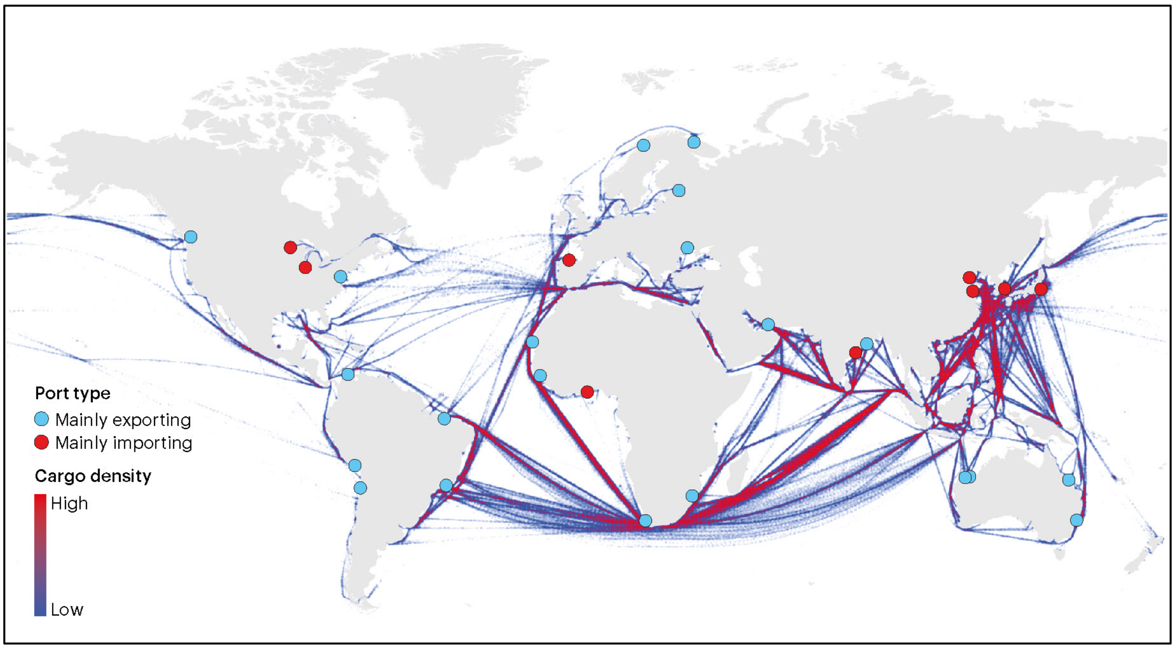
Oil tanker shipping is concentrated along east-west routes, notably from the United States and the Middle East to Europe and Asia.

Tanker shipping is more concentrated along certain east-west routes due to the heavy concentration of oil production in a small number of countries, notably the United States and the Middle East (Figure 5.6). In the US Gulf of Mexico, there are several exporting ports, given the concentration of oil refineries, while the other ports in the country are importers of refined products shipped from the Gulf Coast to the East Coast as well as Europe. Shipments from US ports account for around 16% of total tanker trade. Most tanker shipments from the Middle East go to Asia and Europe. Chinese ports are the biggest recipients of oil from the Middle East. The biggest African tanker export hubs are in Nigeria, though there is only one major exporting port in Figure 5.6, as most oil is exported directly from offshore platforms, which are not assigned to a specific port. The only other notable tanker flows on the north-south axis are small volumes of Australian exports to Asia.

Dry bulk shipping is more diversified than container, with substantial flows along both the north-south and east-west axes (Figure 5.7). Nonetheless, dry bulk movements are relatively concentrated, with the top five exporters being the United States, Australia, Brazil, China and the European Union, each holding roughly a 10% share of global international dry bulk trade in terms of value.

Imports are also highly concentrated, with China alone accounting for 30% of global imports and the European Union, the United States, Australia and Southeast Asian countries combined for around one-quarter. Europe and China are the main hubs for dry bulk imports. The leading suppliers of dry bulk goods to China are Australia (mostly iron ore), Brazil, and Indonesia, accounting for half of imports. A key trade axis is the one linking exports from Australia and New Zealand to Asia, of which 60% go to China. The other main axis of trade is from South America and South Africa to Asia, also making up 10% of global trade value for dry bulk, with half of these flows going from Brazil to China.

Figure 5.7 Major dry bulk shipping routes, 2022



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Notes: Cargo density is estimated based on deadweight tonnage and load factor of ships as per Automatic Identification System data in 2022. The red colour indicates more cargo shipped along the route. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Source: IEA based on United Nations Global Platform (2024) and Verschuur (2022).

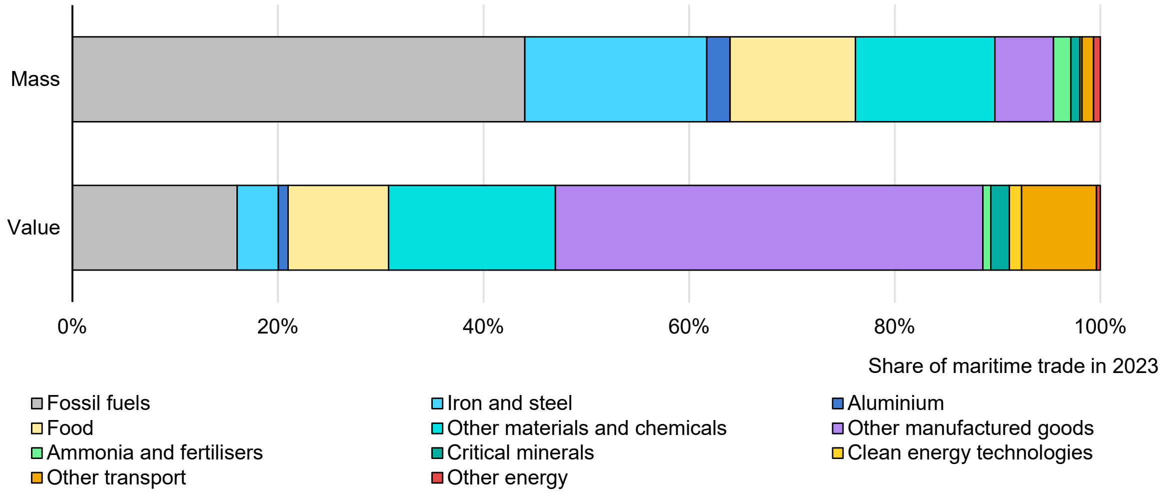
Dry bulk shipping is more diversified than container shipping, with substantial flows along both the north-south and east-west axes, notably between Australia and China.

Shipments from and to China account for 40% of all shipping activity for fossil fuels, iron ore and bauxite and are, in some cases, very concentrated. A single trade route from Western Australian ports – Port Hedland, Dampier and Cape Lambert – to China carrying iron ore accounts for over 700 Mt of bulk transported goods, which is equivalent to 7% of global dry bulk shipping. In mass terms, the single main trade route from Africa to China involves primarily the shipment of bauxite from the port of Kamsar in Guinea; almost 100 Mt of goods were shipped along this route in 2023. Shipments of iron ore, amounting to 250 Mt in 2023, from the ports of Ponta da Madeira and Itaqui in Brazil to China accounted for 2% of global shipping activity, while ports in Queensland in Australia supplied 180 Mt of coal to Japan and Korea, accounting for 2% of global shipping. In the case of copper, around 20% of global supply was shipped from the coasts of Peru and Chile to China.

Clean energy technology and material shipping networks

There is a huge difference between the mass and value shares of international maritime shipping of clean energy technologies and the bulk materials used in their manufacturing. Fossil fuels made up around 40% of total maritime trade in terms of mass in 2023, while iron ore and bauxite accounted for another 15%. However, their combined share of the total value of maritime trade was below 20% (Figure 5.8). On the other hand, the six clean technologies covered in this report – electric vehicles (EVs), batteries, wind turbines, solar PV modules, heat pumps and electrolysers – and the components used in manufacturing them made up around 0.2% of goods trade by mass but close to 1% of total traded value.

Figure 5.8 Shares of types of goods in global international maritime trade by value and mass, 2023



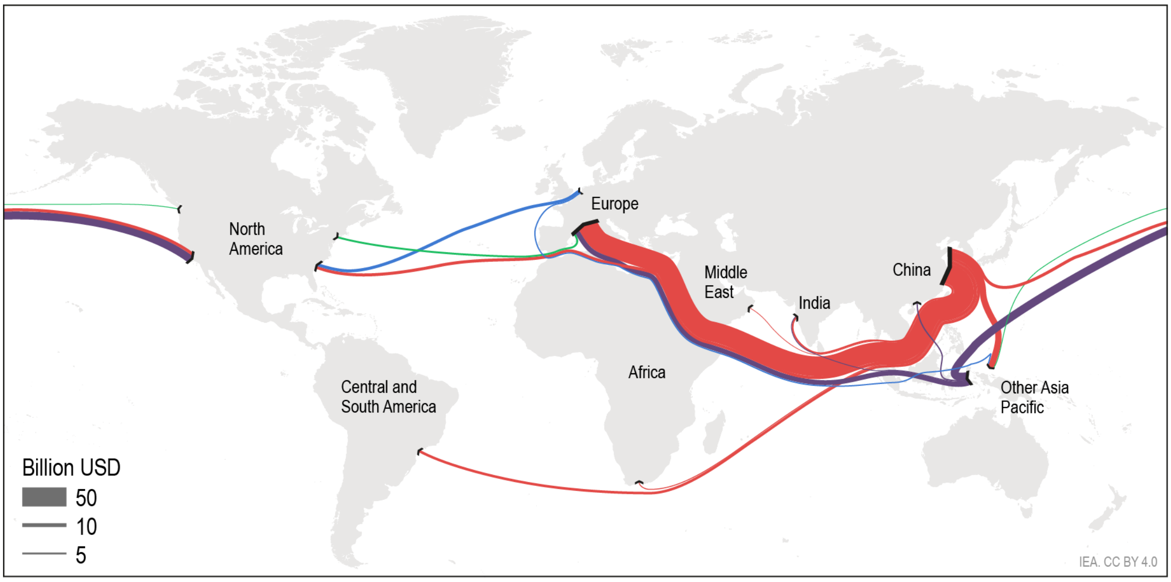
Notes: Clean energy technologies include batteries, electric vehicles, electrolysers, heat pumps, solar PV and wind. Aluminium includes mineral inputs, intermediates (such as alumina and scrap), ingots and semi- and finished products. Iron and steel include mineral inputs, intermediates (such as scrap, pig iron and direct reduced iron) and semi- and finished products. Other energy includes bioenergy, hydrogen, and nuclear fuel. Other manufactured goods include arms and ammunitions, clothing, electronics, machinery, and pharmaceuticals, among others. Other materials and chemicals include cement, chemicals, ethanol, metals, methanol, paper, plastics and rubber and wood. Other transport includes non-electric vehicles including hybrids, aircrafts, ships and other transport equipment.

Sources: IEA based on Oxford Economics Limited (2024); CEPII (2024); IEA (2024a); and Verschuur (2022).

The share of clean energy technologies in the total value of global maritime trade is six times higher than their share in mass.

China is by far the leading exporter of clean energy technologies, followed by other exporters from Asia Pacific, including Korea and Japan, and the European Union (Figure 5.9). Clean energy technologies are relatively high-value goods, mostly transported in containers along busy east-west shipping routes, mostly from China and other Asia Pacific countries to Europe and North America. Trade from Asia to Europe typically passes through the Suez Canal and the Gibraltar Strait, and from Asia to North America it crosses the Pacific when directed to the West Coast, while trade to the East Coast can pass through the Panama or Suez Canal. Trade patterns for clean energy technologies are similar to those of other containerised goods.

Figure 5.9 Trade flows of clean energy technologies between regions in value terms, 2023



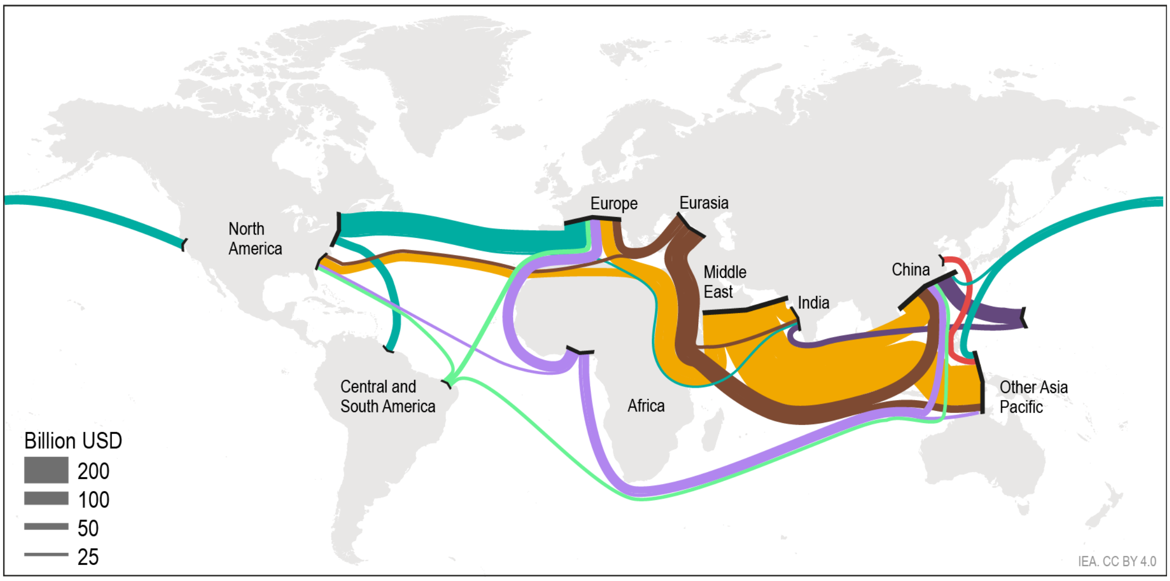
Notes: The colour of flows represent the exporting region. Intra-regional trade is excluded, see Annex for details. Clean energy technologies include solar PV modules, heat pumps, EVs, wind turbine components, batteries, and electrolysers. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA based on Oxford Economics Limited (2024); CEPII (2024); and Verschuur (2022).

Clean energy technologies are mostly transported along east-west shipping routes, with most exports coming from the Asia Pacific region.

Trade flows for fossil fuels are very different to those for clean energy technologies. Unsurprisingly, most fossil fuel trade goes from resource-rich areas to regions with high energy demand, mostly in the northern hemisphere (Figure 5.10). Coal is traded mostly on the north-south axis, while oil is traded mainly on the east-west axis.

Figure 5.10 Trade flows of fossil fuels between regions in value terms, 2023



Notes: The colour of flows represent the exporting region. Intra-regional trade is excluded, see Annex for details. Fossil fuels include oil and oil products, gas and coal. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA based on Oxford Economics Limited (2024); CEPII (2024); and Verschuur (2022).

Most fossil fuel trade goes from resource-rich areas in the Middle East and North America to regions with high energy demand, mostly in the northern hemisphere.

The trade flows for minerals and materials are, again, very different compared with both clean technologies and fossil fuels. China and other Asian countries are both the largest exporters and importers, importing minerals and other raw materials for processing, and exporting mainly iron and steel products to other regions (Figure 5.11). Among bulk materials, iron and steel trade account for the biggest share of trade by mass, making up more than 17%, but less than 5% of traded value. Australia and Brazil are the leading exporters of iron ore, most of which is shipped to China and then from there exported as higher value products. Critical minerals.[1] are also mostly traded along the north-south axis. Their traded mass is comparatively small, amounting to around 5% of that of iron ore.

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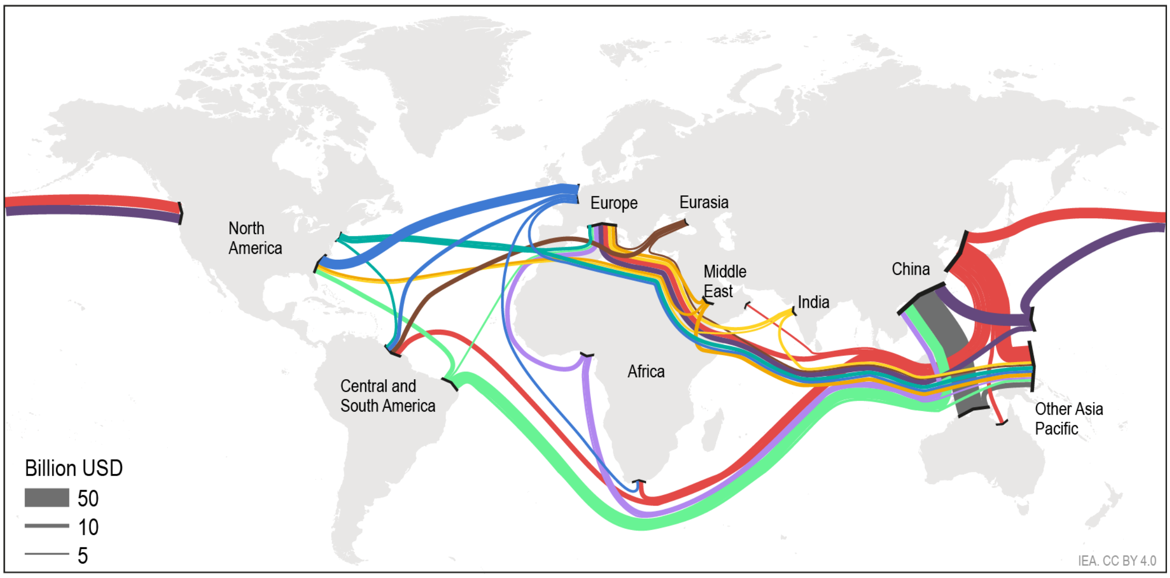
[1] Here defined as cobalt, copper, lithium and nickel.

Figure 5.11 Trade flows of selected materials between regions in value terms, 2023



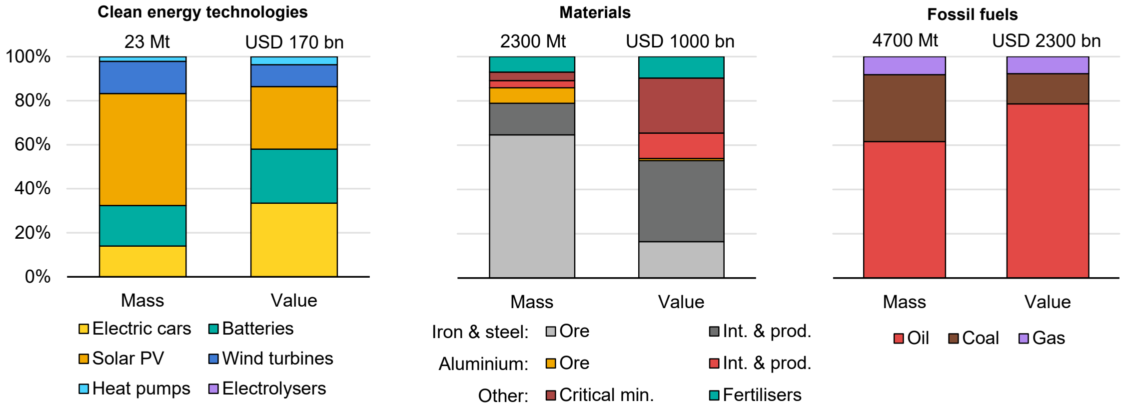
Notes: The colour of flows represent the exporting region. Intra-regional trade is excluded, see Annex for details. Selected materials include iron and aluminium ore, processed iron and steel and aluminium, ammonia and fertilisers. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA based on Oxford Economics Limited (2024); CEPII (2024); and Verschuur (2022).

China and other Asia Pacific countries are both the largest exporters and importers of materials, importing ores and exporting semi-finished products.

Global trade in the clean energy technologies covered in this report is dominated by EVs and batteries, accounting for nearly half of total traded mass of all those technologies and nearly three-quarters in value terms (Figure 5.12). Solar PV and wind turbines make up most of the rest. Within the selected materials, iron ore and aluminium ore (bauxite) account for more than 70% of total trade mass, but only around 20% of traded value, as intermediate and finished products have much higher value-to-mass ratios: steel products account for just about 15% of traded mass but 40% of traded value. For comparison, among the three fossil fuels, coal accounts for 30% of total international trade in those fuels in mass terms, but only 15% in value terms as the energy density and, therefore, price per tonne is lower than for oil and gas.

Figure 5.12 Shares of global traded mass and value for clean energy technologies, associated materials and fossil fuels, 2023



Notes: USD bn = billion USD (2023, MER). Intra-regional trade is excluded, see the Annex for details. Totals displayed at top of each bar. Int. & Prod. = intermediates and products. Fertilisers include the trade of ammonia.
Sources: IEA based on Oxford Economics Limited (2024) and CEPII (2024).

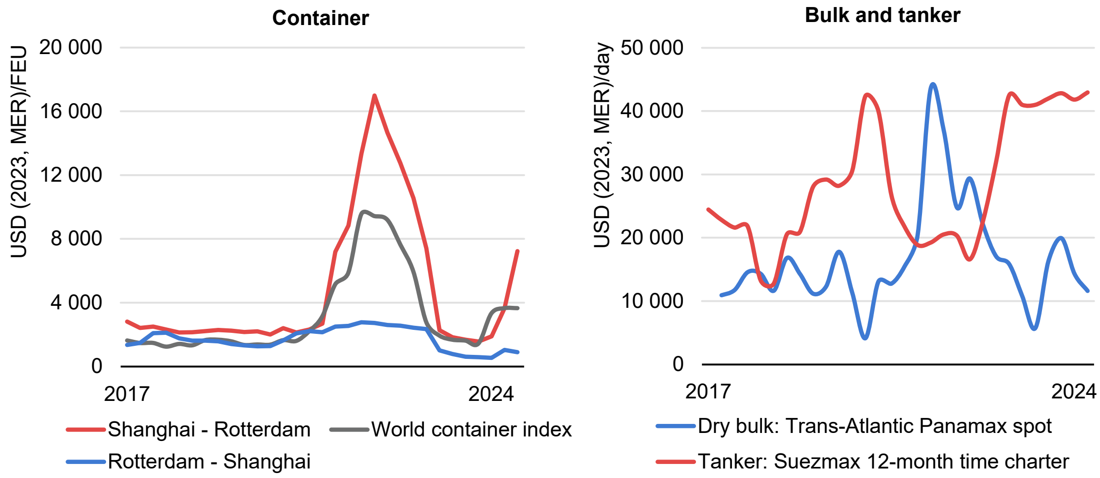
Global trade in clean energy technologies is dominated by solar PV, accounting for almost 40% of the traded mass of all clean technologies

Shipping costs

Shipping costs and prices vary widely according to the type of transportation, with freight rates per tonne-kilometre for containers somewhat higher than for dry and wet bulk cargoes. To transport goods in containers, manufacturers typically pay liner companies a rate in USD per forty-foot (forty-foot equivalent units, or FEU) or twenty-foot (TEU) container. In some cases, cargo owners and shipping companies sign long-term contracts of 1 or 2 years, with the price linked to that on the spot market.

Spot prices for container shipping fluctuate significantly according to changes in supply of and demand for containers along a given route. Periods of stable prices can be followed by periods of great variability. For example, prices were broadly stable between 2017 and early 2020, but then soared due to disruptions to global shipping as the Covid-19 pandemic took hold (Figure 5.13). Prices peaked in mid-2021 at levels more than five times higher than at the beginning of 2020, and then fell back to pre-pandemic levels in late 2023. Prices have since rebounded, mainly due to disruptions to shipping through the Red Sea, which have forced container ships to take the longer route around Southern Africa, increasing journey times and, therefore, reducing the availability of ships.

Figure 5.13 Shipping freight rates for container, and charter rates for bulk and tanker, 2023



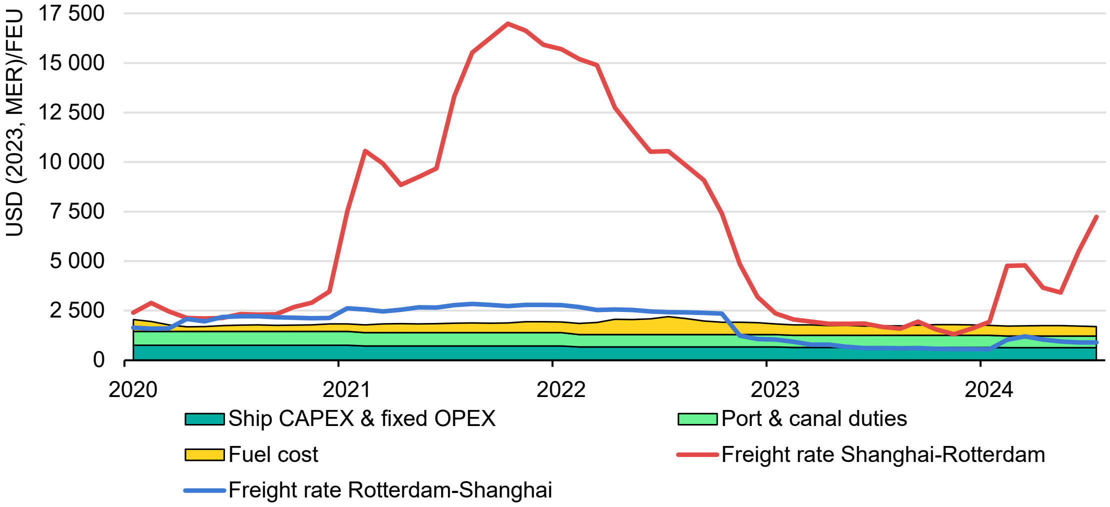
Notes: The container freight rates shown here are based on spot prices. FEU = Forty-foot equivalent unit.
Sources: IEA based on Bloomberg terminal data and Drewry (2024a).

Shipping rates fluctuate according to market conditions, with supply disruptions caused by the Covid-19 pandemic driving up container and dry bulk rates to record highs.

Container freight rates differ depending on the direction of travel and the nature of the route, and are generally less sensitive to distance than bulk carriers. Rates for the route from Asia to Europe, for example have been more than three times as high on average than the other way around over the past 5 years. This is because demand for shipping to Europe is stronger than to Asia, meaning that container ships often return eastwards with less-than-full loads. A similar pattern can be observed for the Asia-United States route.

Short-term fluctuations in container freight rates rarely reflect underlying costs. The main cost components for container shipping are the capital cost of the ship, non-fuel ship operating costs like salaries and maintenance, fuel, port handling fees and canal duties. For a container liner sailing between Shanghai and Rotterdam, the share of fuel costs varies according to the price of bunker fuel at any given moment, ranging from 15-40% over 2020-23 (Figure 5.14). Freight rates for that route ballooned between the end of 2020 and early 2022 due to a shortage of container ships triggered by a rapid increase in demand for goods made in Asia following the pandemic period, but then fell back steadily through to early 2023 as more ships became available. The freight rates from Shanghai to Rotterdam were similar to the estimated total bottom-up cost components throughout 2023, and even lower for the return trip from Rotterdam to Shanghai. In 2024, Shanghai to Rotterdam rates have soared well above costs once again due to disruptions in the Gulf of Aden, whereas return rates have remained low.

Figure 5.14 Container freight rates and cost components for the Shanghai-Rotterdam route, 2020-2024



Notes: FEU=Forty-foot Equivalent Unit. Cost components assume a container ship of capacity 4700 FEU (9400 TEU). Fuel consumption determined by average efficiency of current fleet.

Sources: IEA based on Drewry (2024a). Fuel cost data sourced from USDA (2024).

Container ship freight rates fluctuate according to market conditions, deviating widely from underlying costs.

Fuel costs can represent more than 50% of operational shipping costs depending on the type of tanker and marine diesel and bunker fuel oil prices, but the main determinant of freight rates for all ship types is demand and supply of vessels. In the case of container ships, fuel costs are small relative to freight rates at most times, creating a strong incentive for them to sail as quickly as possible to free up capacity and boost profits. This results in more energy use per tonne-kilometre compared with other ship types of comparable size and, therefore, higher emissions.

For bulk carriers, freight costs vary according to the size of vessel and route they are designed to ply – ranging from small, Handysize, Panamax, Capesize, and Very Large – and the type of good being carried (dry or wet). Dry cargo ships comprise ore/bulk/oil carriers, or combination carriers, and very large ore carriers (VLOCs). Wet bulk carriers include crude oil and product tankers and LNG carriers. As with container ships, freight charter rates fluctuate according to market conditions, with the spot price (known as the time charter price, quoted in USD per day) fluctuating to a similar extent as container rates. For example, the average Panamax dry bulk spot rate shot up from less than USD 5 000/day at the beginning of 2020 to a peak of USD 40 000/day in mid-2021. Oil tanker rates are equally volatile, fluctuating in line with oil demand and availability of transport capacity.

Clean energy technologies

As for most high-value products, clean energy technologies are usually shipped in containers, as this is the quickest and cheapest way to transport them over long distances, and it allows for modularity. However, wind turbines and EVs are exceptions. Wind turbine components can be very large and, therefore, require special operations for sea transport. Blades and towers are typically stowed on the deck of bulk or general cargo ships, while nacelles, which are more compact, can be stowed in the cargo hold of bulk or breakbulk carriers. EVs are generally transported in specialised vessels designed for shipping vehicles, known as roll-on/roll-off (Ro-Ro) vessels. Today's largest Ro-Ro vessels can carry up to 9 000 vehicles.

The theoretical carrying capacity of vessels for different energy sources and clean energy technologies varies enormously (Table 5.2). Of all fossil fuels, oil can be most easily transported, with a single large vessel able to carry roughly 1 700 GWh of energy – equivalent to the yearly oil consumption of roughly 175 000 internal combustion engine (ICE) cars. Among clean energy technologies, roughly 2 GW of solar PV modules could fit in a single container ship – roughly equivalent to Belgium's solar PV capacity additions in 2023. But solar PV modules are capital goods, while fossil fuels are consumable. That number of modules would be able to generate electricity equivalent to the needs of half a million European households for the duration of the modules' lifetime – roughly a quarter of a century. On the contrary, an LNG vessel carrying the equivalent amount of energy would satisfy that electricity demand for less than six months.

Table 5.2 Indicative maximum carrying capacity of a large vessel in energy terms for selected clean energy technologies and fossil fuels

Type of vessel	Cargo	Capacity in energy terms
Container ship (15 000 TEU)	Solar PV modules	2 GW
	Batteries	26 GWh
	Electrolysers	13 GW
Dry bulk (150 000 DWT)	Coal	1 200 GWh
Tanker (150 000 DWT)	Oil	1 700 GWh
LNG carrier (260 000 m^3)	LNG	1 500 GWh

Note: FEU = Forty-foot equivalent unit. DWT = deadweight tonnage. Each vessel is assumed to be fully loaded.

Shipping costs for most clean energy technologies equate to less than 5% of their value (Table 5.3). The main exception is wind turbines, where the complex operations and bulkiness of the components can push up the cost to more than 10% of the total value of the turbine. Similarly, the low cost of some solar PV components, such as cells and wafers, combined with relatively inefficient packing, mean that shipping costs can exceed 5% of their value. The cost of shipping EVs averages around 5% of their value. Lower cost shares are seen for heat pumps and electrolysers. The share is even lower, at under 1%, for batteries, due to their high value and compactness. Cargo insurance typically adds around half a percentage point to total shipping costs for most clean energy technologies. Costs are higher for goods that require special handling, such as wind turbine components, batteries and EVs, reaching around 2% of the value of goods.

Table 5.3 Indicative transport costs for selected clean energy technologies

Transport type	Technology	Loading	Transport cost	Transport cost share
Containers	**Solar PV**	MW/FEU	USD/kW	
	Modules	0.34	7.6	4%
	Cells	0.52	4.9	5%
	Wafers	0.55	4.6	7%
	Polysilicon	6.8	0.4	1%
Containers	**Batteries**	MWh/FEU	USD/kWh	
	Cells	4.2	0.6	0.5%
	Anode	38	0.1	2%
	Cathode	15	0.2	1%
Containers		MW/FEU	USD/kW	
	Heat pumps	0.7	3.6	1%
	Electrolysers	2.0	1.3	0.5%
Breakbulk	**Wind**	MW/vessel	USD/kW	
	Nacelles	42 - 61	28	7%
	Blades	42 - 85	23	15%
	Towers	17 - 36	46	12%
Ro-Ro		Units/vessel	USD/unit	
	Electric vehicles	up to 9 000	1 400	5%

Notes: FEU = forty-foot equivalent units; Transport costs based on an average rates for Asia to Europe and North America. Container costs are assumed to amount to USD 2 600/FEU; break bulk vessel with 20 000 DWT costs USD 1.4 Million. Assumptions reflect typical values for the year 2023.

Sources: IEA based on Bloomberg terminal data; Drewry (2024a).

Materials

Shipping costs for materials are generally lower than for clean energy technologies on a per tonne basis, since their value per tonne is also lower. For raw materials, the shipping costs can be a larger share of the product value, especially when transported with smaller ships, due to the low product value. The largest possible ship is thus normally selected for long distances, exploiting economies of scale. For higher-value bulk materials, transport costs rarely exceed 5% of their value (Table 5.4). The cost per tonne of transporting bulk materials in smaller vessels can be twice as high for larger vessels. Smaller vessels are used when relatively smaller shipments are required, if the origin or destination port does not have the required infrastructure to host a larger ship, or if the vessel needs to go through a given strait that can only fit a given ship size; this is the case for the Panama Canal (for which the Panamax and New Panamax carriers have been designed) and the Suez Canal (Suezmax).

Table 5.4 Typical transport costs as share of product value for raw and bulk materials by ship type, 2023

Commodity (Thousand DWT)	Handymax (35 – 50)	Supramax (50 – 60)	Panamax (65 – 90)	Capesize (~170)	Ammonia gas tanker (~10)
Iron ore	45%	30%	25%	13%	
Bauxite	70%	47%	40%	20%	
Fertilisers	5.2%	3.5%	3.0%	1.5%	
Ammonia					16%
Steel	6.5%	4.5%	3.7%	2%	
Aluminium	2.0%	1.3%	1.1%	0.6%	

Note: Assumes transport over a distance of 10 000 km.
Sources: IEA based on BMT (2024).

The three categories of material covered in this report – iron and steel, aluminium, and ammonia – are transported in different types of vessels:

- Iron ore is typically transported in large quantities using Capesize vessels that can carry around 150 000 tonnes (t) of ore. In some cases, it is shipped in VLOCs, often specifically designed for that raw material, which can transport up to 400 kt of ore, equivalent to about 2 months of production for a small primary steel plant.
- Steel and aluminium products can be transported in bulk carriers or in containers. For large shipments, bulk carriers are cheaper. Even if cargo cannot be stowed

as efficiently as in the case of ore, steel and aluminium have lower transport costs as a share of their value, given that the latter is relatively high. Transporting metals via containers is also possible, but the cost is significantly higher and so is only viable for very small shipments or high-value-added products, such as electrical steel.

- Ammonia, a gas under ambient conditions, is shipped in liquefied form using ammonia tankers, similar to those for liquefied petroleum gas (LPG). It can also be converted into chemicals like urea or other nitrogen-based fertilisers and shipped as a solid in bulk carriers, depending on its end use. Transporting liquefied ammonia is more expensive and requires complex infrastructure, including pressurised and/or refrigerated storage tanks, deepwater ports and special safety measures. Since most ammonia is used in fertilisers, and solid forms are easier to store and transport, fertiliser trade is more common than ammonia trade.
- Critical minerals are usually shipped in smaller-sized dry bulk carriers, due to the comparatively smaller output of their mines and needs for manufacturing.

5.2 Impact of clean energy transitions on shipping

Shipping demand and routes

The future pace of the clean energy transition will have a major impact on the overall demand for shipping, the types of ships required and the pattern of shipping routes for energy-related fuels, materials and technologies. In general, the faster the transition, the slower the increase in global shipping activity. This is largely due to lower demand for energy, thanks to faster energy and material efficiency gains, and a faster decline in the need to import fossil fuels. Both effects more than offset increased shipping from clean energy technologies, alternative fuels, critical minerals, and other cargo, in mass and value.

The three scenarios presented in this report have marked differences on global shipping activity and, to a lesser extent, the value of the goods shipped, a result of major divergences in the use of fossil fuels and materials (Figure 5.15).[2] In all scenarios, the value of trade in non-energy-related goods[3] continues to increase at 3% per year, a rate that is significantly higher than the growth rate observed for

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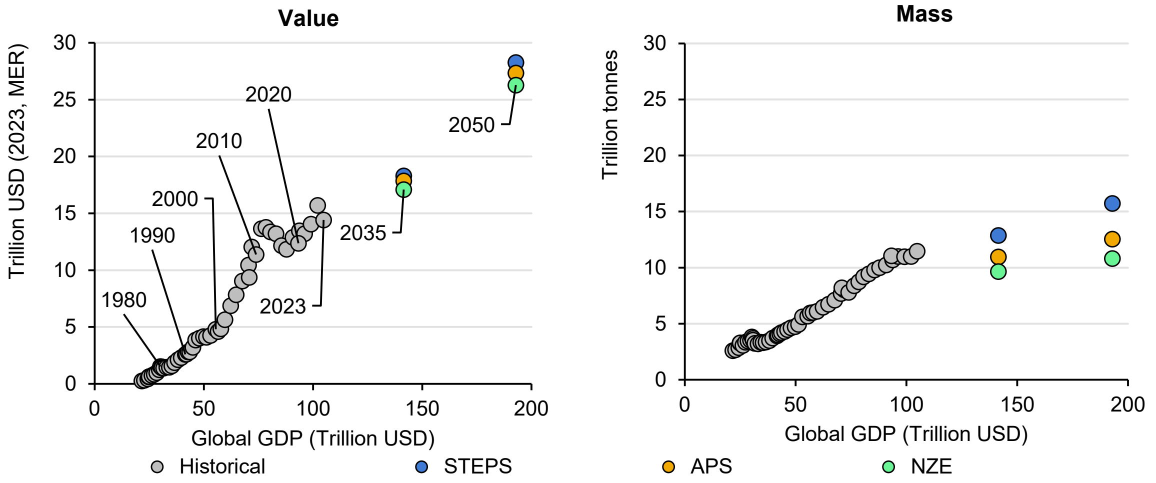
[2] For this edition of Energy Technology Perspectives (ETP), the IEA has developed a new shipping model, which projects activity in international shipping by modelling individually each of its main contributing segments, including tankers and bulk carriers for fossil fuel trade (oil, coal and natural gas), other bulk cargo (e.g. iron ore) and container ships. Please refer to the Annex for more information.

[3] In this chapter, energy-related and non-energy-related goods are defined based on how the energy transition is expected to affect their demand and supply. Energy-related goods: include fossil fuels, clean energy technologies, biofuels, hydrogen-derived fuels, iron ore, iron and steel products, bauxite, aluminium products, and critical minerals. Non-energy-related goods include all other goods.

overall trade in the past decade but lower than the rate seen in the past two decades. Shipping activity for these products more than doubles by 2050, as the global economy grows and international trade increases.

The total value of shipped goods increases much faster than their mass in all three scenarios, because a growing share of traded goods have higher value (more dollars per tonne of mass). The main reason for this is a reduction of trade in fossil fuels, which today account for 40% of traded mass, as well a slowdown in growth for raw materials, mostly iron ore and bauxite. The effect is most pronounced in the Net Zero Emissions by 2050 Scenario (NZE Scenario) and less so in the STEPS. For example, one tonne of iron ore or coal is worth around USD 100, while an average container carries USD 54 000 worth of goods, or roughly USD 4 500/tonne assuming an average of 12 tonnes per twenty-foot container (Notteboom, 2024).

Figure 5.15 International maritime trade of goods in mass and value terms compared to GDP by scenario



IEA. CC BY 4.0.

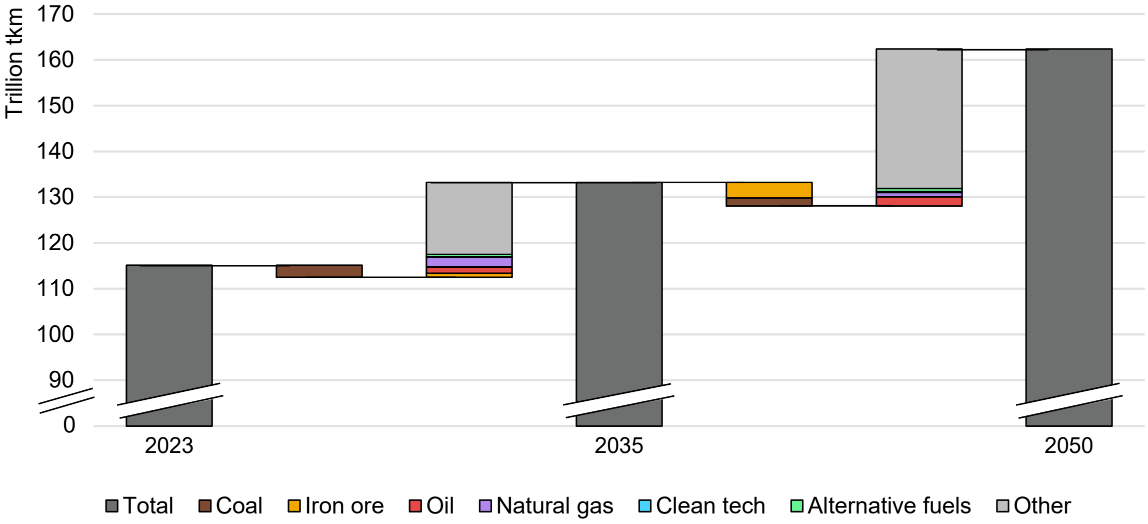
Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. Due to lack of data, historical maritime traded value is estimated to average 75% of global exports over 1971-2012.

Sources: UNCTAD (2024a) and (2024e).

The energy transition speeds up the decoupling between maritime traded value and mass, as trade is driven increasingly by high-value goods, while fossil fuel trade declines.

In the STEPS, international shipping activity of all goods, except coal, continues to grow. Total shipping activity grows by 15% to 2035 and about 40% to 2050 (Figure 5.16), with non-energy related goods accounting for over 95% of the growth by 2050. Maritime trade of oil increases by around 5% to 2035 and around 15% to 2050, while that of LNG increases faster: by 60% and 85%. Shipping of clean energy technologies doubles by 2050, though their contribution to overall activity remains small (as they are relatively light and compact). Shipments by bulk carriers grow at a similar rate, despite a fall in coal trade of 30% to 2050 as renewables displace its use in the power sector and shipments of iron ore stagnate, as an increase in the use of scrap steel as an input to steel production reduces the need for iron ore, despite a 30% increase in global steel production through to 2050. The increase in the availability of scrap – most notably in China, which is the largest iron ore importer by far today – allows its use to rise from around 30% of the total metallic inputs to the steel industry today, to around 50% in 2050.

Figure 5.16 Changes to international shipping activity by product category in the Stated Policies Scenario, 2023-2050



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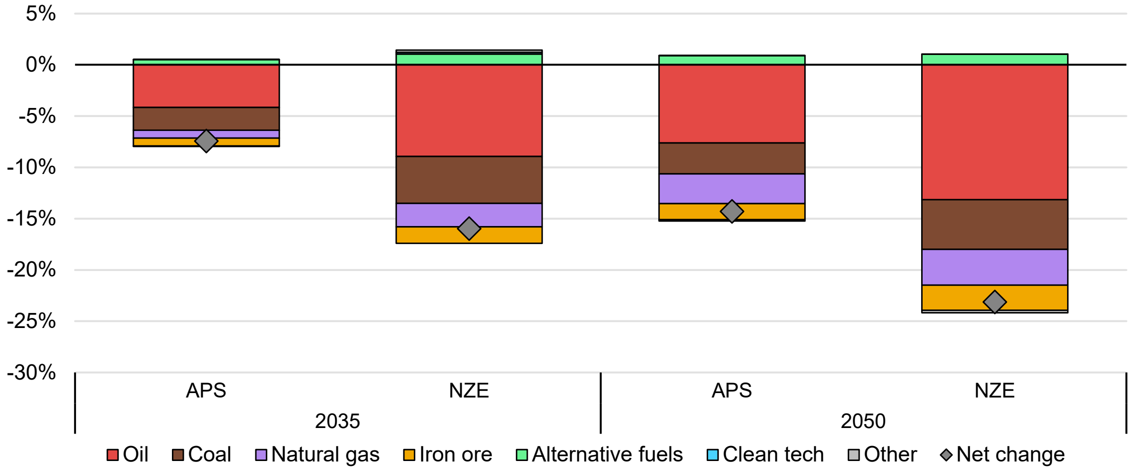
Notes: tkm = tonne-kilometre. "Other" includes all traded goods not specifically labelled. Shipping activity in this figure includes all ship types.

In the STEPS, shipping activity rises more than 40% by 2050, driven mostly by trade in non-energy related goods. Coal and iron ore trade fall compared to today.

In the APS, international shipping activity increases 20% to 2050 (Figure 5.18) – only half as fast as in the STEPS, due to a more rapid decline in fossil fuel trade, which partially offsets the growth in energy-related goods. Neither trade in clean energy technologies nor of near-zero emission fuels are significant drivers of shipping activity to 2050, despite their increase compared to STEPS. Only around 250 Mt of near-zero emission fuels are traded in the APS in 2050, 20 time less than oil traded today. These are mainly synthetic ammonia and methanol for use as shipping fuel and in electricity generation, as the majority of demand for hydrogen and its derivatives is met from domestic sources. For materials, the main contribution to reduced shipping activity relative to the STEPS comes from material efficiency measures, which lower demand in particular for steel, reducing the need for primary iron production and trade of iron ore. Demand for shipping of iron ore falls by more than 10% in 2050 relative to the STEPS. In the APS, an increasing share of iron is produced in areas with abundant renewable resources, while steelmaking remains closer to demand centres. This leads to a 60% increase in iron traded mass in the APS compared to STEPS – however, absolute amounts are comparatively low (around 70 Mt), so this trend does not make a significant difference in terms of activity.

In the NZE Scenario, overall shipping activity and energy-related shipping grow even more slowly than in the APS (Figure 5.17), due to much lower demand for energy in general and fossil fuels in particular, reducing the need to import fossil fuels. Total shipping activity falls by 2% between 2023 and 2035 with a rapid switch away from fossil fuels which offsets the growth in activity from other products, but then recovers with rising economic activity. By 2050, shipping is nearly 10% higher than in 2023.

Figure 5.17 Changes in total international shipping activity in the Announced Pledges Scenario and the Net Zero Emissions by 2050 Scenario versus the Stated Policies Scenario, by product category, 2035 and 2050



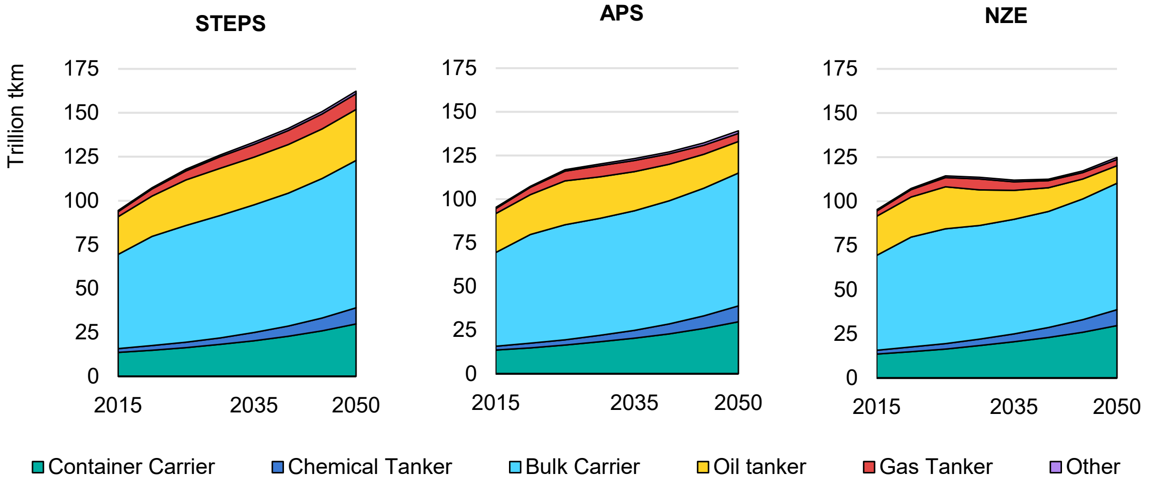
IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. “Other” includes all traded goods not specifically labelled.

Shipping activity in 2050 is 15% lower in the APS than in the STEPS, mostly due to a 45% reduction in shipping of fossil fuels.

The divergences in the trends between the three scenarios would have far-reaching implications for regional trade patterns and the types of ships required. The decline in fossil fuel imports would affect primarily shipping of oil, coal and natural gas to Europe and Asia. In total, shipments of fossil fuels to Europe are 70% lower in 2035 and 50% lower in 2050 in the APS compared with the same year in STEPS. By 2035, shipping of oil from the Middle East to China is 25% lower in the APS while trade of coal from Australia and Africa to China is also reduced by 60%. In addition, iron ore exports from Australia and Brazil to China are 20% lower in 2050 in the APS due to an equivalent drop in total Chinese demand.

Figure 5.18 International shipping activity by type of vessel and scenario, 2015-2050



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. "Other" includes all other vessel types not listed here.

The share of container ships in total shipping activity increases from 14% in 2023 to over 20% in 2050 in the APS and the NZE Scenario as fossil fuel shipping declines.

Activity for container ships nearly doubles in all scenarios, as trade in containerised goods continues to trend upwards. The faster deployment of clean energy technologies in the APS and the NZE Scenario compared to in the STEPS would have only a small impact on global shipping activity. While clean energy technology freight in containers more than doubles in the APS over 2023-50, its share in total container freight increases to a mere 2%, as overall container shipping activity increases at a similar rate.

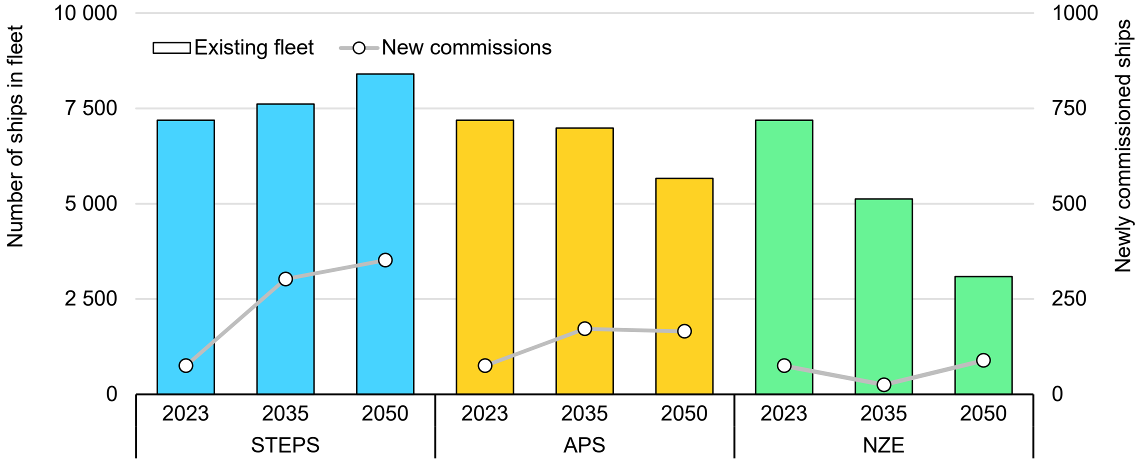
Around 10% of Ro-Ro ship capacity for the transport of vehicles is currently used for EVs. This share increases rapidly in all scenarios, especially the NZE Scenario, but this has little impact on overall demand for Ro-Ro ships, as EV volumes simply displace existing capacities used for ICE vehicles today. The need for additional Ro-Ro ships is expected to be limited in the long term, especially given the prospect of a significant rise in ships in the near term: the number of Ro-Ro ships on order to be delivered in the next 3 years is about 50% higher than over the past 3 years.

Dry bulk shipping activity for coal and iron ore drop is also markedly different across the scenarios. By 2050 it falls by 20% in the STEPS, nearly 40% in the APS and over 50% in the NZE Scenario. Overall, dry bulk activity increases in all scenarios as growth in other commodities, including grains and other metals, outstrips these declines. Demand for critical raw minerals and materials increases by up to 60%, however, these minerals and materials contribute very little to overall bulk shipping activity, and those increases are dwarfed by the reduction in fossil fuel trade in both scenarios.

The biggest differences between the three scenarios concern oil tankers. The fall in oil shipping through to 2050 in the APS would significantly reduce the need for tanker capacity and, therefore, new vessels to replace ageing ones as they are retired. The number of oil tankers, which totals about 7 200 today, declines steadily to around 5 500 in 2050. As a result, the need for yearly new commissions drops to nearly 150 in 2050 in the APS, compared with 350 annual ship commissions in the STEPS. Nevertheless, the current high average age of the world's tanker fleet means that there is still a need to build more ships in the coming decades to maintain the necessary fleet for oil trade, despite declining shipments of oil. In the STEPS, the number increases to more than 8 000 (Figure 5.19).

Expansion in trade in alternative fuels like ammonia or hydrogen does not offset to any significant degree the decline in oil trade in the APS and the NZE Scenario, so the scope for converting oil tankers for shipping those fuels (notably LPG carriers for shipping ammonia) is likely to be limited. Even in the NZE Scenario, in which most ammonia shipping in 2050 is for its use as an energy carrier, total ammonia shipping activity is equal to less than 20% of total oil-related shipping activity today. Shipping liquid hydrogen is expected to require new ships, as converting LNG carriers is likely to be costly. In any case, the hydrogen-related shipping activity in 2050 in the NZE Scenario is around 10% of the shipping activity of the LNG carrier fleet today.

Figure 5.19 Global oil tanker fleet and new commissions by scenario, 2023-2050



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario.

The need for oil tankers falls significantly in the APS and even faster in the NZE Scenario in line with plunging global demand for oil.

Chokepoints

With the continued expansion of global shipping, concerns about physical disruptions to supply at the various chokepoints around the world are coming to the fore. The implications for energy markets of any major disruption to international shipping at various chokepoints along international shipping routes, whether caused by a natural disaster, accident, geopolitical conflict, or act of piracy, would depend to a large degree on the volume of shipping affected. The world's ten most important chokepoints, based on the share of global maritime trade going passing through them, are: the Strait of Malacca, the Strait of Gibraltar, the Strait of Bab el Mandeb, the Suez Canal, the English Channel, the Strait of Hormuz, the Panama Canal, the Danish Straits, the Turkish Straits, and the Lombok Strait. Nearly 60% of the world's shipping by value, including the majority of clean energy technologies and related materials, passes through at least one of these chokepoints, with fossil fuel trade most exposed to the risk of physical supply disruptions (Figure 5.20). Among these, the busiest is the Strait of Malacca, through which a quarter of the world's trade passes today.

Figure 5.20 Share of global seaborne trade transiting selected chokepoints, 2023

Notes: Trade routes are not mutually exclusive: the same ship can go through several chokepoints. Shares are calculated in terms of monetary value. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA analysis based on IMF Ports Watch (2024); Oxford Economics Limited (2024); and Verschuur (2022).

Nearly 60% of the value of traded goods shipped worldwide passes at least one chokepoint, with fossil fuel trade most exposed to the risk of physical supply disruptions.

This concentration of seaborne traffic inevitably creates a risk of major supply chain disruptions. An obstruction at a chokepoint means that significant shares of global shipping might be forced to re-route to longer routes which require more time to reach the destination. This increases the price of shipping, given that as the journey time is longer, there is less carrying capacity globally across the same number of vessels, and more fuel is required. It can also lead to delays in deliveries and disrupt port operations, leading to port congestion and further delays. Several such disruptions have occurred recently. For example, the grounding of the Ever Given container vessel in the Suez Canal in 2021 halted all traffic for about a week, holding up the transportation of an estimated USD 10 billion of goods with huge knock-on effects for global supply chains.

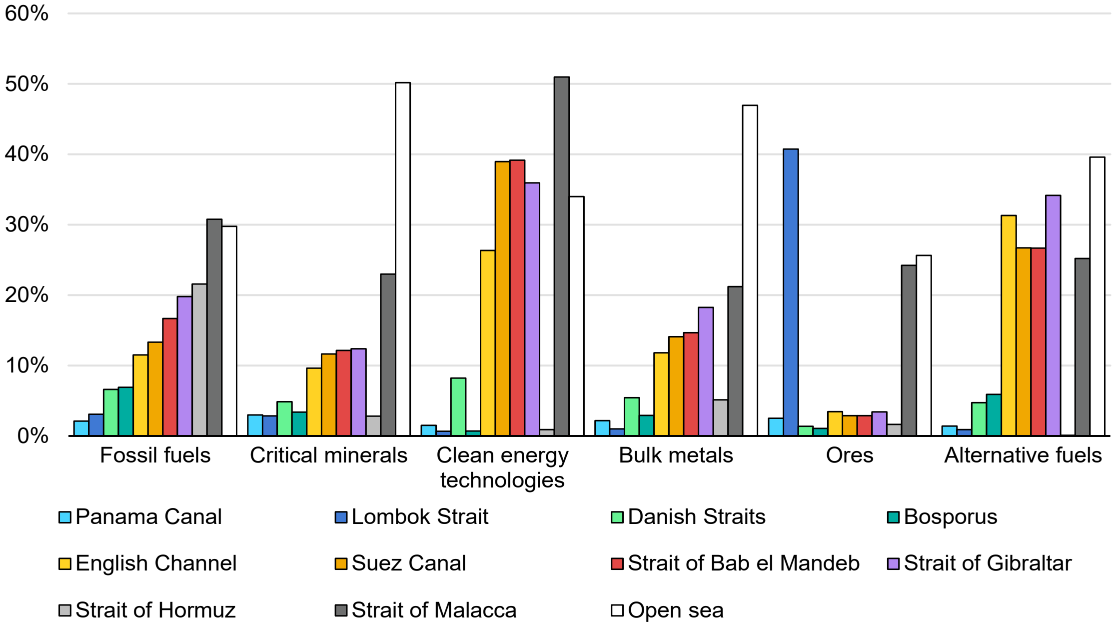
Geopolitical tensions and environmental or weather-related disruptions can also have a significant impact (IMF, 2024). For example, risks associated with Houthi activity affecting vessels in the Gulf of Aden have reduced traffic through the Suez Canal, which about 15% of global maritime trade volume typically passes through. Shipping companies on the route from Asia to Europe have been forced to use the alternative route around the Cape of Good Hope in South Africa, increasing delivery times by 10 days on average, raising costs and reducing available ship capacity. The disruptions in the Gulf of Aden have also increased congestion at some ports, including Algeciras in Spain and Tangier in Morocco, where a need to move cargoes between ships has also arisen because of the increased need for feeder vessels to serve ports in the Mediterranean.

Restrictions on shipping through the Panama Canal due to low water levels in Gatun Lake, the main water reserve for the Canal, are another example. Since June 2023, the Panama Canal Authority has reduced the number of daily transits between the Atlantic and Pacific oceans to limit the use of water from the lake and has set limits on vessels' draft — the maximum depth of the hull below the waterline. Some shipping lines have circumvented the draft restrictions by dropping off containers at one end of the Canal, which leaves the vessel sitting higher in the water, with the offloaded cargoes then being shipped by rail. Freight rates have increased as a result, and Panama's revenues from the Canal's tolls have dropped by USD 100 million per month (Reuters, 2024). These disruptions may intensify and become more frequent as a result of climate change, given the dependence on water resources.

The majority of the world's chokepoints are located on routes linking Asia to Europe and the North Atlantic. For example, the shortest route for a vessel travelling from Shanghai to Rotterdam passes through the Strait of Malacca, the Strait of Bab el Mandeb, the Suez Canal and then the Strait of Gibraltar. However, alternative routes, such as those through the Arctic Circle, are emerging as potential options, especially as ice melts and seasonal navigation becomes more feasible – this route is, however, not practicable today. Trade across the Atlantic, Indian and Pacific Oceans involves fewer chokepoints.

Chokepoints have always been important for trade in energy, notably oil. At present, roughly 80% of global oil trade in value passes through at least one chokepoint. The Strait of Hormuz – the exit point for most Middle East oil exports – is of particular importance due its proximity to areas of conflict, previous disruptions and its importance to oil supplies. Around 25% of global oil trade value currently passes through that chokepoint. The share of oil trade value passing through the Strait of Malacca is even higher, at over 30%, as nearly all imports into East Asia need to pass through Malacca. Similarly, most oil imports into Europe pass through the Strait of Bab el Mandeb and the Suez Canal, accounting for around 15% of global oil trade value respectively. The dependency on chokepoints is slightly lower for gas, with less than 70% of trade value going through at least one chokepoint, while for coal the share is 40%, and the shares at each chokepoint are all below 15%. In total, more than two-thirds of global traded value in fossil fuels passes through at least one chokepoint (Figure 5.21).

Figure 5.21 Share of global trade by value passing through selected chokepoints by commodity and location, 2023



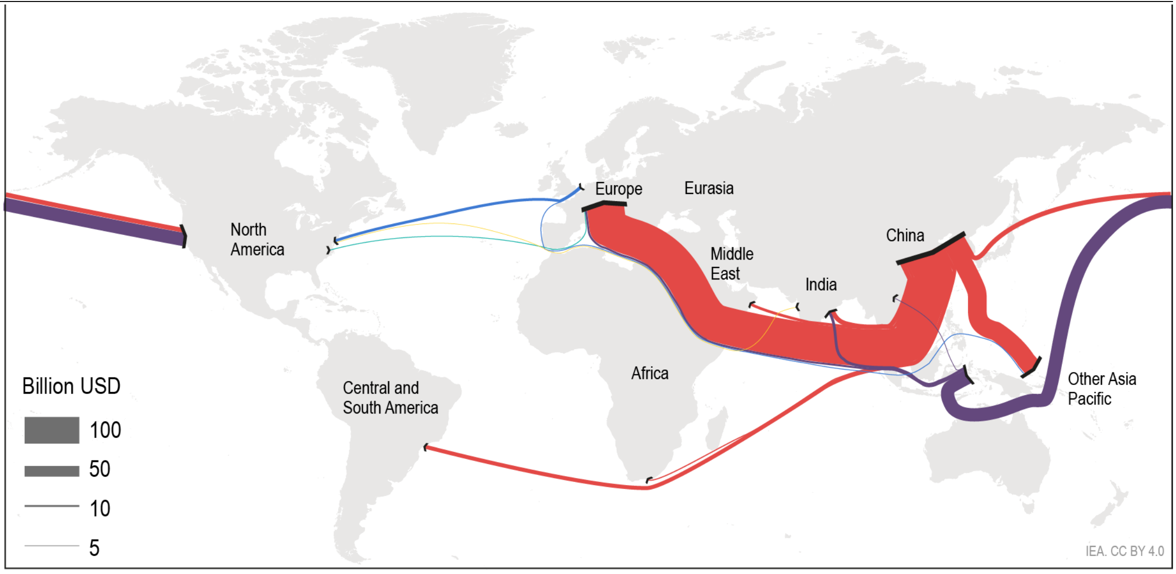
Notes: Trade passing through each chokepoint is calculated by combining global trade data with shortest shipping routes between ports. Open sea refers to the share not going through any of the chokepoints.
Sources: IEA analysis based on IMF Ports Watch (2024); Oxford Economics Limited (2024); and Verschuur (2022).

Over half of clean energy technology traded value passes through the Strait of Malacca, a significantly higher share than for fossil fuels.

Critical mineral trade is more concentrated along north-south axes with vessels mostly crossing oceans, so 50% of global trade value goes through at least one chokepoint. The most important chokepoint is the Strait of Malacca, through which roughly 20% of critical mineral trade passes, mainly to China – a major importer of raw minerals and exporter of refined minerals. Among critical minerals, around the 70% of the trade in cobalt passes through that chokepoint on its way to China for processing.

Bulk metals are also dependent on chokepoints, with roughly 55% of total trade value going through at least one. Again, the principal chokepoint is the Strait of Malacca, through which exports to China from Latin America, South Asia and Africa pass. In the case of ores, the Strait of Lombok is by far the most important corridor, accounting for around 40% of all ores traded globally and 40% of iron ore trade (due to the large amount of ore shipped from northwest Australia to China). Three-quarters of global traded value in iron ore and bauxite currently passes through one of the ten main chokepoints.

Figure 5.22 Main inter-regional trade flows for key clean energy technologies in the Stated Policies Scenario, 2035



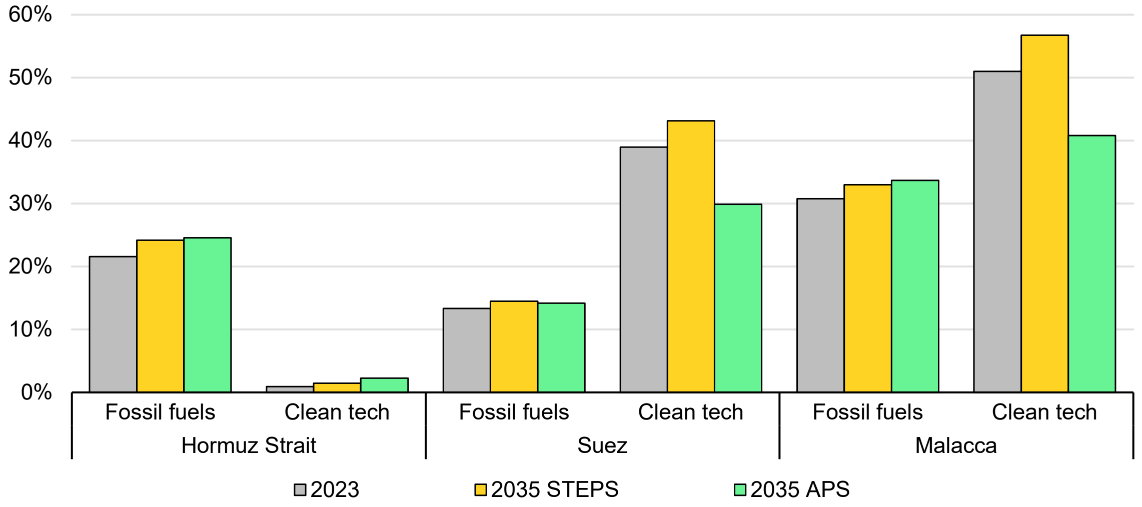
Notes: Intra-regional trade is excluded, see Annex for details. Clean energy technologies include solar PV modules, heat pumps, EVs, wind turbine components, batteries, and electrolysers. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Sources: IEA based on Oxford Economics Limited (2024); CEPII (2024); and Verschuur (2022).

Asian countries are the main exporters of clean energy technologies by 2035 in the STEPS.

The importance of chokepoints varies between clean energy technologies, critical minerals and associated bulk materials. The share of clean energy technology trade that passes through chokepoints is about two-thirds, slightly lower than that for fossil fuels. Because of China's role as the main manufacturing hub for those technologies, half of all such traded value passes through the Strait of Malacca – a significantly higher level of concentration than that for oil through the Strait of Hormuz. Around 40% of global clean energy technology trade passes through the Strait of Bab el Mandeb and about 35% through the Strait of Gibraltar in terms of value. Among the six clean energy technologies, trade for solar PV modules is most exposed to chokepoints, with more than two-thirds of total trade value passing through the Strait of Malacca, and 45% through Suez. Trade of electric cars, heat pumps and batteries – technologies for which a significant share of trade is between China and Europe – is also heavily concentrated through Malacca.

Figure 5.23 Share of total maritime trade value passing through selected chokepoints by product category in the Stated Policies and Announced Pledges Scenarios, 2035



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Clean technologies include solar PV, wind, EVs, batteries, heat pumps and electrolysers. Intra-regional trade is excluded, see Annex for details. Calculated in value terms.

Source: IEA analysis based on IMF Ports Watch (2024) and Oxford Economics Limited (2024).

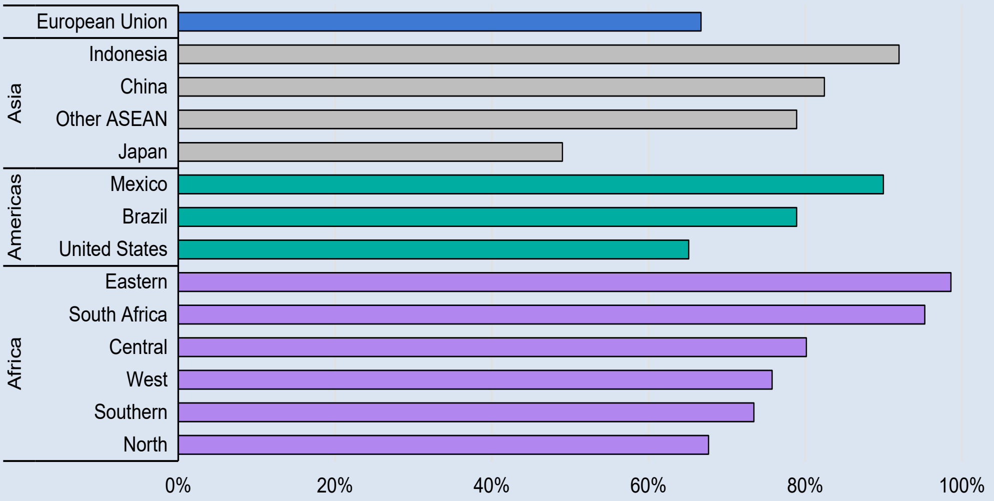
The exposure of trade in clean energy technologies to maritime chokepoints increases in the STEPS as trade flows become more concentrated.

Trade in clean energy technologies is similarly exposed to maritime chokepoints as fossil fuel trade, by 2035 this is projected to change as clean energy technologies become more exposed than fossil fuels. However, the clean energy transition holds the promise of reducing the value of energy-related trade passing through chokepoints. In the APS, the overall value of inter-regional trade in the six clean technologies covered in this report increases by fourfold between 2023 and 2035, but this is more than offset by a 40% fall in trade in fossil fuels. In this scenario, most exports of clean energy technologies come from Asian countries, while the main importers are the European Union and the United States. These trade flows pass through several chokepoints (Figure 5.22). The Strait of Malacca is set to become even more crucial for clean energy technology trade by 2035 in the STEPS (Figure 5.23). The same is true for the Suez Canal. Trade in fossil fuels also becomes slightly more concentrated in the Strait of Malacca as Asian imports remain relatively strong, and through the Strait of Hormuz, as exports from the Middle East make up a higher share of oil demand. In the APS, as the manufacturing of clean energy technology becomes geographically more diverse, the exposure of trade to chokepoints falls relative to the STEPS, despite an increase in the absolute value of trade.

Box 5.1 The effects of increasing trade in clean energy technologies on port infrastructure

Port infrastructure is not expected to be a bottleneck for most advanced economies and China even as their trade, in terms of mass, will double by 2035 because they start from such a small share of container trade. That may not be the case in certain emerging markets and developing economies. The maximum throughput of a port is primarily determined by its quay length, which determines how many ships it can host at a time. In some cases, capacity could be limited by the number of cranes available to unload containers, or by the availability of terminal yard capacity (space to store containers). Port utilisation rates, particularly for container ships, are very high in some regions, and therefore ports might not be able to handle additional cargo without major investments. In most advanced economies, the average container ports are far from their capacity limits (Figure 5.24). By contrast, utilisation rates are over 90% in Indonesia, Mexico, South Africa and in the East Africa region, and around or over 80% in Brazil and other ASEAN countries.

Figure 5.24 Utilisation rate of container ports in selected countries/regions, 2023



Notes: ASEAN = Association of Southeast Asian Nations; Country-level port utilisation rates are calculated as the weighted average utilisation rate of individual ports. For each port the utilisation rate is calculated based on the port's quay length, crane capacity and terminal area.

Sources: IEA based on MDST (2024).

The need to boost container port capacity is particularly pressing in Indonesia, where the government is aiming to develop the downstream segments of clean energy supply chains and boost exports of intermediate and finished products, which would require more container terminals. A major port expansion project is currently under construction (Patimban Port), which would increase container handling capacity by 7.4 million TEUs, which is around two-thirds of existing

Indonesian handling capacity (DGST, 2017). Major additions to export capacity are also needed in Mexico, which is expected to play an important role in the production of clean energy technologies for the North American market.

5.3 Decarbonising shipping

Technologies for low-emissions shipping

There are two main categories of measures to reduce GHG emissions from maritime shipping: energy efficiency and switching to low-emissions fuels. The former holds potential to significantly lower emissions in the short to medium term, while the latter will be needed to achieve net zero in the longer term.

Energy efficiency

Energy efficiency can be improved either by changing operational practices, notably reducing the average speed of ships, known as “slow steaming”, or by technical measures to improve fuel efficiency. Slow steaming does not require any physical modification of the ships themselves but can have an indirect impact on costs: the overall reduction in the sector’s fuel costs may be outweighed by the corresponding reduction in shipping capacity (as more ships would be required at any given moment). It can also have a business impact, especially for sectors that rely on just-in-time delivery, which is typical for goods shipped by containers.

Technical measures to improve the energy efficiency of a ship can be deployed at the time it is built or retrofitted to an existing one. The principal measures available today include rigid sails, rotor sails (large vertical rotors design to use the Magnus effect for propulsion), waste heat recovery (applied to the main engine and/or steam generator), anti-fouling hull coatings (that prevent the build-up of subaquatic organisms, which can impair the performance and durability of a ship), optimisation of the shape of the hull to reduce water resistance and air lubrication (the creation of a carpet of microbubbles on the full flat bottom of a vessel's hull to reduce frictional resistance).

Since 2010, the design energy efficiency of new-build ships has increased by 30-50% depending on the type of ship (IMO, 2023b). This has been driven by the adoption of several initiatives developed by the IMO, including the adoption of the energy efficiency design index (EEDI) in 2011, which requires a minimum energy efficiency level per tonne-kilometre (tkm) for new ships of different type and size segments. This regulation prescribes further improvements up to 2025 for some ship types. Many of the necessary technologies are already commercially available or at the commercial demonstration stage (Table 5.5), but their current penetration in the fleet is still limited. As a consequence, in the STEPS, further efficiency gains of 5-10% are projected by 2030 compared to 2023, depending on the ship type, and 25-50% in the APS and NZE Scenario. Further improvements are projected after 2030.

The Carbon Intensity Index (CII) regulation by the IMO applies to all ships, old and new, and specifies a maximum tank-to-wake emission intensity per tkm that becomes more stringent over time. A 2% per year emission intensity reduction is in place for 2023-26. This regulation can be met by a combination of design measures, operational measures and fuel switching. Accordingly, an improvement of the average technological energy efficiency by ship type of 1.3-2.8% per year over 2024-2050, in line with historical trends, is assumed on average in the STEPS. This is obtained mainly through retrofitting of energy efficiency technologies on existing ships in the short run and fleet renewal with more efficient ships in the long run. In the APS and NZE Scenario, the faster penetration of energy efficiency technologies results in a faster improvement of 1.6-4.0% per year over 2024-50, depending on ship type.

Some technologies, such as anti-fouling hull coating, are applicable to all types of ships, while others can only be applied to certain types. For example, steam plant operation improvements are suitable mainly for oil tankers. Several energy efficiency technologies can be combined on a given ship, provided that they are technically compatible (rotor sails and kites, for example, will not normally be combined), though the overall energy efficiency improvement is generally lower than the sum of the effects of the individual technologies. The latest technologies are expected to have a significant impact on fuel consumption. For example, a bulk carrier built in 2030 incorporating pre/post swirling devices, anti-fouling hull coating, hull shape optimisation, air lubrication, rotor sails, waste heat recovery by using the organic Rankine cycle, and operating systems optimisation technologies could improve efficiency by around 40% compared with a ship built in 2023. Retrofitting the applicable measures from the same package on an existing container ship would provide energy savings of about 30%.

The cost and economic and financial viability of the various energy efficiency technologies varies considerably. In many cases, they can provide a net financial benefit, i.e. the savings in fuel costs offset the upfront investment. The investment could represent less than 0.5% of the total cost of the ship in the case of hull coating and as much as 5% for rotor sails. For a representative 75 000 deadweight tonne (DWT) bulk carrier, implementing hull form optimisation would typically involve a cost of USD 250 000 for an energy efficiency gain of around 7.5%, while for kite sails, the capital cost would be around USD 1.2 million for a gain of 2.5%.

Table 5.5 Summary of the status of selected technologies to decarbonise shipping

Technology	TRL		Importance for net zero emissions	Deployment status
	2020	2024		
Operational energy efficiency				
Slow steaming (intentionally operating at a lower speed)	11	11	High	Speed routinely lower than design
Dynamic route optimisation (taking into account winds and currents)	9	9-10	Moderate	Commercially available
Trim and draught optimisation (optimise ship loading)	9	9	Moderate	1 000 ships equipped
Technological energy efficiency				
Rotor sails (Flettner rotors using Magnus effect)	8	8-9	High	At least 15 ships equipped
Kite sails	6	7	Moderate	Full scale prototype 2021
Waste heat recovery (from main engine)	8-9	8-9	Moderate	Over 30 deployed today
Anti-fouling hull coating	9	9-10	Moderate	Commercially available
Hull form optimisation	10	10	Moderate	Commercially available
Air lubrication (air bubbles or layer between hull and water)	8-9	9	Moderate	Around 200 ships equipped
Fuel switching				
Ammonia combustion engine powered ships	4-5	6	Very High	Over 20 ships on order
Methanol combustion engine powered ship	8-9	9	High	Around 300 ships in operation or on order
Hydrogen combustion engine powered ship	4-5	4-5	Moderate	Small-scale demonstration 2022
Hydrogen fuel cell powered ship	7	8	Moderate	Over 20 vessels in operation or on order
Battery electric ship	8-9	9	Moderate	Almost 500 plug-in vessels in operation or on order
Nuclear propulsion	3-4	3-4	Low	AiP granted for SMR design
Cold ironing (using onshore power when at port)	9	9	High	Over 30 ports with at least 1 berth
Carbon capture and storage				
Onboard Carbon Capture (with onshore final storage)	3	5-6	Low	Partial testing since 2021

Notes: TRL = technology readiness level; SMR = small modular reactor AiP = Approval in Principle by a classification agency. The TRL provides a snapshot in time of the level of maturity of a given technology. It provides a common framework that can be applied consistently to any technology to assess and compare the maturity of technologies across sectors. A more detailed table and the definition of each TRL level are available in the Annex.

Sources: IEA (2024c); US Department of Transportation (2022); and GloMEEP (2019). Ship order books from United Nations Global Platform (2024); and DNV (2024b).

Switching to low-emissions fuels

Improving the energy efficiency of ships fuelled by fossil fuels can reduce but cannot eliminate emissions, so switching to low-emissions fuels will also be needed to get to net zero. A range of options are being considered, including: biodiesel, bio- or synthetic methanol, bio- or synthetic methane, near-zero emission ammonia and low-emissions hydrogen.

Some fuels are known as drop-in fuels, as they do not necessitate any major modifications to ships; for example, diesel engines can run on biodiesel from hydrotreated vegetable oil (HVO), while LNG engines can run on biomethane, as well as synthetic methane. But the availability of such fuels will be limited by the quantity of available sustainable biomass, in the case of biofuels; and by the high production costs in the case of synthetic diesel. Competition with other sectors, especially aviation, is high for liquid drop-in fuels.

The alternatives – methanol, ammonia, and hydrogen – all require modifications to the ship engine, tanks, layout and additional safety measures, as well as special facilities to supply the fuel to the port, store it and fuel the ships. The adoption of these vessels with alternative propulsion systems would require technological innovation, as well as new safety codes and standards.

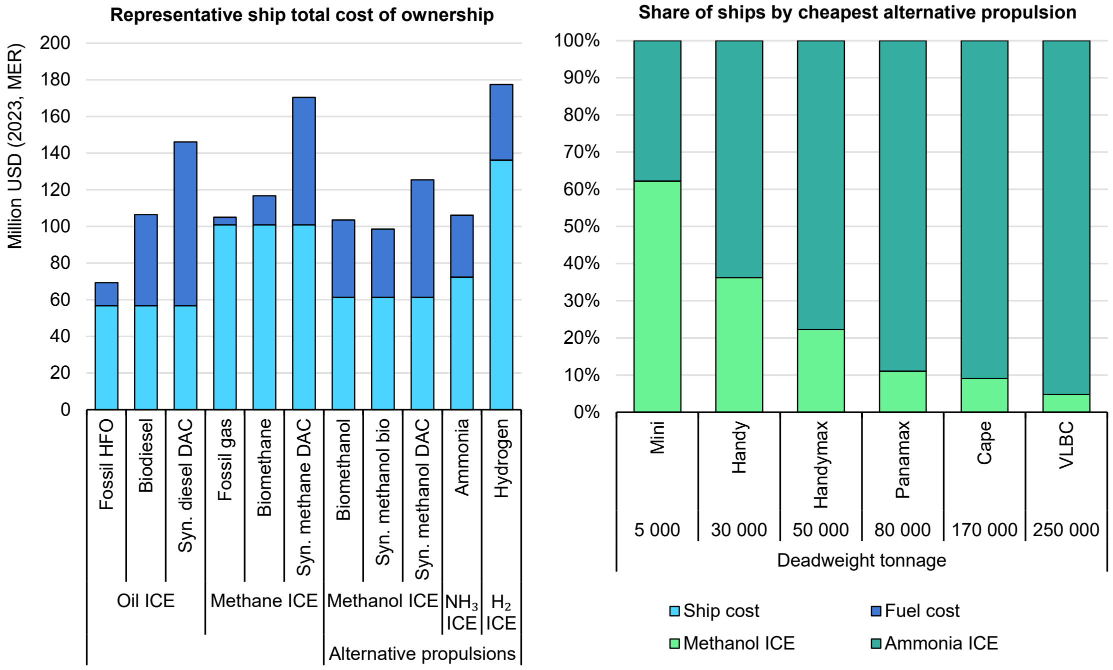
Methanol is one option that has been gaining traction recently. The first methanol-fuelled container ship with a dual-fuel engine sailed from Korea to Denmark in 2023, and there are around 300 methanol-fuelled vessels in operation or on orderbooks. In terms of safety, the IMO has already issued the “Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel” (MSC.1/Circ.1621) – a first step towards establishing common design and operation safety standards.

Ammonia is another option, which, unlike methanol, does not require a source of carbon. However, ammonia-powered vessels are at a lower stage of technology readiness level despite an acceleration in innovation in the past few years. Ammonia engines have progressed from the small-scale prototype stage in 2020 to the full commercial scale prototype today, and over 20 ships powered by ammonia dual-fuel engines are now on order books around the world, with deliveries due to start in 2026. Ammonia-powered shipping is also at a less mature stage in terms of safety regulations, though several classification agencies have issued tentative or provisional requirements. The IMO is in the process of revising the International Code for Safety of Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) and International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC) to allow the use of ammonia as a marine fuel, with the revision expected to come into effect in early 2028 (IMO, 2023d).

Hydrogen-fuelled vessels have also received some attention, with over 20 vessels in operation or on order. IMO interim guidelines for the safety of ships using hydrogen as fuel are also in preparation, with the same timeline as for ammonia.

When deciding what technology to choose when investing in a new ship, a shipping company takes into account the total cost of ownership, including the cost of the ship and the fuel cost over its life. Biomethanol, synthetic methanol from electrolytic hydrogen and biogenic CO_2 and ammonia from electrolytic hydrogen, used with an ICE, are the cheapest alternative fuels for shipping on average in 2035 in the APS, though both cost significantly more than conventional heavy fuel oil on a full lifetime cost basis (Figure 5.25). The fuel cost of methanol is higher than that of ammonia, but the cost of the ship is lower (costing only about 10% more than a conventionally fuelled ship). An ammonia ship typically requires a higher upfront investment than a methanol ship, due to the need to refrigerate the fuel tanks, the larger volume of the tanks for the same energy contents and the enhanced safety features; operating costs are also expected to be higher. Drop-in fuels, biodiesel and biomethane, have the lowest vessel costs, since no deviation from existing designs is needed, but their total cost of ownership tends to be higher than the other low-emissions alternatives.

Figure 5.25 Total lifetime cost of ownership of a representative new bulk carrier and cheapest alternative propulsion option in the Announced Pledges Scenario, 2035



Notes: HFO = heavy fuel oil; ICE = internal combustion engine; NH_3 = ammonia; LNG = liquefied natural gas; H_2 = hydrogen; VLBC=Very Large Bulk Carrier, biodiesel = Biomass-to-Liquid; Syn. diesel DAC = synthetic oil from electrolytic hydrogen and CO_2 from direct air capture; Syn. methane DAC = synthetic methane from electrolytic hydrogen and CO_2 from direct air capture; Syn. methanol bio= synthetic methanol from electrolytic hydrogen and biogenic CO_2; Syn. methanol DAC = synthetic methanol from electrolytic hydrogen and CO_2 from direct air capture; Ammonia = near-zero emissions ammonia, produced mainly from electrolytic hydrogen. Based on a 50 000 deadweight tonne vessel with an annual activity of 2.5 billion tonne-kilometres. For the right-hand chart, average fuel unit costs per propulsion type have been used, reflecting the mix of different pathways (fossil, bio- and synthetic) in the projections over the 25 years of life of the ship (for methanol, the share of synthetic goes from 65% to 100%). CO_2 prices are not included.

Source: The right-hand chart is based on travel speeds and distances for international trips derived from 2023 data from the United Nations Global Platform (2024).

Methanol and ammonia are the cheapest alternative propulsions for shipping on average in 2035 in the APS, though both cost significantly more than conventional heavy fuel oil.

The most competitive alternative fuel in the APS in 2035 varies according to the size of the ship and normal travelling patterns (speed and distance). Smaller ships tend to have lower speeds and travel shorter distances, so their fuel consumption is proportionally lower: the cheapest configuration for them tends to be methanol. For larger ships, the cheaper option is generally ammonia. For the smallest mini bulk carriers, methanol is the cheapest option in almost two-thirds of cases (with ammonia the cheaper option only for ships that travel longer distances and/or at a higher speed). But for larger ships, ammonia is the cheaper option in the vast majority of cases – two-thirds for Handysize 30 000 DWT ships and around 95% of very large bulk carriers (VLBCs).

Methanol and ammonia-powered vessels under construction today are all dual-fuel combustion engines, which can also be operated with conventional and drop-in fuels. Dual-fuel vessels can have an efficiency penalty compared to single fuel options – for example early-stage fuel cell ammonia vessels hold the promise of higher efficiency compared to internal combustion powertrains. However, interoperability of vessels with respect to different fuels is of paramount importance given the uncertainty about the future price and availability of different fuels, as well as to ensure continued operation on varying regional routes (which is particularly important for dry bulk vessels). Interoperability can also increase resilience against potential supply shocks for any one fuel. The transition towards alternative fuels is therefore likely to involve dual-fuel vessels.

In the mid to long term, the rate of penetration of near-zero emissions fuels in maritime shipping will be constrained by the turnover of the fleet. Ships being built today will only account for about 35% of the fleet in the STEPS by 2035, and about 40% of the fleet in the APS and NZE Scenario, as they have a long operational lifetime, typically in excess of 25 years. Ships with conventional or LNG propulsion still dominate order books today, making up almost 90% of orders worldwide in terms of gross tonnage (DNV, 2024a). This number falls to less than 15% by 2035 in the APS. Retrofitting existing ships to alternative propulsion systems, or early retirement of the older traditional propulsion ships, are ways to increase the penetration of fuel switching.

CO_2 emissions and energy trajectories by scenario

CO_2 emissions from international maritime shipping have grown in recent decades, as strong growth in trade has more than offset improvements in fuel efficiency. Those emissions have rebounded strongly since the Covid-19 pandemic, reaching 0.67 Gt CO_2 in 2023 – about 2% of global energy-related CO_2 emissions. Emissions have grown in parallel with energy use, which remains almost entirely in the form of fossil fuels.

The prospects for shipping emissions depend on policies to drive faster efficiency gains and a switch to low-emissions fuels, and to support innovation. In the

STEPS, shipping activity increases by 40% between 2023 and 2050, while the overall emission intensity in the fleet continues to improve at a rate of 1.6% per year on average – close to the recent historical trend and as per the IMO's Carbon Intensity Indicator regulation (Box 5.2). As a result, energy demand rises by about 20% over the same period. Emissions peak in 2030, under the influence of the FuelEU maritime standard, which becomes much more stringent after 2040, giving rise to greater uptake of low-emissions fuels, primarily biofuels (Figure 5.26).

Box 5.2 Maritime shipping regulations

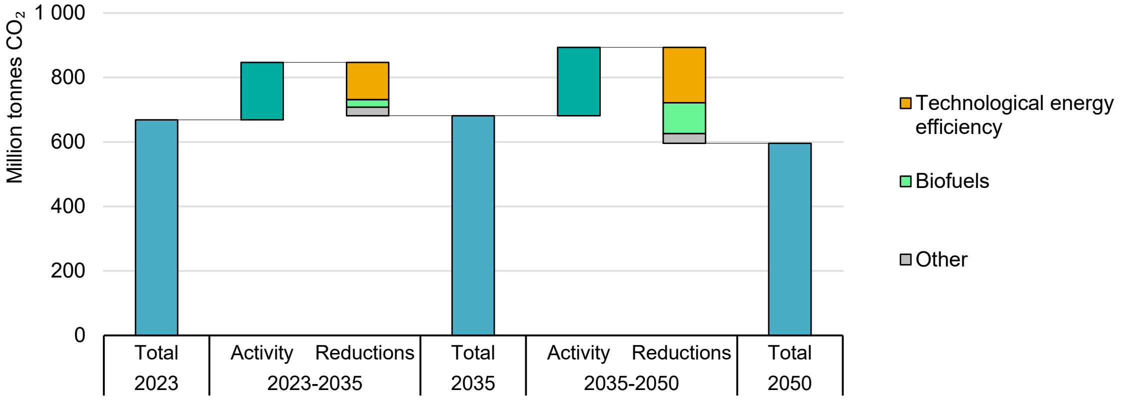
International shipping is governed by supranational bodies, notably the IMO – a UN agency with 176 member states, which regulates prevention of pollution from ships through the International Convention for the Prevention of Pollution from Ships (MARPOL) and issues global standards and technical guidance. Several policies have been enacted in the past few years (and are, therefore, taken into consideration in the STEPS), including the following:

- IMO measures: The EEDI and the Ship Energy Efficiency Management Plan, an operational mechanism to improve the energy efficiency of a ship in a cost-effective manner, both came into force in 2013. In addition, in 2021, the IMO adopted a new set of technical and operational measures comprising the Energy Efficiency Existing Ship Index and the CII, which entered into force on 1 January 2023.
- European Union: The FuelEU Maritime Initiative, which came into force in 2023, includes a number of measures to cut shipping emissions, including the introduction of a fuel well-to-wake emission intensity standard (expressed in grammes of CO_2 equivalent per megajoule [g CO_2-eq/MJ] of fuel). The stringency of the standard increases progressively, starting with a 2% reduction in 2025 and rising to 6% in 2030 and 80% in 2050. In addition, ships with a gross tonnage of 5 000 or above entering EU ports were brought into the scope of the EU Emissions Trading Scheme (ETS) from the beginning of 2024. Both schemes cover 50% of emissions from voyages starting or ending outside of the Union (allowing the third country to decide on appropriate action for the remaining share of emissions) and 100% of emissions that occur between two EU ports, which combined account for about 10% of global shipping fuel use. For the EU ETS, CO_2 emissions are covered immediately and methane and nitrous oxide emissions will be covered from 2026. Shipping emissions from maritime transport are included in the overall ETS cap, which defines the maximum amount of GHGs that can be emitted under the system.

In 2023, the IMO adopted the revised GHG Strategy (IMO, 2023a), updating the original 2018 version, which aims for "peak GHG emissions from international shipping as soon as possible and to reach net zero GHG emissions by or around, i.e. close to, 2050". It includes "indicative checkpoints" on total annual GHG emissions from international shipping, compared with 2008 levels: to reduce emissions by at least 20% (striving for 30%) by 2030 and by at least 70% (striving for 80%) by 2040. The uptake of "zero or near-zero GHG emission technologies and/or energy sources" is to represent 5% (striving for 10%) of the energy used by international shipping by 2030. Both the levels of ambition and indicative checkpoints "should take into account the well-to-wake GHG emissions of marine fuels". These goals are taken into consideration in the APS. In order to implement this strategy, a set of mid-term measures is currently under discussion, including a goal-based standard on GHG emission intensity of marine fuels, as well as a GHG emissions pricing mechanism. The mid-term measures are expected to be approved at the end of 2025 and come into force in 2027.

Individual countries can also have their own regulations. For example, the Clean Shipping Act of 2023 was proposed by the US House of Representatives, which would set carbon intensity standards for marine fuels, including 100% zero emission fuels from 2040 (US Congress, 2023). In China, the 14th Five Year Plan for Water Transportation, which was released in 2022, aims to promote the "green and low-carbon transformation" of the shipping industry (CN MoT, 2022). In the United Kingdom, the government has announced its intention to include international shipping emissions in its carbon budget and Nationally Determined Contribution for 2035 (UK Parliament, 2024).

Figure 5.26 Global energy-related CO_2 emissions in international shipping and drivers of change in the Stated Policies Scenario, 2023-2050



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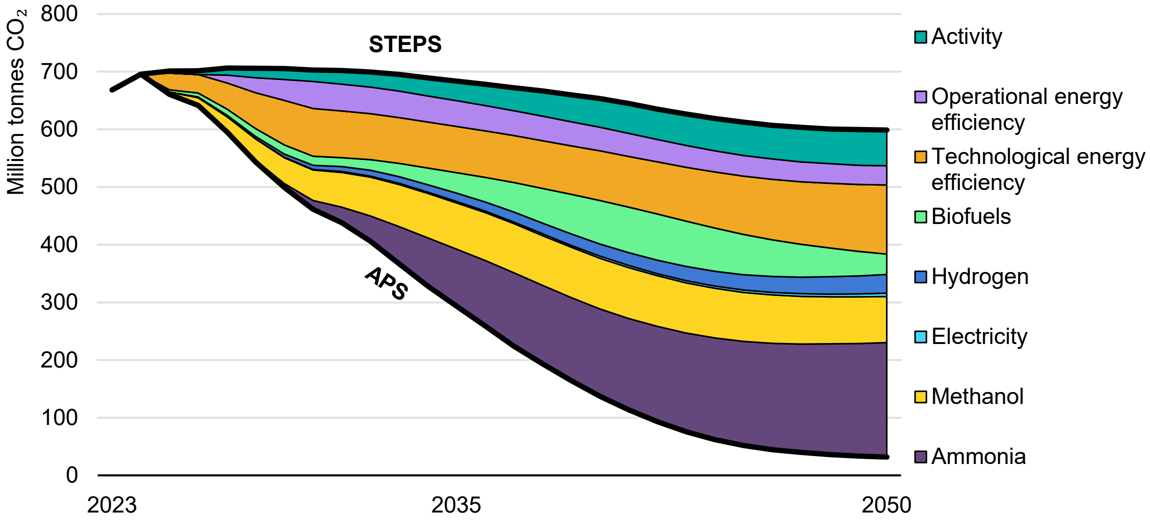
Notes: Emissions include both emissions at port and at sea. Technological energy efficiency includes the effect of the deployment of sails, waste heat recovery, and drag reduction technologies (see Table 5.5). "Other" includes the effects of fuel switching (from oil to methanol, ammonia, LNG, hydrogen, electricity); of changing average emissions intensity of fossil fuels; and of operational energy efficiency.

With current policy settings, shipping emissions are set to drop marginally by 2050, as technical and operational efficiency gains outweigh the impact of increased activity.

Shipping emissions fall much faster in the APS, which takes into account the targets set out in the recently revised IMO GHG Strategy. In the APS, emissions in 2050 are reduced by more than 90% relative to 2023 and by more than 90% relative to STEPS, mainly due to switching to low-emissions fuels – notably ammonia (Figure 5.27). In total, alternative fuels account for over 60% of all the reductions in the APS relative to the STEPS in 2050, operational and technical efficiency measures for almost 30%, and reduced shipping activity for around 10%. The share of fossil fuels in total energy use in the shipping sector plunges from almost 100% in 2023 to less than 30% by 2040 and less than 10% in 2050.

Figure 5.27 Global energy-related CO_2 emissions in international shipping by scenario and reductions in the Announced Pledges Scenario relative to the Stated Policies Scenario by mitigation measure



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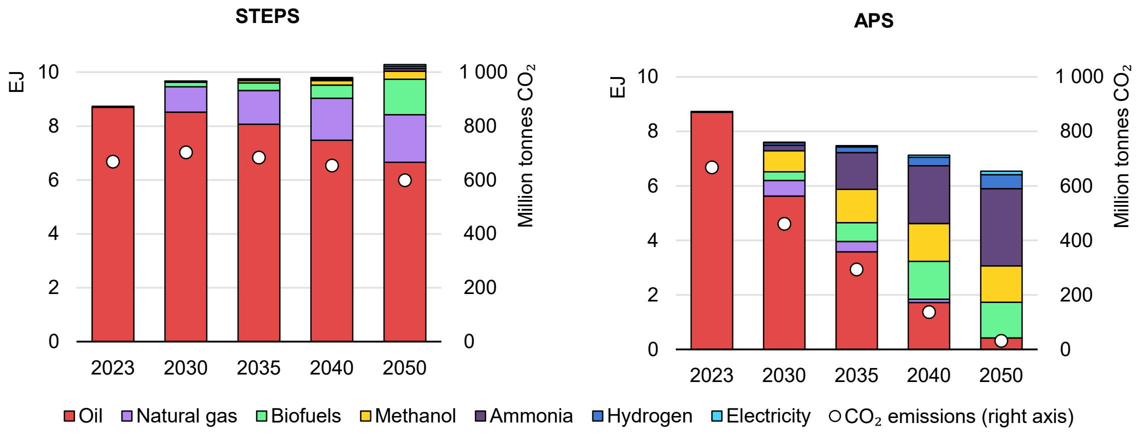
Notes: STEPS = Stated Policies Scenario (upper line); APS = Announced Pledges Scenario (lower line). Biofuels include biodiesel and biomethane but exclude biomethanol. Hydrogen refers to low-emissions hydrogen as defined in the Annex. Methanol refers to low-emissions methanol and it includes biomethanol. Ammonia refers to near-zero emissions ammonia as defined in Box 1.1. Emissions include both emissions at port and at sea. Emissions reductions due to energy efficiency improvements are split into an operational and a technological component. Operational energy efficiency includes the effect of speed reduction, whereas technological energy efficiency includes the effect of the deployment of sails, waste heat recovery, and drag reduction technologies (see Table 5.5).

Shipping emissions fall much faster in the APS than the STEPS, in line with the targets set out in the IMO's latest GHG Strategy, led by switching to ammonia and efficiency gains.

The emissions trajectory in the APS is very similar to that of the NZE Scenario, since the targets set out in the IMO GHG Strategy are in line with the milestones required to achieve net zero emissions by 2050. There are, nonetheless, some differences in the *way* the emissions reductions are achieved, the most important of which is the lower activity in the NZE Scenario compared with the APS (resulting in around 10% less activity in 2050), driven by a faster decline in oil tankers, LNG carriers and bulk carriers carrying coal. This results in residual emissions of around 20 Mt of CO_2 in 2050 in the NZE Scenario, compared with more than 30 Mt in the APS, as a small proportion of the shipping fleet continues to rely on fossil fuels. The lower shipping activity due to less fossil fuel trade in the NZE Scenario means that the emissions reductions are achieved with 20% lower investment needs compared to the APS.

The contributions of the different technologies and measures to reducing shipping emissions in the APS vary over time. Up to 2035, the main contributors are improvements in energy efficiency, through more efficient new builds and retrofitting, slower journeys and the displacement of fossil fuels by biofuels (Figure 5.28). Emissions reductions in this period are determined to a large extent by the existing vessel order book, which limits the possibility of changing the stock of vessels over the coming decade. Currently, almost 95% of vessels on order books (with deliveries until 2027) are designed to run on fossil fuels. Due to the increasing demand for biofuels across all transport sectors, the supply of biofuels is insufficient to displace much fossil fuel use in shipping (see Box 5.3). From the 80 EJ global supply of sustainable biomass in 2035, only 12 EJ are converted to liquid bioenergy, of which about 1 EJ, or 10%, are used in the shipping sector, with the majority going to road transport and aviation. Unlike biofuels, near-zero emission ammonia production is not limited by any biomass supply constraints. Ammonia is currently used almost exclusively to produce fertilisers. In the APS, near-zero emissions ammonia demand from the shipping sector by 2050 becomes comparable to today's overall ammonia demand.

Figure 5.28 Global energy consumption and energy-related CO_2 emissions in international shipping in the Stated Policies Scenario and Announced Pledges Scenario, 2023-2050



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Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Biofuels include biodiesel and biomethane but exclude biomethanol. Hydrogen refers to low-emissions hydrogen as defined in the Annex. Methanol refers to low-emissions methanol and it includes biomethanol. Ammonia refers to near-zero emissions ammonia as defined in Box 1.1. Energy and emissions in port, as well as at sea, are included. The Net Zero Emissions by 2050 Scenario is not shown, as the trajectories are very close to those in the APS. Energy values in 2023 are determined by IEA Energy Balances.

Reduced shipping activity and faster efficiency gains cut energy use in the APS, with a switch to near-zero emissions fuels – notably ammonia – displacing most oil use by 2050.

After 2035 in the APS, ammonia and synthetic fuels emerge as the leading contributors to emissions reductions in shipping. Methanol is the more important fuel initially, as the technology for methanol engines is more mature and the costs for new ships fitted with such engines are lower than for ammonia-powered ships, but is then overtaken by ammonia. Methanol-powered ships of most sizes are not cost-competitive with ammonia-powered ones when the methanol is produced using synthetic pathways, which is the case in APS due to the limited amount of sustainable bioenergy. The introduction of methanol- and ammonia-powered ships to the fleet is mainly through new builds, but retrofitting of existing fuel-oil-powered ships plays an important role until the mid-2030s. In this scenario, increased demand for alternative fuels requires parallel growth in refuelling infrastructure, which could be an opportunity for ports located in areas with low alternative fuel production costs (see below).

Retrofitting existing ships to alternative fuel propulsion has been taken into account based on age and size eligibility criteria. By 2040 in the APS, retrofitted ships represent about 30% of all alternative-fuel-powered ships in the global fleet, though this share falls to less than 20% by 2050 as the pool of eligible ships starts to run out. Older ships that cannot be retrofitted are fuelled either by biodiesel or continue to run on fossil fuels. Hydrogen and battery-powered ships make small contributions to reducing emissions in the 2040s, mainly for short journeys, accounting for around 7% of total reductions in 2050 compared to in the STEPS.

Increased shipping costs

The decarbonisation of international shipping through more energy efficient vessels, new propulsion technologies and alternative fuels will raise the cost of international trade. Installing any of these technologies increases the capital expenditure (CAPEX) for a ship. For instance, a container ship with an ammonia engine is about 25% more expensive than the equivalent ship with an engine designed to use conventional liquid marine fossil fuels. In addition, the use of low-emissions fuels raises bunkering costs, as they are generally more expensive than fossil fuels on a per-unit energy basis. Today, the running costs, including CAPEX, non-fuel OPEX and fuel costs, of a hypothetical ammonia-powered container ship would be twice as high as for a conventional ship (Figure 5.29). Due to technology learning effects and economies of scale, near-zero emissions fuels are expected to become cheaper over time; in the APS, the cost of ammonia falls by almost 40% in real terms between 2023 and 2050. Moreover, energy efficiency upgrades cut the fuel consumption of ships and thereby mitigate the impact of higher fuel costs.

Box 5.3 International co-operation on CO_2 shipping

New business models for carbon capture, utilisation and storage (CCUS) projects are emerging (IEA, 2023), including the possibility to capture CO_2 in one country and store it in another. While it remains unlikely that a global market for transporting and storing CO_2 will emerge, increased demand for shipping CO_2 will have implications for port infrastructure, shipping capacity and international regulatory obligations for the offshore storage of CO_2.

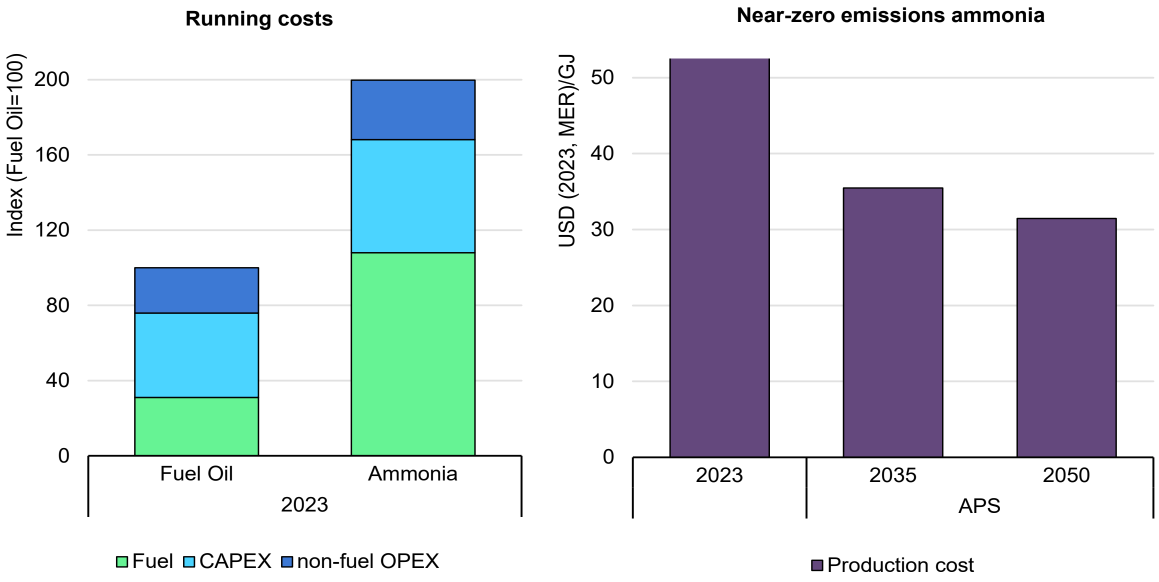
Transboundary projects (i.e. those where the CCUS value chain involves two or more countries) are currently proposed in Europe, East Asia and Oceania. In Europe, around 20 cross-border infrastructure projects are being developed to access storage resources in the North Sea and in southern Europe. Policy support from the European Union is a major driver, with over USD 500 million being provided to CO_2 transport and storage projects under its Connecting Europe Facility programme in 2023 (CINEA, n.d.), and 14 cross-border CO_2 network projects selected as Projects of Common Interest (European Commission, 2023). In East Asia and Oceania, countries with limited CO_2 storage are exploring partnerships for CO_2 shipping to Indonesia, Malaysia and Australia. In Japan, seven CCUS hubs were selected for funding by the Japan Organization for Metals and Energy Security in 2023 (METI, 2023), including two in Malaysia and Oceania. A memorandum of understanding (MOU) was signed in 2020 by Singapore and Australia (Government of Australia and Government of Singapore, 2020), and a letter of intent (LOI) on cross-border CO_2 storage was recently signed by Singapore and Indonesia (MTI, 2024).

The London Protocol, a global treaty, overseen by the IMO, aims to protect the marine environment from pollution caused by the dumping of wastes and other matter into the sea (IMO, 1996). Since 2006, the London Protocol has provided a basis in international law to allow CO_2 storage beneath the seabed and to regulate the injection of CO_2 into sub-seabed geological formations for permanent isolation. However, Article 6 of the London Protocol prohibits the export of waste or other matter for marine dumping purposes, presenting a barrier to transboundary CCUS projects. In 2009, it was amended, effectively allowing CO_2 to be exported for CCUS purposes between Contracting Parties under certain conditions. However, the amendment to Article 6 is not yet in force, as it must be formally accepted by two-thirds of the 54 Contracting Parties. Currently, only 12 countries have ratified it, among which eight have issued a declaration of provisional application. As an interim solution, the Protocol Parties adopted in 2019 a resolution to allow provisional application of the 2009 amendment, enabling countries to export and receive CO_2 for offshore geological storage, pending its entry into force.

Several countries have signalled their interest in developing transboundary CCUS projects, with several recently signing MOUs or LOIs to collaborate on future projects. MOUs, LOIs, bilateral agreements or arrangements under the Protocol must contain confirmation that permitting responsibilities have been allocated between the two countries and the IMO must be notified. As of June 2024, the IMO has only been notified of one arrangement, submitted by Belgium and Denmark in 2022.

To facilitate the licensing process, the Contracting Parties adopted in 2012 a “Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures” and the “Specific Guidelines on Assessment of CO_2 Streams for Disposal into a Sub-Seabed Geological Formations”. These documents provide advice on how to capture and sequester CO_2 in a manner that meets all the requirements of the London Protocol and is safe for the environment, both marine and atmospheric, for the short and long term. In addition, a guidance document setting out the responsibilities of Parties and the requirements of the agreements or arrangements which must be entered into by Parties who wish to undertake export of CO_2 – “Guidance on the Implementation of Article 6.2 on the Export of CO_2 Streams for Disposal in Sub-seabed Geological Formations for the purpose of Sequestration” – was developed in 2013. The Contracting Parties are now working to update the guidelines, supported by a correspondence group, co-led by Japan and Australia, drawing on recent experience in managing and operating CCUS projects.

Figure 5.29 Running costs of a container ship powered by fuel oil and ammonia and global average cost for near-zero emissions ammonia production in the Announced Pledges Scenario, 2023-2050



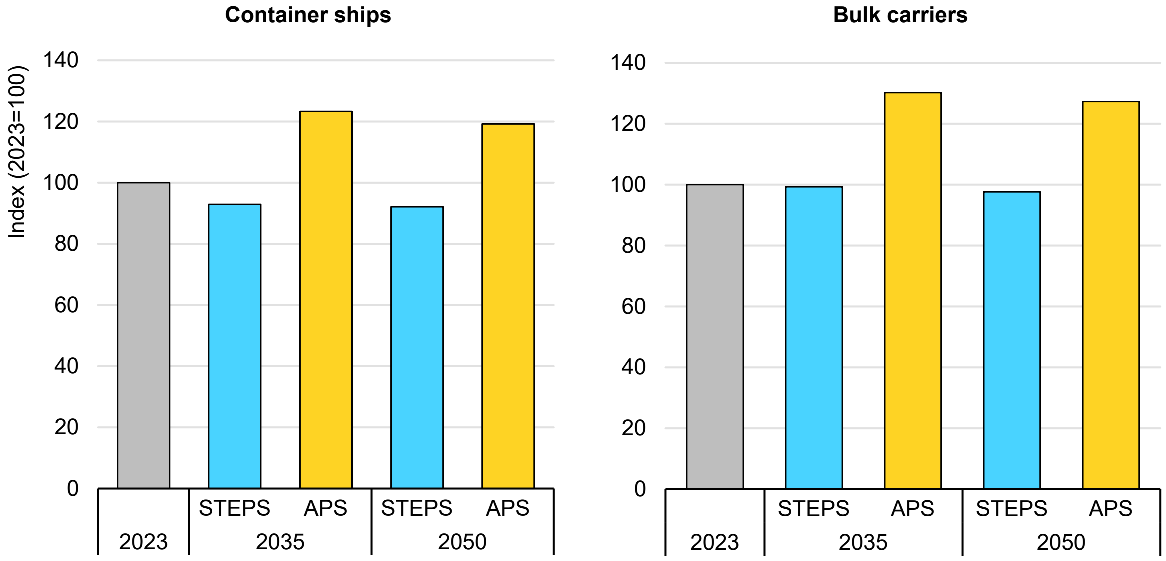
IEA. CC BY 4.0.

Notes: CAPEX = capital expenditures (vessel cost); Non-fuel OPEX = operating expenditures (includes crew, maintenance, vessel insurance and administration). Costs are calculated based on a 9 400 twenty-foot equivalent unit (TEU) container ship. Fuel costs are calculated with the average fuel efficiency of ships built in 2023. Running costs are in USD per container and have been calculated for a typical Asia to Europe voyage. Near-zero emissions ammonia cost in 2023 represents the lower bound of ammonia production costs from renewables (IEA, 2024b); in the APS these are calculated by weighting regional production costs by regional production, from both electrolysis and natural gas with CCUS. CO_2 prices are not included.

Operating a vessel with ammonia rather than oil would cost twice as much today, though ammonia production costs fall by almost 40% in 2050 in the APS.

When accounting for energy efficiency improvements and gradual increase of low-emission fuel shares, the running costs of container ships in the APS are set to increase by around a quarter on average between 2023 and 2035 (Figure 5.30). Alternatives to fuel oil and marine diesel are 2-5 times more expensive in 2035, with Fatty acid methyl ester (FAME) and HVO on the lower end, synthetic methanol and biomass-to-liquid (BTL) at the higher end, and ammonia in between. Those running cost differentials narrow through to 2050 as significant energy efficiency improvements and falling costs of alternative low-emissions fuels (thanks to technology learning and economies of scale) help to offset the impact of switching to them, as they remain more costly than conventional fuels (the prices of fossil marine fuels also fall over time in the APS, as demand declines). In the case of bulk carriers, average running costs increase by around 30% by 2035 in the APS. In the STEPS, shipping costs remain broadly stable through to 2050 as gradual efficiency improvements in the fleet offset the impact of a modest degree of switching to alternative fuels.

Figure 5.30 **Change of average international shipping running costs for container ships and bulk carriers in the Stated Policies and Announced Pledges Scenarios, 2023-2050**



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Costs include capital expenditures (vessel costs), non-fuel operating expenditures (crew, maintenance, vessel insurance and administration) and fuel costs, and are based on a 9 400 twenty-foot equivalent unit (TEU) container ship and a 75 000 deadweight tonne (DWT) bulk carrier. Fuel costs are calculated with the average fuel efficiency of such ships in the fleet in the respective year and taking into account the fuel mix as per Figure 5.28. Running costs have been calculated for a typical Asia to Europe voyage. CO_2 prices are not included.

Low-emission fuels are more expensive than conventional fuels, but overall running costs are capped at around 25% higher in the APS thanks to efficiency and technology learning.

Mapping low-emissions fuel supplies

Regional differences in production costs

The cost of making low-emissions fuels for maritime shipping is likely to vary significantly across countries and regions, depending mainly on the availability and cost of the renewable energy sources used to make them. Together with the cost of transporting the fuels, these differences will determine where it is most cost-effective to refuel ships and, therefore, the need for refuelling infrastructure.

The bulk of near-zero emissions ammonia for fuel applications is expected to be produced using nitrogen extracted from the air and renewable hydrogen obtained from water electrolysis using renewable energy[1]. The overall cost of producing ammonia is largely determined by the cost of hydrogen, which is in turn mainly a function of the cost of the renewable electricity and of the electrolyser CAPEX. It follows that countries with abundant renewable energy endowments will be best-placed to produce ammonia at least cost. At present, producing ammonia from electrolysis powered by renewables can cost between USD 1 000 and USD 2 000 per tonne (about USD 50/GJ and USD 110/GJ) depending on the availability of renewable resources, but costs are expected to fall sharply as production ramps up. The United States, the Middle East, China and Australia, which have the best solar and wind resources, are expected to be able to achieve the lowest production costs, falling below USD 40/GJ by 2030 in the APS for some regions (Figure 5.31).

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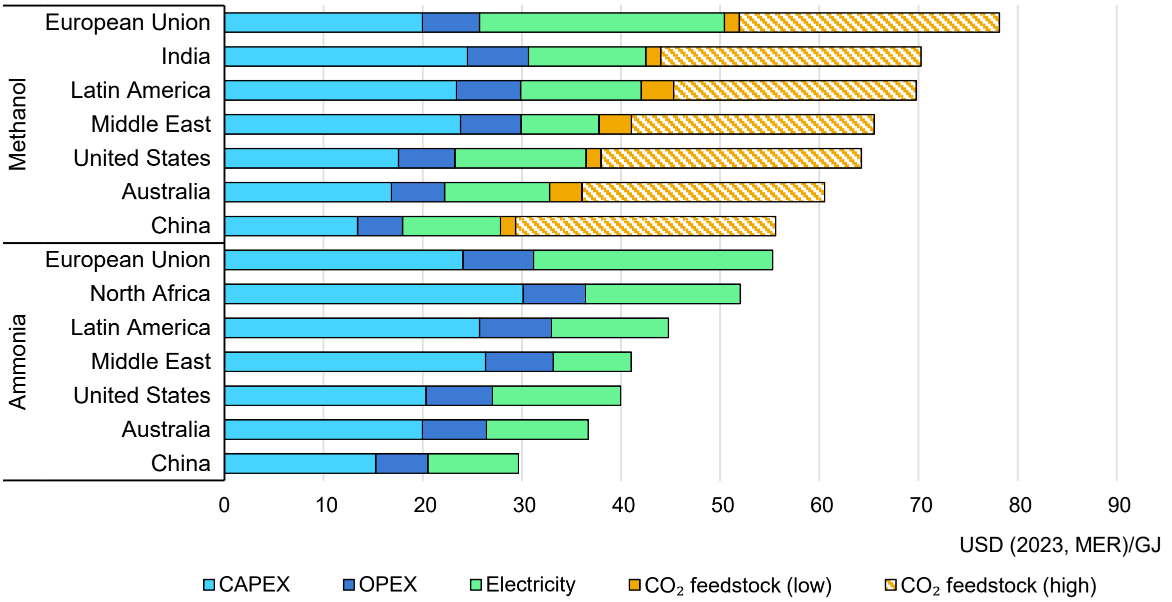
[1] Near-zero emissions ammonia can also be produced through other technology routes such as fossil fuels with CCS. However, in the APS most of the ammonia for fuel applications (75% by 2050) is produced through water electrolysis with renewable electricity.

Figure 5.31 Indicative levelised production cost of electrolytic methanol and ammonia by component in selected regions in the Announced Pledges Scenario, 2030



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Notes: CAPEX = capital expenditures; OPEX = operational expenditures. For each country/region, the levelised cost of ammonia and methanol production is the weighted average of the lowest cost of producing them from electrolysis with hybrid wind and solar resources, based on announced projects with a specified location and planning to be operational by 2030.

Source: Based on IEA (2024b).

Renewable electricity and CAPEX costs are the main factor affecting the cost of near-zero emissions fuels; for methanol, CO_2 feedstock prices shape the difference in costs.

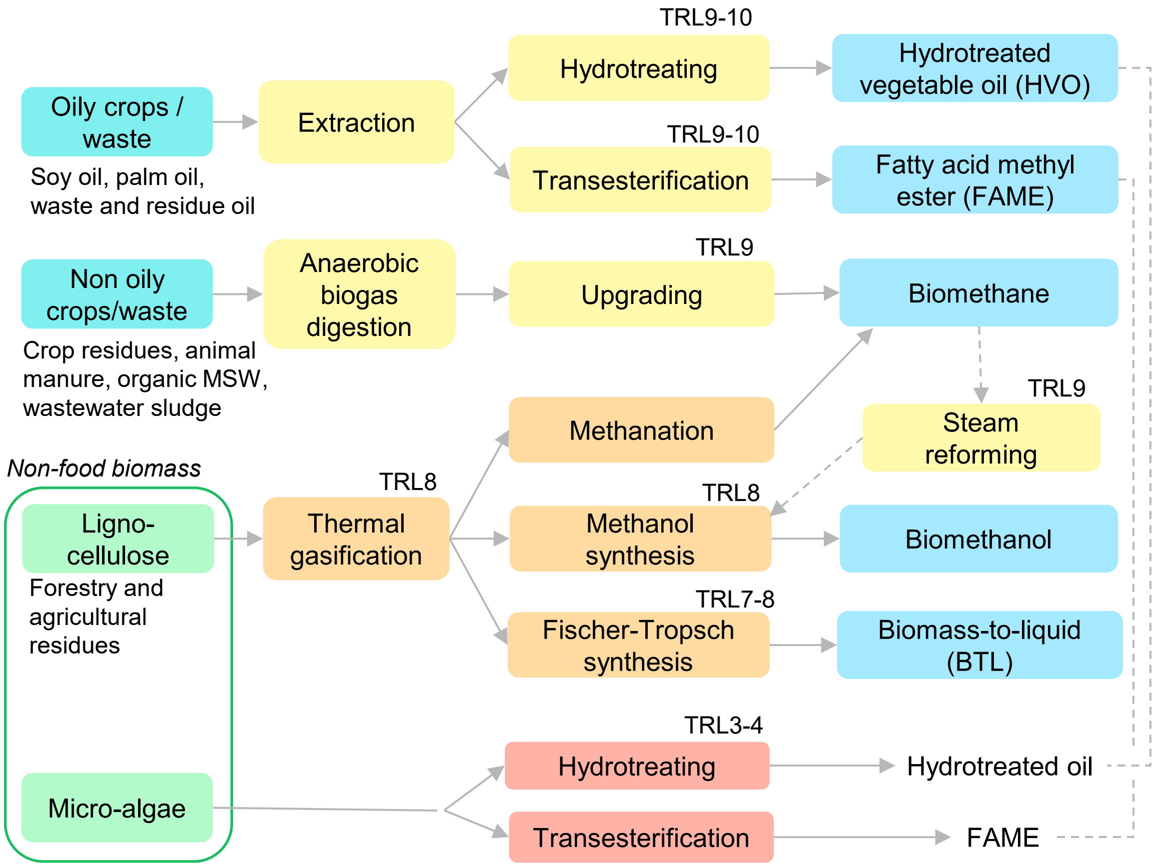
The cost of producing synthetic ammonia is, nonetheless, higher than that for conventional ammonia using natural gas as feedstock, due to low gas prices and higher energy intensity of the near-zero emissions process. Most of the differences in total production costs are explained by the cost of renewable electricity as well as the CAPEX for electrolysis and synthesis equipment.

Low-emissions methanol can be produced in two main ways: biomethanol from sustainable biomass feedstock, typically using gasification technology and synthetic methanol (sometime referred to as e-methanol) derived from the chemical reaction between CO_2 and electrolytic hydrogen. The carbon footprint of synthetic methanol depends on the source of the CO_2: it is zero or near-zero if the used CO_2 is captured using direct air capture (DAC) or from biogenic origin and captured at bioenergy conversion plants.

The cost of producing synthetic methanol depends largely on the cost of capturing the CO_2 and producing electrolytic hydrogen (the rest is made up of capital and operating expenditures). Supplies of biogenic CO_2 from bioethanol or pulp and paper cost between USD 30/tonne and USD 65/tonne, while CO_2 from DAC is expected to cost about USD 550/tonne of CO_2 in 2030. While ports with access to cheap biogenic CO_2 (due to the proximity of concentrated biogenic CO_2 sources) and low-cost renewable electricity, like those located in the United States or in Brazil, may be among the first movers, aggregating CO_2 from disparate sources may prove costly. The Middle East and Australia will remain among the lowest-cost producers of hydrogen and ammonia from renewable electricity or natural gas with carbon capture and storage (CCS), although in the near term they are less well-placed to produce cheap synthetic methanol because of the scarcity of biogenic CO_2.

Biofuels available for use in the maritime sector include biodiesel, biomethane and biomethanol. The first two are drop-in fuels for liquid and gas-powered engines and can be used by existing ships without any major modification, whereas biomethanol requires a different type of engine and storage facilities. They can be produced from different sources of biomass, which influence their sustainability and their cost. The different production pathways are also at different levels of technological maturity (Figure 5.32).

Figure 5.32 Maritime biofuel production pathways



Notes: MSW = municipal solid waste, TRL = technology readiness level; hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) and biomass-to-liquid (BTL) are also referred to as biodiesel here.
Source: Based on IEA (2024c).

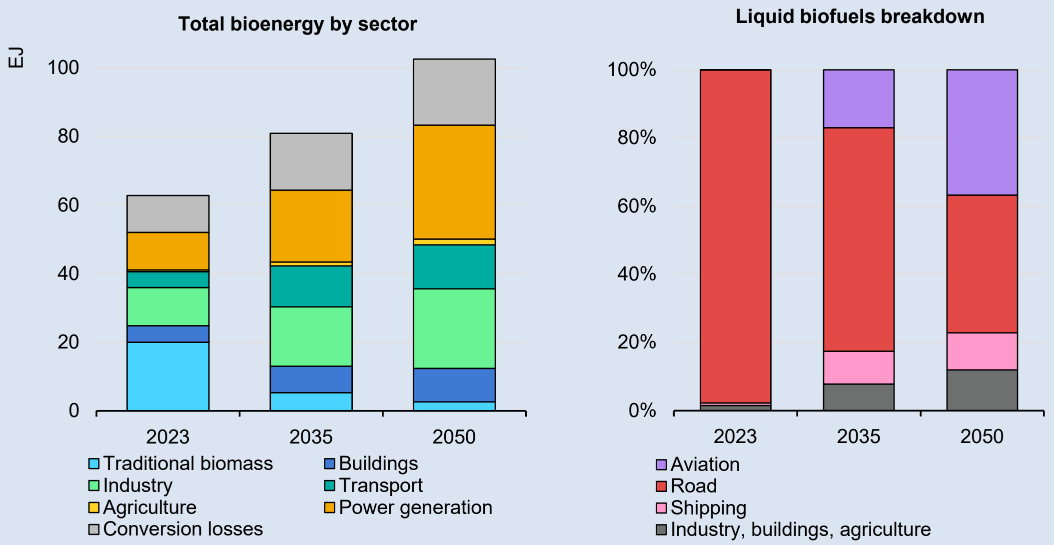
Maritime biofuels can be produced from different sources of biomass, with different production pathways at varying levels of technological maturity.

Box 5.4 The use of biofuels in different sectors

The shipping sector is in competition with other sectors of the economy requiring dense energy carriers – especially aviation – for liquid biofuels derived from sustainable biomass. Today, traditional use of biomass makes up around 30% of total bioenergy demand, while modern sustainable bioenergy is mainly used in the industry and power sectors (Figure 5.33). In the APS, the use of traditional biomass declines sharply from 2023 to 2050, while modern bioenergy demand more than doubles, mainly driven by the power sector (almost 40% of the growth) and industry (almost 20%). Within the transport sector, road vehicles initially remain the primary end users of liquid biofuels, but their share of total liquid biofuel use declines progressively through to 2050 as EVs become more prevalent. By 2050, aviation accounts for more than 35% of available sustainable liquid biofuel consumption worldwide, with maritime shipping taking a 10% share and road transport and industry most of the remaining half.

The transport sector as a whole (including conversion losses) absorbs about 30% of total primary bioenergy supply in 2050 in the APS.

Figure 5.33 Global demand for bioenergy and waste by sector in the Announced Pledges Scenario, 2023-2050



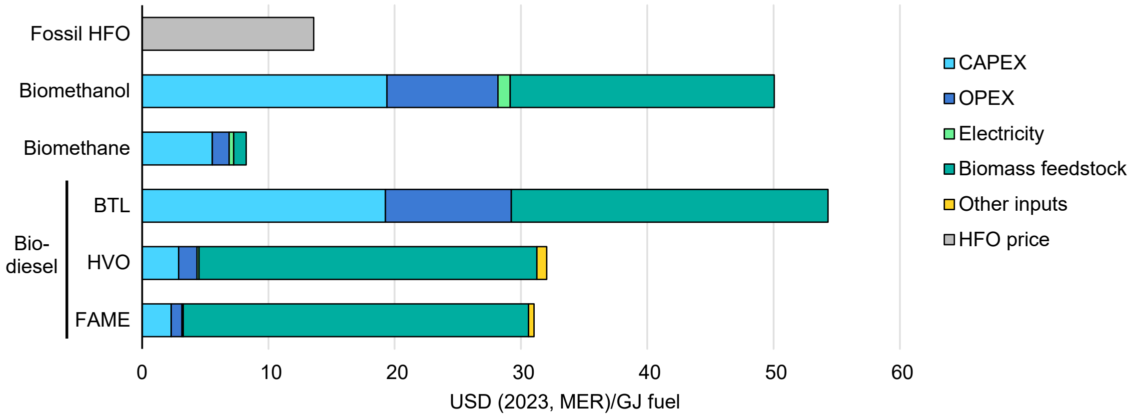
IEA. CC BY 4.0.

Notes: Traditional biomass (see definition in the Annex) denotes total traditional use of biomass for all sectors. The values by sector show the use of modern bioenergy only. The conversion losses are linked to liquid biofuels production, largely going into the transport sector.

Feedstocks processed today using commercial technologies include vegetable oils, sugars, starches and residue fats, oils and greases. However, supplies of non-waste feedstocks are in competition with their use as food, and can also have an impact on deforestation. This has led several countries and the European Union to cap their use. Non-food biomass sources such as forestry and agricultural residues, short rotation woody crops and municipal solid waste could be used for biofuel production, and could be available in larger quantities, but technologies to process them are less mature (with technology readiness level, or TRL, of 8 or lower).[2] and their cost is expected to be higher.

Expected production costs for the different types of biofuels that could be used in ships vary enormously. Among the technologies for producing biodiesel, HVO and FAME are the cheapest in 2035 in the APS (Figure 5.34), but their supply is expected to be constrained by the availability of sustainable biomass feedstock. Biodiesel produced using Fischer-Tropsch synthesis or BTL technology could be available in larger volumes, but at a much higher cost, due mainly to the higher cost of building and operating the processing plants. Biomethane and biomethanol are cheaper to produce than BTL, but they necessitate substantial modifications to the ships to accommodate their use.

Figure 5.34 Production costs for selected biofuels in the Announced Pledges Scenario, 2035



Notes: HVO = hydrotreated vegetable oil; FAME = fatty acid methyl ester; BTL = biomass-to-liquid; HFO = heavy fuel oil; CAPEX = capital expenditures; OPEX = operating expenditures. CO_2 prices are not included.

HVO and FAME biodiesel are the cheapest forms of liquid biofuels for shipping, but their supply is expected to be constrained by the availability of sustainable biomass feedstock

Alternative fuel refuelling infrastructure needs

Switching to low-emissions fuels for shipping would have major repercussions for refuelling (bunkering) infrastructure needs worldwide. Bunkering today is highly concentrated, with just 17 ports covering more than 60% of the world's refuelling

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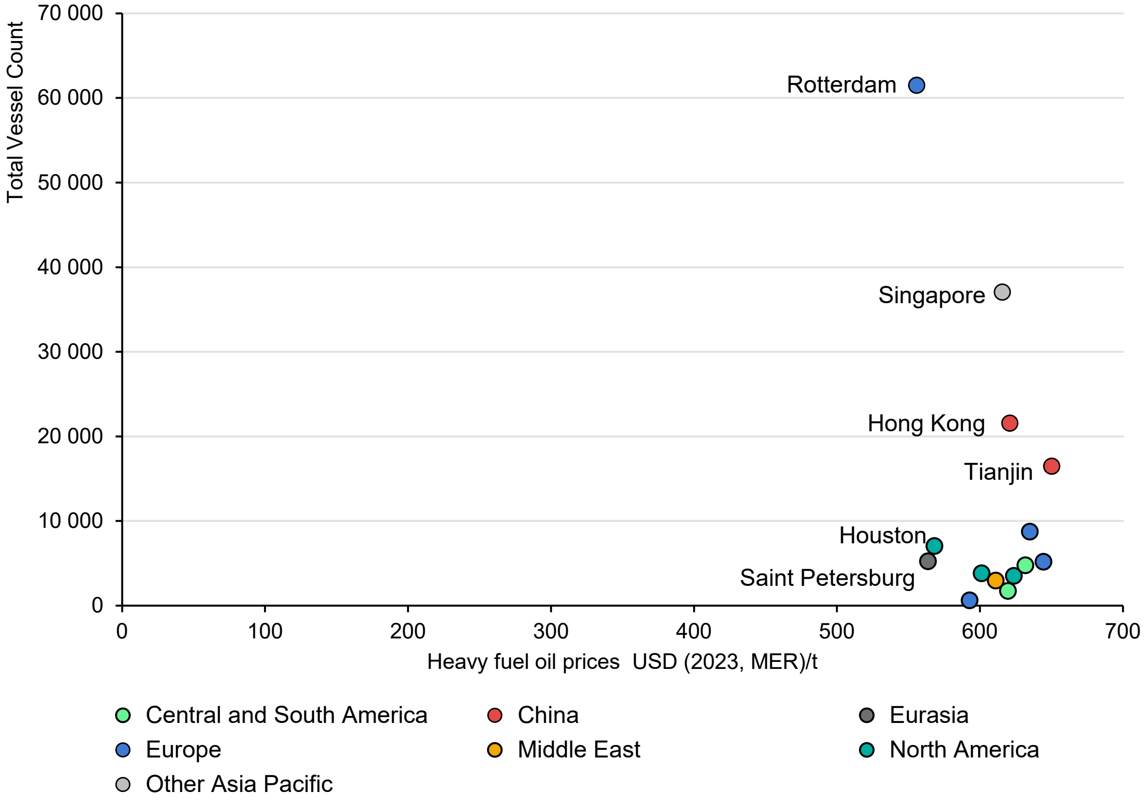
[2] See Annex for an explanation of the TRL scale.

needs and two major hubs alone – Singapore and Amsterdam-Rotterdam-Antwerp – for nearly half. This geographic concentration is because of huge economies of scale: the larger the port is, the much cheaper the refuelling provided is, as the infrastructure can be used more efficiently. For example, Rotterdam is one of the busiest ports in the world as measured by vessel throughput and has the lowest heavy fuel oil prices (Figure 5.35).

Figure 5.35 Vessel count and average heavy fuel oil price at selected ports, 2023



Note: Heavy fuel oil prices refer to the average of Q3 and first half of Q4 2023.
Sources: IEA based on Ship&Bunker (2024) for fuel prices and IMF Ports Watch for vessel count (2024).

Rotterdam – one of the busiest ports in the world – has the lowest heavy fuel oil prices, thanks to economies of scale in refuelling.

Both Rotterdam and Singapore, which also has relatively low fuel prices, are located close to major refining centres, which minimises the cost of supply of marine fuels to the port, though this makes only a small difference as the cost of transporting them over long distances is relatively low. These ports are currently at the forefront of alternative fuel infrastructure development: the port of Rotterdam was the first to refuel a vessel with methanol in 2021 (Port of Rotterdam, 2024), while the first ammonia refuelling trial was conducted in Singapore in March 2024 (Reuters, 2024).

As the shipping sector switches away from fossil fuels, the highly concentrated model of the refuelling industry could change significantly. The cost of transporting ammonia and methanol is higher (in part due to their lower energy density and due to the need for special vessels needed to transport them due their physical characteristics), so their growing use in ships might encourage the creation of bunkering hubs located close to low-cost sources of those fuels. This is particularly the case for ammonia, since it needs to be liquified and cooled down to -33°C for transportation. At present, it costs over 10 times more to transport one MJ of methanol and over 20 times more to transport ammonia than heavy fuel oil (Table 5.6). In addition, the lower energy density of these fuels means that ships using them will be able to carry less energy and, therefore, will need to refuel more often, unless they reduce their payload capacity to make up for the additional fuel needed to maintain the same range as for conventional petroleum fuels.

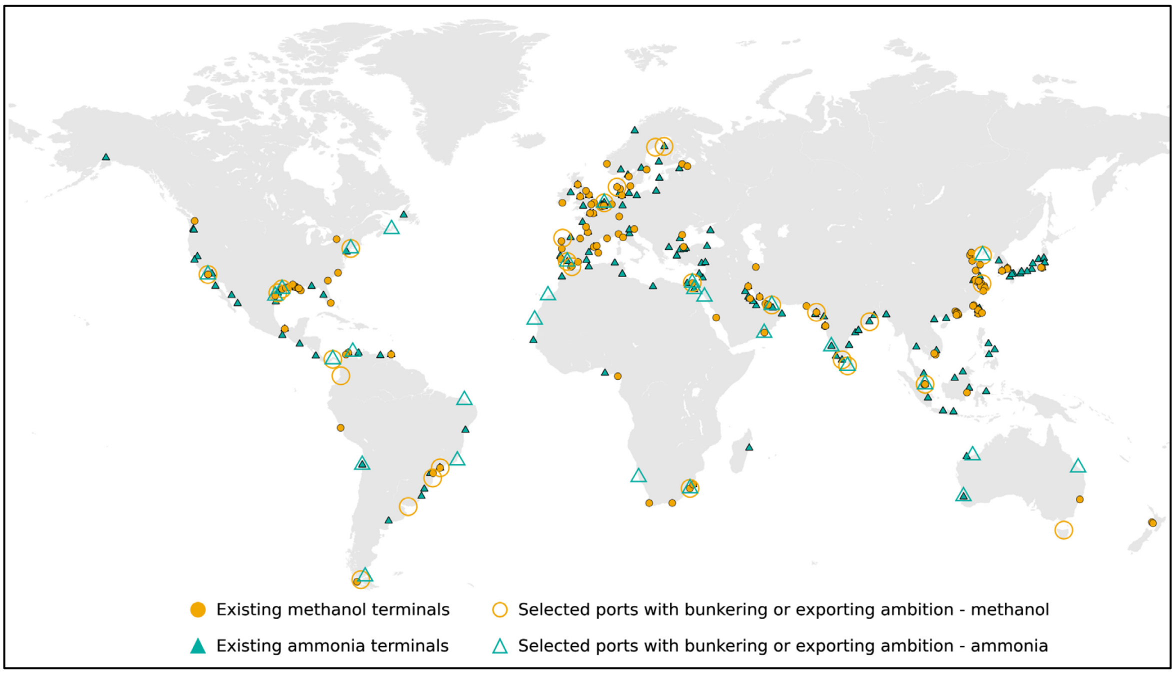
Table 5.6 Comparison of average transport costs (absolute and as share of price) and energy density for selected marine fuels, 2023

Fuel	Transport cost [USD/MJ/km]	Transport cost over price	Energy density [GJ/t]
HFO	0.02	1%	42
Biodiesel	0.14	4%	38
Methanol	0.25	6%	20
Ammonia	0.42	16%	19

Notes: HFO = heavy fuel oil. Transport cost over price is the cost of transport, assuming a distance of 10000 km, divided by the price of the fuel. The average price used in the calculation for methanol and ammonia refers to fossil fuel origin**.**

Near-zero emissions ammonia and methanol can, in principle, be produced almost anywhere in proximity to low-cost clean electricity, water and, for methanol, CO_2. Hundreds of ports already have export terminals for these fuels, creating a window of opportunity for ports located in areas with large renewable energy resources and the required infrastructure to become major suppliers. However, having an export terminal for these fuels is not sufficient to become a low-emissions bunkering centre: first, low-emissions fuels must be available and separately stored from conventional products; second, dedicated refuelling infrastructure needs to be developed. There are several ports around the world that have made plans to become suppliers of these fuels (Figure 5.36). For example, the port of Huelva in southern Spain is collaborating with Maersk, a liner operator, to produce e-methanol, while a project in Egypt to produce near-zero emissions ammonia close to the Suez Canal to exploit abundant local solar resources is planned.

Figure 5.36 Major existing methanol and ammonia terminals and ports with bunkering or exporting ambition



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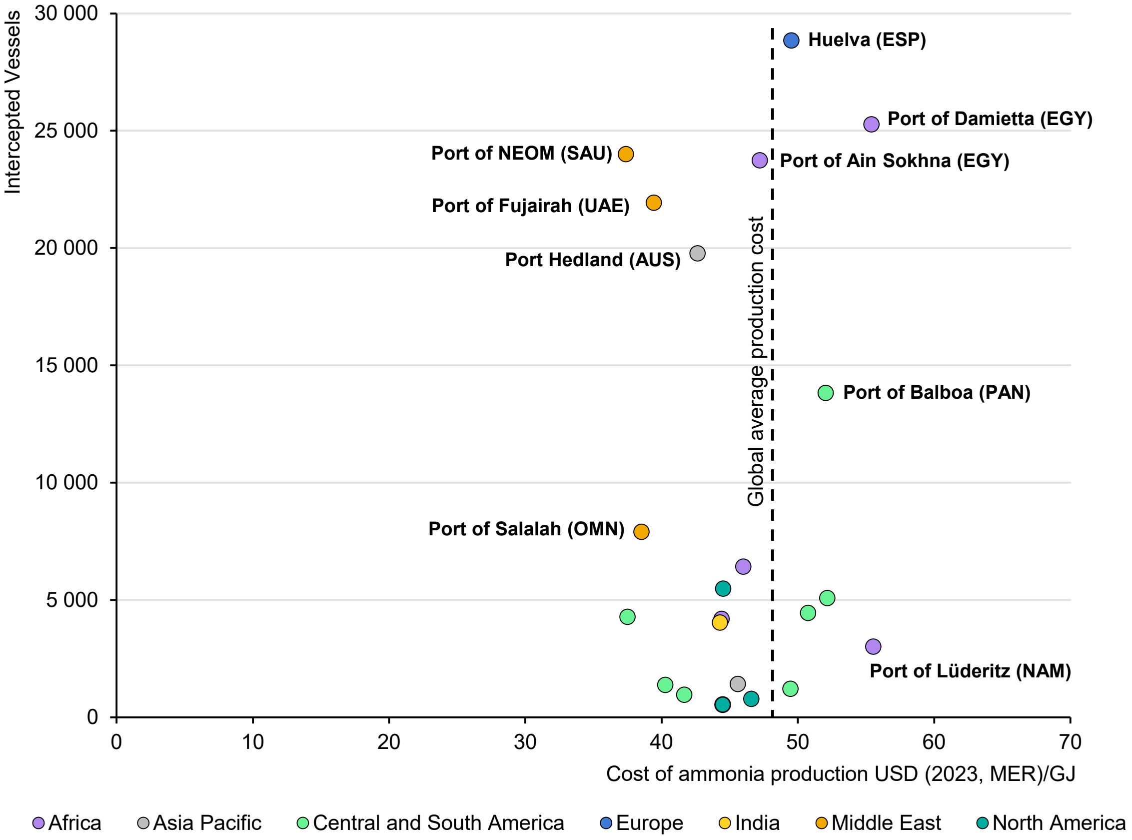
Notes: selected ports with refuelling ambition are based on announced projects and renewable potential. Note that some ports may have been selected both for methanol and ammonia. This document, as well as any data and map included herein, are without prejudice to the status of sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Many ports have existing ammonia and methanol terminals but ports aiming to build refuelling facilities are mostly located in other areas with good renewable resources.

The attractiveness of developing alternative fuel refuelling facilities at major ports depends to a large degree on their proximity to shipping routes, measured by the number and size of vessels passing within a 200 km radius of each port, and low-cost resources to produce those fuels competitively. A set of ports was selected for this analysis based on announced projects for the production of near-zero emissions ammonia and methanol as well as on the availability of renewable resources (see the Annex). Ports located close to commercial routes, including the Pilbara ports (Australia), port of Huelva (Spain), and the port of NEOM (Saudi Arabia) are well-placed to attract vessels for refuelling, firstly as only a minor deviation from their route would be involved (Figure 5.37). At the same time, these ports are well-placed to be able to produce ammonia at a competitive cost, putting them in a good position to become bunkering hubs in the future. Ports located in very densely populated areas are unlikely to be able to produce significant quantities of renewable energy in their proximity to satisfy demand.

Figure 5.37 Cost of producing electrolytic ammonia and maritime traffic at selected ports in the Announced Pledges Scenario, 2030



Notes: Intercepted vessels are estimated based on intercepted trade, that is maritime traffic that passes within 200 km of the selected ports, and assuming an average trade mass carried per vessel of 60 000 t. The cost of ammonia production is the lowest cost of producing electrolytic ammonia within 100 km of the selected port with hybrid wind and solar resources. Global average production cost is a weighted average based on announced projects planning to use solar PV, onshore wind, offshore wind or a hybrid configuration of these as electricity source for the electrolyser, with a specified location, planning to be operational by 2030.

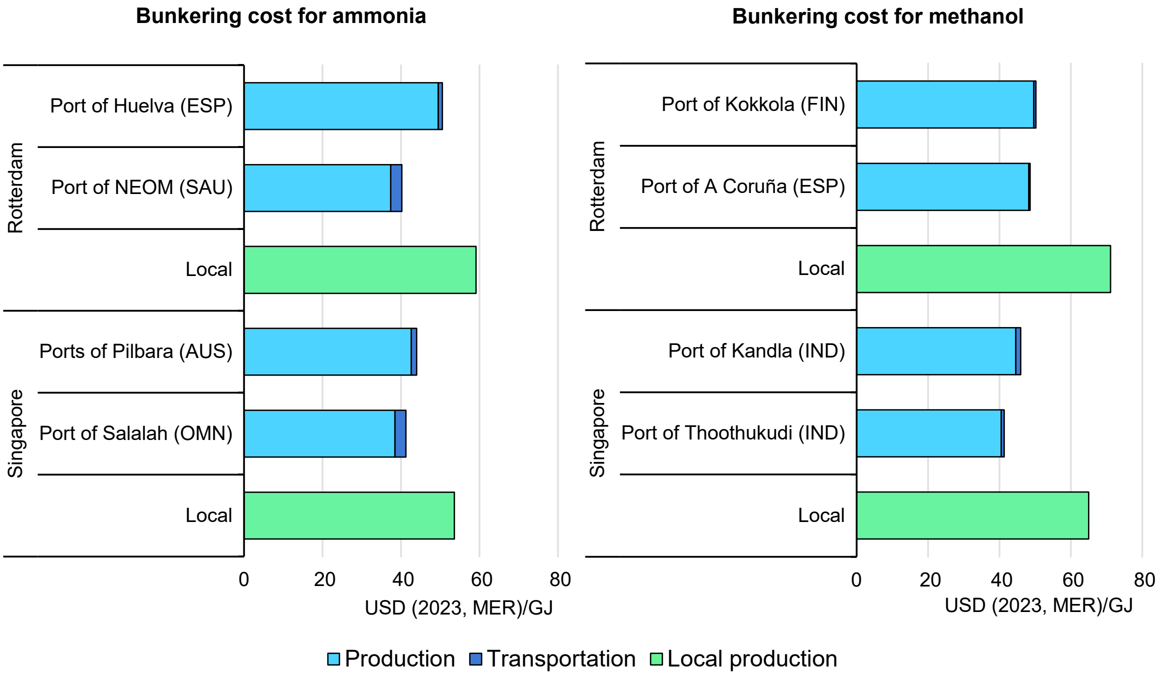
Sources: IEA analysis based on Verschuur (2022); IEA (2024b); and Forschungszentrum Jülich (2024).

Several ports, mostly located close to chokepoints, are well-placed to become new hubs for refuelling ships with ammonia at low cost.

Existing major refuelling ports could take advantage of the bunkering infrastructure already in place and their extensive experience in bunkering operations to become major low-emission refuelling hubs. They could produce near-zero emissions ammonia or methanol locally if renewable energy is available, or they could import the fuels. The latter would be a less costly option for methanol, as the cost of transporting the fuel per unit of energy and relative to the total cost of the fuel is smaller than for ammonia, though it depends on the distances involved. In the case of Singapore, locally produced methanol would cost much more than that imported from India (Figure 5.38). Similarly, for Rotterdam, the cost of locally produced methanol would not be competitive with imported supplies from southern or northern Europe.

The picture is a little different for ammonia. The cost of transport represents a bigger share of the total cost of supplying the bunker fuel, but, unlike methanol, the production cost does not depend on the cost of CO_2. In the case of Rotterdam, locally produced ammonia is not competitive with imports from Spain or the Middle East, while imported ammonia from the Middle East or Australia is among the cheapest options for Singapore. There are important economies of scale at port level for bunkering, and ships prefer to bunker where cargo loading/unloading takes place. As such, while some additional bunkering hubs close to low-cost fuel production may emerge, major bunkering hubs could continue importing fuel produced more cheaply elsewhere and rely on their existing experience and infrastructure, and high traffic volumes to remain competitive.

Figure 5.38 Production and transport costs at selected major ports for ammonia and methanol by local or imported source in the Announced Pledges Scenario, 2030



Notes: The cost of ammonia and methanol production is the lowest cost of producing them from electrolysis within 100 km of the selected port with wind and solar resources. The cost of biogenic CO_2 feedstock is assumed to be between USD 30/tonne and USD 65/tonne (at 2023 prices). For each major port hub, two representative low-cost potential suppliers among the list of selected ports with plans to become exporters of near-zero emissions fuels are compared.

Sources: IEA analysis based on IEA (2024b) and Forschungszentrum Jülich (2024).

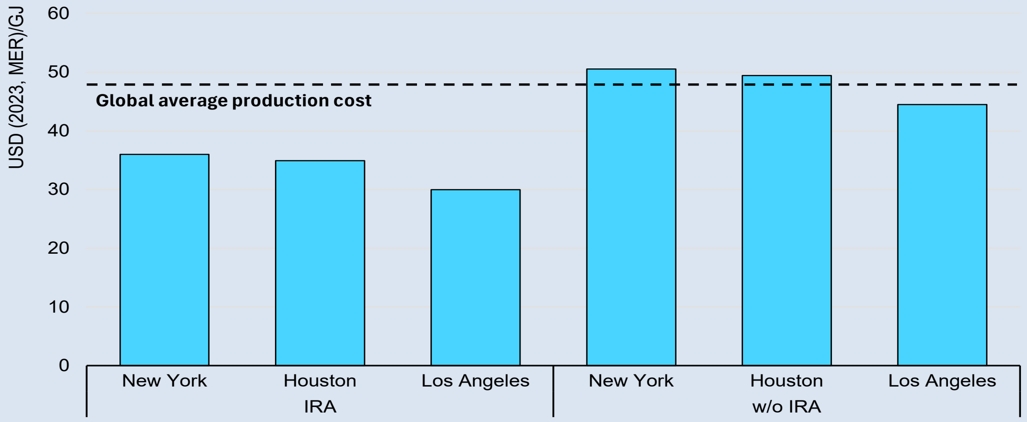
In most cases, locally produced methanol and ammonia would not be competitive with imported supplies, creating opportunities for other ports to become major exporters.

This could create new trade routes for ammonia and methanol, from ports with abundant resources to major shipping hubs. Subsidies and tariffs for renewable electricity, hydrogen and ammonia production could substantially affect the relative competitiveness of supplying ammonia to local ports. For example, financial support under the 2022 Inflation Reduction Act (IRA) in the United States could make locally produced ammonia highly competitive with imported fuel (Box 5.4).

Box 5.5 The impact of the Inflation Reduction Act on the cost of supplying ammonia for bunkering in the United States

The IRA provides various incentives to accelerate the deployment of clean energy technologies and could have a major impact on the production costs of methanol, methane and ammonia in the United States, with major repercussions for international trade in alternative maritime fuels. The most relevant for hydrogen is the Clean Hydrogen Production Tax Credit (45V), which grants a tax credit for a period of 10 years for projects that are placed in service before January 2033 and produce clean hydrogen. The amount of the tax credit varies from USD 0.12 to USD 0.6 per kilogramme of hydrogen produced depending on the emissions intensity of the hydrogen production. The value of these credits is multiplied by five if the facility meets certain labour conditions. Hydrogen produced from renewable electricity can, in addition, benefit from the 45Y tax credit for renewable electricity generation of USD 3/MWh, with a multiplier of five when meeting certain labour conditions and a 10% increase when meeting domestic content requirements. The combination of the 45V and 45Y tax credits introduced by the IRA can lower the production cost of hydrogen from renewable hydrogen by up to USD 1.5 /kg H_2 over 25 years. In the APS, the cost of supplying ammonia from renewable electricity to major US ports decreases on average by about 30% to less than USD 40/GJ as a result of the financial support provided by the Act (Figure 5.39). This would undercut the cost of producing and transporting ammonia to the United States from most other regions, including those with substantially lower renewable electricity costs.

Figure 5.39 Indicative levelised cost of supplying electrolytic ammonia for bunkering at major US ports with and without financial support from the Inflation Reduction Act in the Announced Pledges Scenario, 2030



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Notes: IRA = Inflation Reduction Act; w/o = without. The IRA includes a USD 1.5/kg H_2 tax credit for electrolytic hydrogen from solar and wind electricity, assuming that the 45V and 45Y tax credits are paid for 10 years over the 25-year lifetime of the project. The cost of ammonia production is the lowest cost of producing electrolytic ammonia within 100 km of the selected port with hybrid wind and solar resources. Global average production cost is a weighted average based on announced projects planning to use solar PV, onshore wind, offshore wind or a hybrid configuration of these as electricity source for the electrolyser, with a specified location, planning to be operational by 2030.

Sources: IEA analysis based on IEA (2024b) and Forschungszentrum Jülich (2024).

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Chapter 6: Strategic considerations

Highlights

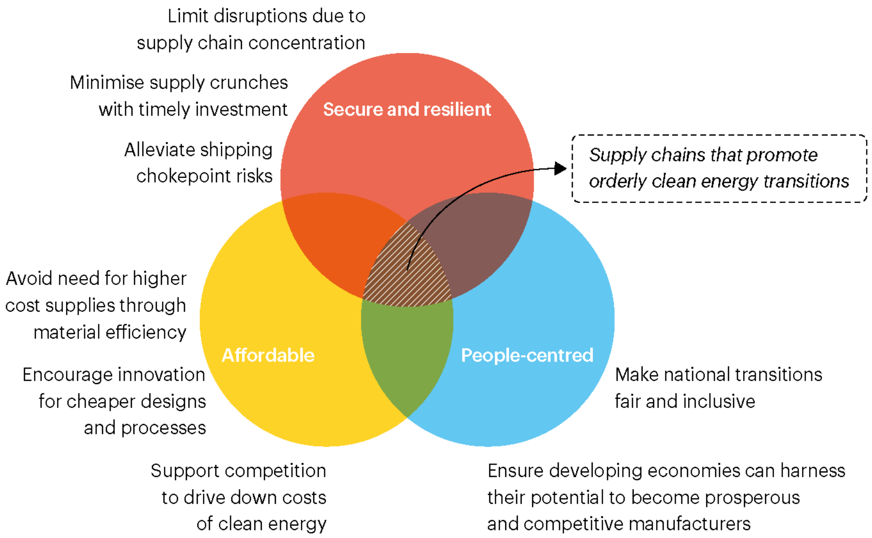
- Achieving orderly clean energy transitions that protect and enhance economic prosperity for all requires all governments to address three key policy dimensions for clean energy manufacturing supply chains in a balanced manner: security and resilience, affordability, and people-centred transitions. This calls for more integrated energy, climate, industrial and trade policies. International co-operation on emerging issues, such as standards, is essential.
- Risks to secure and resilient supply chains include supply concentration, physical trade bottlenecks and measures affecting trade. Risks to affordable clean energy and materials include a lack of support for innovation and competition, and low material efficiency across supply chains. Risks to equitable outcomes of energy transitions include slow investment in emerging and developing economies, and diminished economic opportunities in places that could lose existing manufacturing capacity.
- Policy makers face inevitable trade-offs between some of these risks and will need to take clear-eyed, data-driven approaches to balancing long-term goals. Progress on mitigating the risks can be monitored using a variety of metrics at the national and international levels, but better data will be required in several areas.
- Six strategic responses can help address the identified risks to supply chain resilience, jobs and prosperity:
    - Design industrial policy packages that are targeted, responsive and robust, and promote international competitiveness.
    - Enhance competitiveness by fostering innovation ecosystems.
    - Enhance competitiveness by encouraging co-location and integration.
    - Support a broad diversification of manufacturing, in particular to emerging and developing economies through partnerships.
    - Anticipate developments in shipping, including risks associated with chokepoints and the implications of rising low-emissions fuel demand.
    - Support the collection of better data on trade, capacities and emissions to aid decision-making by firms and governments.

This chapter presents a set of insights for effective policy making in relation to competitive clean energy manufacturing and trade based on the analysis set out in the previous chapters. That analysis reveals major economic opportunities for both advanced economies and emerging market and developing economies (EMDEs) to make and trade clean technologies and materials as markets for those products grow with the energy transition. Three key policy dimensions of clean energy supply chains are assessed; the risks associated with each dimension are reviewed and examples of how governments around the world have responded to them are provided. Metrics that can be used nationally or globally for monitoring policy progress in each area are presented. The chapter concludes with a review of the overarching strategic policy responses that governments need to consider, including with respect to industrial development, innovation, co-location and integration, support for greater participation of EMDEs, shipping and data requirements.

6.1 Policy dimensions

Meeting the overarching objective of orderly energy transitions that protect and enhance economic prosperity for all requires all governments to address in a balanced manner three key policy dimensions for the realisation of supply chains that are secure and resilient, affordable, and people-centred (Figure 6.1). With well-designed policies, these three dimensions can be mutually reinforcing and can promote the competitiveness of clean energy technologies and related materials produced by a given country or compared with conventional technologies and fuels at the global level. However, there are bound to be tensions between them, requiring governments to minimise trade-offs. Each country must find the balance that suits its national priorities while enhancing the ability of the world to move as quickly as possible towards a net zero emissions future. It is important not to lose sight of the tremendous security risks posed to all countries by continued reliance on fossil fuels and rising GHG emissions (Box 6.1).

Figure 6.1 Policy dimensions of clean energy manufacturing and trade



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In pursuing net zero emissions, well-designed policies need to balance the goals of supply chain security and resilience, affordability and people-centred transitions.

In each of the three dimensions, policy interventions must be driven by the aim of maximising opportunity while minimising risk. The supply chain risks for clean technologies are different from those for fossil fuels. The good news is that, in a net zero emissions energy system, they are expected to be lower overall than in today’s fossil fuel-based system. However, in the earlier stages of the transition, there are real risks of clean technology supply shocks or reduced competitiveness in some cases. Given the importance of energy-related industrial activities in many countries, governments are understandably concerned about how the future geography of clean energy manufacturing will affect employment, inward investment and the affordability of energy for households and businesses. Since the pace of the uptake of clean energy technologies depends in large part on government action to create bankable demand for clean technologies, policy makers are under pressure to ensure that the benefits of new clean energy markets and industries are shared widely among their citizens. Distributional and economic effects will shape public support for the clean energy transition and, therefore, the ability of governments to accelerate the implementation of energy and climate policies.

The aim of governments everywhere is to formulate industrial, energy and climate policies and strategies to steer manufacturing towards the goal of net zero emissions as rapidly and in as orderly a manner as possible. The energy sector has long been shaped by countries' industrial policies, including support for innovation and measures that affect trade. With the rising importance of manufacturing and industrial production in energy outcomes, the role of industrial policies is growing and, in some parts of the energy system, has tilted the playing field in favour of a small number of manufacturing regions. This does not change the long-term goal of an energy system underpinned by low-friction trade, comparative economic advantages and harmonised regulation or pricing of environmental harms. However, to achieve the near-term priorities of secure and resilient supply chains, especially as markets for clean technologies and materials mature, there is a case for well-designed and time-limited industrial policies to support clean energy transitions in ways that support resilience and trade simultaneously.

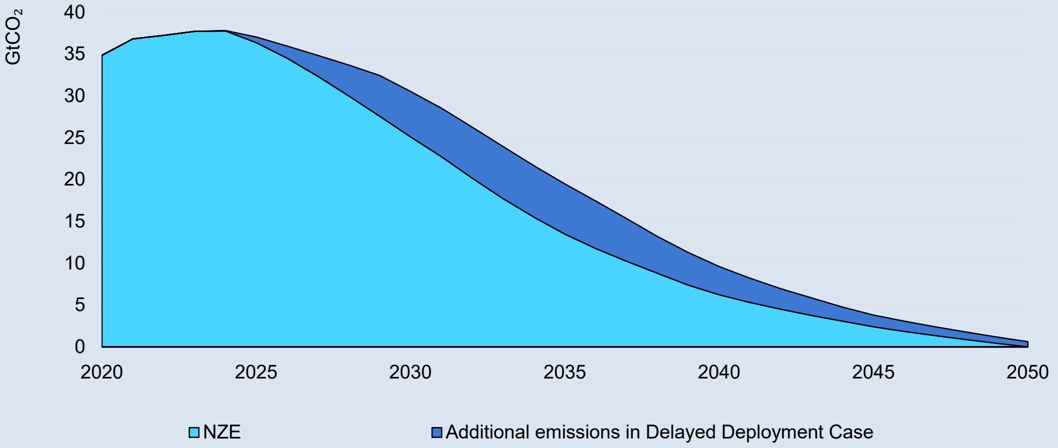
Box 6.1 Climate and security risks

Climate goals have a strong security dimension. Any short-term delay in building a cleaner energy system presents a risk to medium- and long-term climate security, due to the accumulation of GHGs in the atmosphere and the threat of tipping points beyond which changes in climate become irreversible.

Climate change is increasingly affecting ecosystem services, water and food security, health and well-being, culture, infrastructure and economic growth. A temperature rise of more than 1.5°C could severely affect many livelihoods, including through heatwaves, droughts, tropical cyclones and crop failures. A changing climate also poses threats to energy security by changing patterns of energy demand and threatening the reliable supply of electricity, fuels and other resources. Energy infrastructure is vulnerable to weather-related outages, diminished efficiency or water shortages, while climate change-related events will affect global shipping routes and can raise countries' defence expenses.

There has been a sharp increase in project announcements for clean technology manufacturing in the past 3 years, but delays to their realisation – particularly in the next few years – would jeopardise climate goals. If fewer solar PV modules, wind turbines, heat pumps, electric vehicles (EVs) and hydrogen electrolysers were produced, the products and services they provide would instead be met by more emission-intensive technologies. Were a delay in expanding the manufacturing of those five products to stymie their deployment over the next 5 years, cumulative global energy sector CO_2 emissions from now until 2050 would be more than 20% higher, assuming manufacturing and deployment gets on track with the Net Zero Emissions by 2050 Scenario (NZE Scenario) thereafter (Figure 6.2). Given that the rate of emissions reduction in that scenario is close to the limits of what is technically feasible, such a delay would surely put the 1.5°C target out of reach.

Figure 6.2 Global net energy sector CO_2 emissions in the Net Zero Emissions by 2050 Scenario and in a Delayed Deployment Case, 2020-2050



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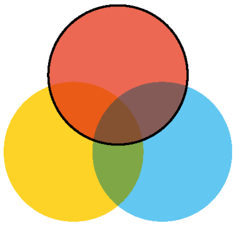
Note: NZE = Net Zero Emissions by 2050 Scenario. The Delayed Deployment Case is characterised by residual net emissions in 2050 due to an assumed 5-year delayed deployment of key clean energy technologies (solar PV, wind, EV batteries, electrolysers, heat pumps) across the global energy system during the second half of the 2020s.

6.2 Secure and resilient supply chains

Secure and resilient supply chains are characterised by adequate and uninterrupted supplies of raw and intermediate materials, components and equipment at each step of the production process and delivery of finished products to final consumers. They are able to respond and adapt quickly to sudden market shocks related to supply, demand or price, including through co-ordination with other supply chains that can deliver an equivalent technology or service. They involve a diversity of suppliers and technologies, which encourages competition, provides flexibility and maintains an efficient level of spare supply capacity. That ensures stable and predictable prices that are as low as possible, while transparent price formation facilitates efficient investment signals for, and hedging by, market participants.

In practice, there are very real risks to security and resilience, which can have a major impact on energy markets. The main risks include a lack of diversity of supply, shipping bottlenecks and pronounced mismatches in supply and demand due to uncoordinated investment.



Secure and resilient supply chains

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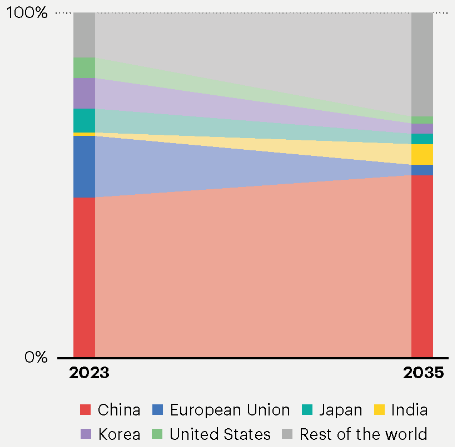
Key risks

- **Shocks due to lack of diversity of supply.** Heavy reliance on a small number of suppliers – countries, companies or assets – whose output could be curtailed by natural disasters, geopolitical events or localised economic upset.
- **Shocks due to shipping bottlenecks.** Heavy reliance on a small number of transport hubs or routes that could be temporarily or permanently obstructed.
- **Resilient infrastructure is not built out in a timely manner.** Uncoordinated investment across clean technology value chains could cause cyclical "boom and bust" price cycles, with value chain steps out of sync, reducing security of supply and delaying energy transitions.

Ten potential chokepoints for clean technology trade

Shares of exports of clean technologies, APS



Types of possible policy responses

- Support domestic manufacturing
- Co-ordinate stockpiling internationally
- Improve market data
- Support alternative trade routes
- Agree and uphold international maritime conventions
- Create demand
- Reduce project lead times
- Ensure availability of personnel

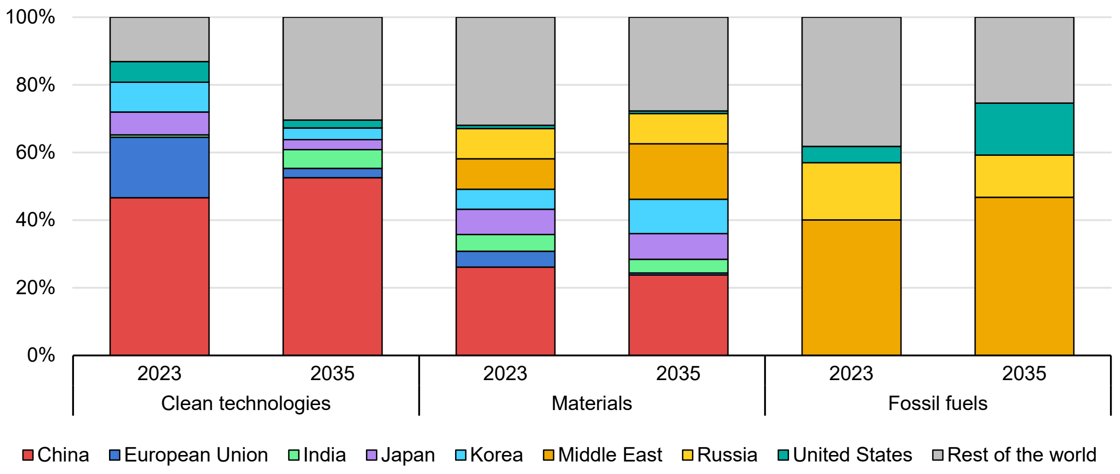
Risk of supply shocks due to a lack of diversity of supply

Supply chains that are dominated by a small number of countries, companies or assets are more vulnerable to supply disruptions resulting from natural disasters, accidents, geopolitical conflicts or deliberate actions to manipulate supply or price. Sudden changes to policy measures that affect trade can also disrupt markets if exporters or importers are overly reliant on a single trading partner. Physical disruptions in major exporting countries can have a large impact on international prices, yet the potential costs of trade disruptions are often inadequately considered in pricing. Market concentration can arise from the comparative advantage of certain regions, and the high level of concentration in clean energy technology manufacturing and trade today reflects a mix of relative production costs, policies that transfer costs from producers to taxpayers, and measures that affect trade.

Monitoring supply chain diversity

As clean energy transitions proceed, there are several ways in which governments and other stakeholders can track whether the risks associated with supply chain concentration are changing over time. One such indicator is the level of geographical concentration for a given technology or material. The share of exports needs to be tracked in the context of the proportion of total demand in these markets that is met by international trade. In the Announced Pledges Scenario (APS), trade in clean energy technologies remains relatively concentrated to 2035, trade in associated materials stays more diverse, and that of fossil fuel trade becomes more concentrated (Figure 6.3).

Figure 6.3 Shares of the value of exports of clean energy technologies, materials and fossil fuels by country/region in the Announced Pledges Scenario, 2023 and 2035



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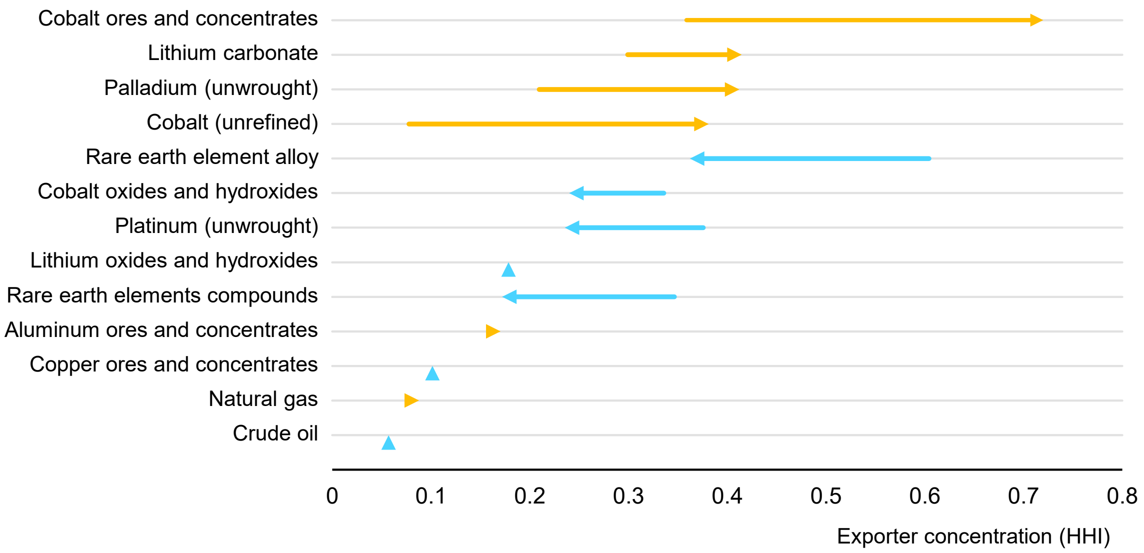
Notes: Regional shares are based on each exporter's net trade balance in each clean technology category or in each of coal, natural gas, crude oil and oil products. Clean technologies include solar PV, wind, electric vehicles (including batteries), heat pumps and electrolysers. Materials include aluminium, iron and steel, ammonia and fertilisers.

Clean technology exports are more concentrated in China than fossil fuel exports from the Middle East; while this persists to 2035, exports from other regions diversify in the APS.

Market analysts have developed tools for understanding market concentration, including metrics such as the Herfindahl-Hirschman Index (HHI). This index can be applied at the country level to commodity exports. Over the past two decades, there have been notable increases in the international concentration of exports of certain critical minerals for clean energy technologies, which are typically much more concentrated than for crude oil (Figure 6.4). Individual governments could apply the same metrics to their import sources.

Figure 6.4 Change in global market concentration of exports for selected commodities between the period 1999-2008 and the period 2009-2018



Notes: HHI = Herfindahl-Hirschman Index. Calculated based on country export shares of the global trade total. Arrows lead from one time period to another in the direction of the more recent value. Typically, a score of more than 0.25 implies high concentration, between 0.15 and 0.25 is moderate concentration, and lower than 0.15 is low concentration (Galeazzi & Anadón, 2023). The index is unable to shed light on the number of firms or facilities exporting the commodity, only the market share of individual countries.

Sources: IEA analysis based on Galeazzi & Anadón (2023).

The export markets for several key commodity inputs to clean energy technologies have become more concentrated in a smaller number of countries in recent years.

The biggest difficulty in tracking of import and export market concentration is a lack of data. At present, global customs reporting does not reliably track trade in clean energy technologies. Moreover, there are no international standards for collecting coherent data on near-zero emissions materials trade. Data on the diversity of individual companies, factories or substitutable production routes, which is not readily available for now, would also help shed valuable light on the security and resilience risks related to supply chains.

Examples of policy responses

Several policy tools are available to governments to address risks to the security and resilience of clean technology supplies, including diplomacy and measures to reduce the obstacles to trade and limit the potential for monopolies or cartels to reduce market diversity. International co-operation to minimise the costs of non-tariff measures (NTMs) and facilitate trade, such as free trade agreements (FTAs) and multilateral initiatives, can promote diversification and investment (this is discussed in detail in the next section). Other policy measures include support for domestic manufacturing, co-ordinating stockpiling and improving market data.

Direct support to domestic producers

Financial support in the form of grants, loans, financial guarantees, cheap land or tax incentives is a common way for governments to attract investment to raise supply chain diversity, often in combination with other policy goals such as maintaining jobs (see Chapter 1). Given the low share of capital costs in the total production costs of most clean technologies and materials, there are limits to how much of a cost gap with respect to imports can be bridged by support for capital costs. Governments can pay a portion of manufacturers' operational costs via performance-based-payments, contracts-for-difference, tax incentives and reduced utility prices. Targeting support to producers with the lowest emissions can help reconcile the goal of supporting local manufacturing with that of accelerating the energy transition, by ensuring that the environmental impact of domestic production is below that of imported products. Examples include the following:

- The Production Linked Incentive (PLI) in India provide incentives to both foreign and domestic manufacturers to expand production and exports and make Indian companies competitive. The government has introduced PLI schemes for various energy technologies, including solar PV, batteries and EVs.
- Tax credits for hydrogen under the 2022 US Inflation Reduction Act (IRA) are set at different levels of compensation depending on the emissions intensity of the hydrogen produced, with a threshold above which no credits are available.
- To reduce reliance on unreliable uranium supplies from Russia and Niger, both the United Kingdom and United States are investing over USD 1 billion between them in local production of an alternative called High-Assay Low-Enriched Uranium (HALEU) (US DOE, 2024a; UK DESNZ, 2024).
- In the 1960s, Korea offered various forms of support to its major manufacturers, but closely monitored their ability to efficiently meet economic targets and compete in in domestic and international markets. Underperformers were sanctioned with a loss of state support, thereby reducing incentives to profit from protectionism in the home market through rent-seeking (Seth, 2017).

It is not unusual for countries to require a percentage of materials or equipment to be from local suppliers when seeking to scale up a new industry. The effectiveness of this approach varies. In all cases, policy makers must take into account the administrative costs associated with implementing these requirements, which can be as burdensome for those assessing compliance as those needing to prove it. Examples include the following:

- In the United States, under the Investment Tax Credit for clean energy, projects that meet the domestic content requirement receive up to a 10-percentage point bonus.
- In Europe, the Net-Zero Industry Act (NZIA) encourages public tenderers to include non-price “resilience” criteria that assess the share of components coming from foreign suppliers that control over 50% of supply to the European Union (EC, 2024a). The application of these criteria is required for at least 30% of the renewable energy capacity auctioned each year to contribute to the development of European supply chains, unless this would increase costs by more than 15%.
- Brazil has linked local content requirements for clean energy to access to finance (Box 6.2).

Some countries use export restrictions and tariffs to support local production. This type of approach tends to be more common in countries that can control a large share of a geographically restricted primary input to the manufacturing process and do not have the budgetary means to offer domestic producers substantial financial support. However, if exports are diverted to domestic markets, prices in the domestic market fall, undermining investment. Examples include the following:

- Indonesia announced in 2020 that it would restrict the export of unprocessed nickel and did the same for bauxite in 2023 and copper ore in 2024.[1]
- Zimbabwe banned lithium exports in 2022.
- China imposed export controls in 2023 on graphite, gallium- and germanium-related items.
- In 2024, both the United States and the European Union have announced sharp increases in tariffs and special taxes on imports of EVs from China.
- The United States introduced import tariffs on solar PV cells and modules in 2018 to promote domestic manufacturing. They caused US prices to be higher than they would otherwise have been and – prior to the IRA – were not paired with sufficient incentives for investing in US-based production, hindering deployment (USITC, 2024).

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[1] The ban on copper ore exports has been waived until the end of 2024.

Box 6.2 Local content requirements in Brazil

In the early 2000s, Brazil linked the availability of concessional finance from its national development bank (BNDES) for wind energy to projects with 60% of the value of inputs coming from Brazilian producers. As with many similar initiatives, the result was that the threshold was met by relocating only the least technically sophisticated manufacturing to Brazil, a situation that the government sought to change in 2012 (Bazilian, Cuming, & Kenyon, 2020). Under the revised rules, wind developers wishing to take advantage of BNDES financing have had to comply with a schedule of progressive minimum content targets for each part of the turbine. By 2016, local manufacturing was able to meet around 80% of blade demand and a similar share of towers, bearings and castings.* Nacelle production in Brazil also rose, but only met 4% of national demand in 2019, in part due to a reduction in BNDES' budget. Importantly, local manufacturers have had to compete with international suppliers on an equal footing in all ways except for access to BNDES loans.

* Brazil's success in blade manufacturing relates in part to the presence of companies with existing expertise in aeronautics, as well as the country's large but dispersed domestic market due to its excellent wind resource.

Co-ordinate stockpiling internationally

Stockpiles can be effective when they are co-ordinated internationally to share costs and pool resources to have the largest possible impact on prices. As well as being able to make good any shortfall in supply at times of emergency, the existence of stockpiles can dampen price volatility because markets account for their potential use. However, while stockpiling has proved to be an effective part of a portfolio of measures addressing short-term fluctuations in supply and demand for fossil fuels and minerals, it ties up substantial working capital and is less likely to be helpful in addressing the heavy geographic and market concentration of clean energy technology manufacturing. Innovation is constantly changing the market for clean energy technologies, reducing their shelf life. The logistics of stockpiling items like wind turbine blades or electrolysers would be very complex. For that reason, stockpiling is more likely to be effective for critical minerals:

- China has recently stepped-up stockpiling of cobalt to take advantage of low prices.
- The IEA has co-ordinated a stockpiling mechanism as a bulwark against a lack of supply diversity in oil markets since the 1970s. The potential for co-ordinating stockpiles of some critical minerals is being considered by the IEA's new Voluntary Critical Minerals Security Programme.

Improve market data

Underinvestment in diversified supplies can result from a lack of transparency about supply, demand and prices**.** Tracking of imports and exports of clean energy technologies and materials is currently difficult because the classification systems do not yet include them. In particular, solar PV, heat pumps and hydrogen electrolysers are not identifiable in customs data. Examples of recent moves to improve market data include the following:

- The World Customs Organization updates the Harmonized Commodity Description and Coding System (HS) every 5 years and last did so in 2022. Manufacturing of solar PV and PV inverters will be included for the first time in the International Standard Industrial Classification of All Economic Activities (ISIC) in 2024.
- The United Nations Statistics Division is in the process of revising the Standard International Energy Product Classification, the international system for collecting harmonised energy data, to include, among other things, low-emissions fuels such as hydrogen.
- The IEA is undertaking a review of its classification system for energy research and development (R&D) spending by technology area – the first since 2012.
- Sector-specific international bodies, such as the OECD Steel Committee, co-operate on collecting data and providing a forum for closely monitoring market conditions that could potentially be replicated for near-zero emissions products.

Risk of supply shocks due to shipping bottlenecks

The supply chains of most clean energy technologies and their components and material inputs depend heavily on maritime shipping. As the volume of international trade continues to grow, the risk of severe congestion and physical supply disruptions at chokepoints along the main shipping routes, caused by geopolitical instabilities, weather-related events, piracy or accidents, will most likely increase (see Chapter 5).

Monitoring chokepoints

Flows of clean energy technologies and associated materials through the main potential shipping chokepoints are set to continue to rise in all the scenarios presented in this report. The volumes of other key commodities and products for healthcare, nutrition and agriculture are also likely to continue to grow. It is incumbent on all governments to monitor current and future volumes of trade in energy-related goods to assess whether the amounts of each of these products passing through different chokepoints is creating undesirable risks.

Examples of policy responses

Policy options to address risks to the security and resilience of clean energy supply chains posed by maritime shipping bottlenecks include support for investment in alternative routes and diplomatic efforts to reinforce international agreements. They are likely to be most effective when pursued in combination with one another.

Support alternative trade routes

In the event of disruptions, it is not always possible or economically viable to redirect goods to less vulnerable maritime routes. Likewise, redirecting trade to airborne transport is rarely viable and would significantly increase the emissions intensity of trade in clean energy technologies. But land-based alternative transportation routes offer some potential to reduce risks related to blockages at chokepoints. Examples of policy initiatives to diversify transport routes include the following:

- The Belt and Road Initiative (BRI) was launched by China in 2013 as the centrepiece of its foreign and economic policy. Among its projects are overland routes for road and rail transportation through landlocked Central Asia and connections to ports in Pakistan and Myanmar, aimed at reducing China's reliance on the Strait of Malacca (Wilson Center, 2024).
- Mexico is investing in the 309 km Trans-Isthmus Railroad as an alternative route to the Panama Canal. It forms part of a 1 000 km network that the government hopes to renovate and commission from 2024 onwards (Railway Gazette, 2024).
- Thailand is promoting the Thai (or Kra) Canal project, which would connect the Gulf of Thailand with the Andaman Sea, to provide an alternative route to the Strait of Malacca. Cost, environmental and geopolitical concerns have so far prevented a final decision (Mattoo, 2023).
- India, with backing from the United States, is proposing an India-Middle East-Europe ship and rail corridor as an alternative to the maritime route through the Red Sea and Suez Canal (The White House, 2023a).
- Between 2021 and 2023, Israel and some of its neighbours explored options to bypass the Red Sea and Suez Canal, including a USD 27 billion rail link and a possible road route, both between Dubai and the Mediterranean Sea (Reuters, 2023; The Times of Israel, 2023).

Agree and uphold international maritime conventions

Establishing and maintaining legal and political norms around the security of maritime chokepoints is essential**.** Keeping maritime routes open ultimately rests on the observance of international law and on the willingness and capacity of the international community to enforce it if necessary. Notable maritime conventions regulating the right of passage through key chokepoints include (Emmerson & Stevens, 2012):

- The Copenhagen Convention of 1857 to abolish tolls on shipping through the Danish Straits.
- The Convention of Constantinople of 1888 to guarantee passage of ships through the Suez Canal during war and peace.
- The Convention regarding the Regime of the Straits (or Montreux Convention) of 1936 to guarantees "complete freedom" of passage for civilian vessels through the Bosporus and Dardanelles in peacetime and regulates the operations of military vessels.
- The treaties between the United States and Panama of 1977 to open the Panama Canal to shipping of all countries. Since 2000, its stipulations remain in place under Panamanian control.
- The UN Convention on the Law of the Sea of 1982 to establish a regime of “transit passage” for straits used for international navigation. However, not all the countries adjacent to such straits have ratified it.

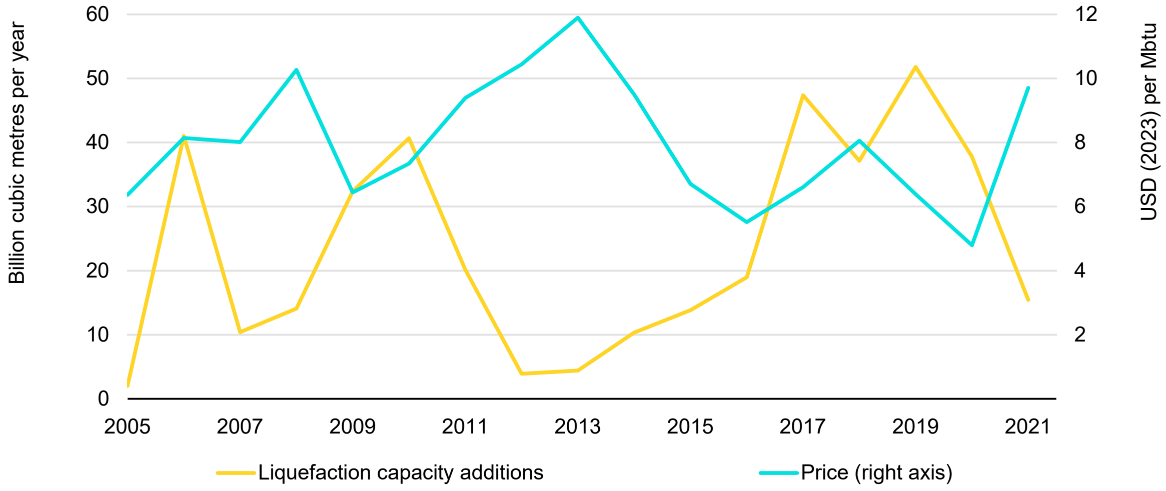
Risks to the timely build-out of resilient infrastructure

In any energy system, underinvestment in one or several parts of the global supply chain of key technologies, fuels or materials can lead to a shortfall in supply, making supply chains less resilient and driving up prices. Underinvestment in projects and people can lead to higher and more volatile prices, and lengthen project lead times. That has been the cause of the pronounced volatility of oil and liquefied natural gas (LNG) prices in the past. Cyclical investment behaviour driving “boom and bust” price responses is exemplified by the inverse relationship between capacity additions for gas liquefaction plants and LNG prices (Figure 6.5).

The timeliness of clean energy technology supply chain investment is especially important as many sectors are at an early stage of development. For example, the supply of low-emissions fuels for shipping is an area where investment may struggle to keep pace with demand, with underinvestment in supply potentially leading to higher costs as ships that run on ammonia or methanol are already being ordered and built. Concerns about a lack of investment in supplies of critical minerals such as copper have surfaced in recent years.

Underinvestment in people and in an adequate workforce could lead to gaps in some sectors. The expansion of manufacturing of clean energy technologies is driving up demand for workers, with facilities in some regions already struggling to attract and maintain adequate numbers of staff. Regions with large existing manufacturing workforces have greater potential to retrain workers from other manufacturing sectors to more rapidly ramp up clean energy manufacturing to meet future demand (see below).

Figure 6.5 Global liquefied natural gas liquefaction capacity additions and EU liquefied natural gas import prices

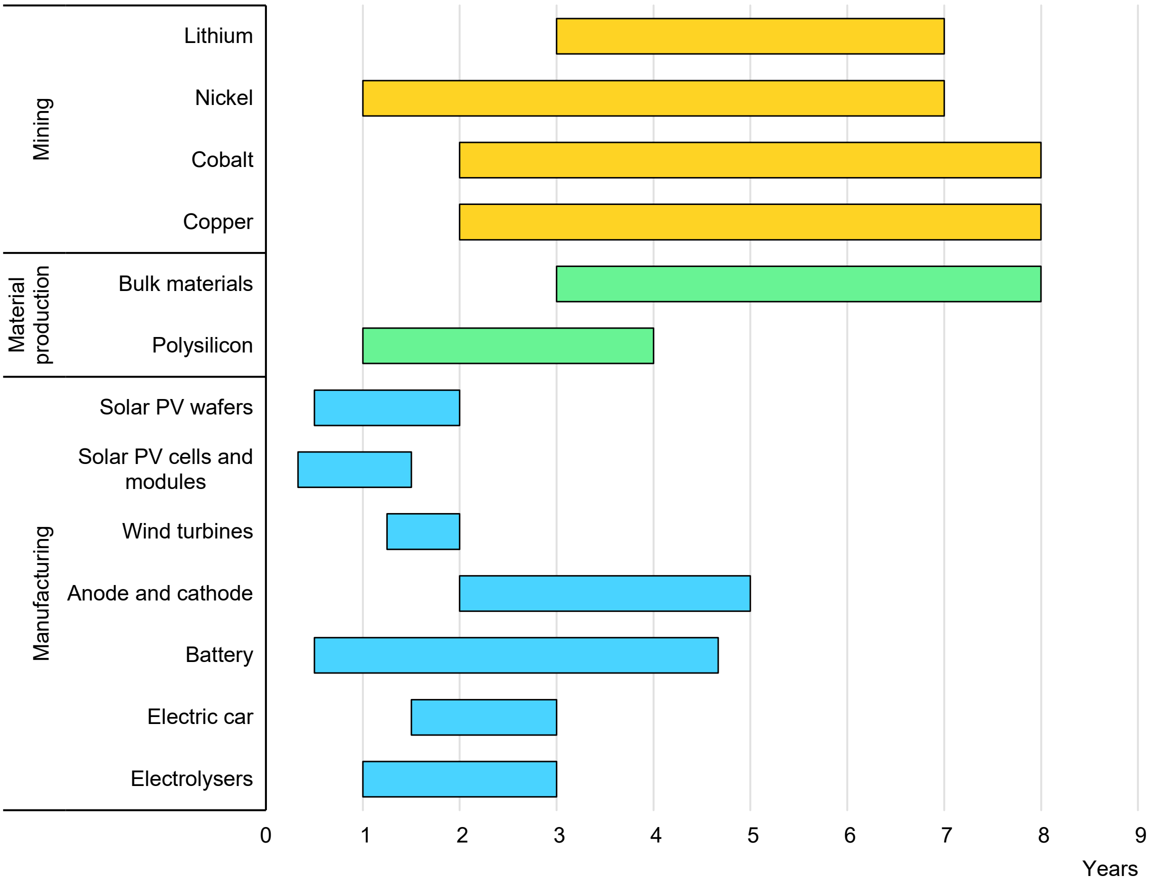


IEA. CC BY 4.0.

The inverse relationship between capacity additions for gas liquefaction plants and LNG prices illustrates the "boom and bust" price impact of cyclical investment.

The impact of underinvestment in projects and people on the security and resilience of supply chains depends to some degree on the time it takes for projects to start operating. Lead times vary widely across clean energy supply chains (Figure 6.6). It can take up to 3 years to build a new EV production line by converting an internal combustion engine (ICE) factory or installing a new one. A new battery gigafactory typically takes up to 5 years. Each battery factory requires inputs from multiple factories for cathodes, anodes and precursors, each of which takes several years to develop. Developing mining projects for the critical minerals – including copper, lithium, cobalt and nickel – needed to make batteries takes even longer: exploration can take up to 10 years and planning and building a mine can take at least another 4 years. While markets are usually capable of adjusting investment in response to price signals as they pass along the value chain, there are significant risks of price spikes and temporary shortages as demand ramps up quickly, translating into higher EV prices. For this reason, many car companies are trying to co-ordinate their future supplies of the most basic inputs – something that is usually unnecessary with mature ICE value chains. At a global level, governments can ensure that demand signals are strong and dependable. If these signals are more-or-less synchronised across countries, early-stage investment risk is further reduced.

Figure 6.6 Project lead times for selected global clean energy technology value chains



IEA. CC BY 4.0.

Notes: PV = photovoltaic. Bulk materials include iron and steel, cement, aluminium, chemicals. For mining, the figure shows feasibility studies and mine opening, but exclude initial exploration and assessment (which can take more than a decade).
Source: IEA (2023a).

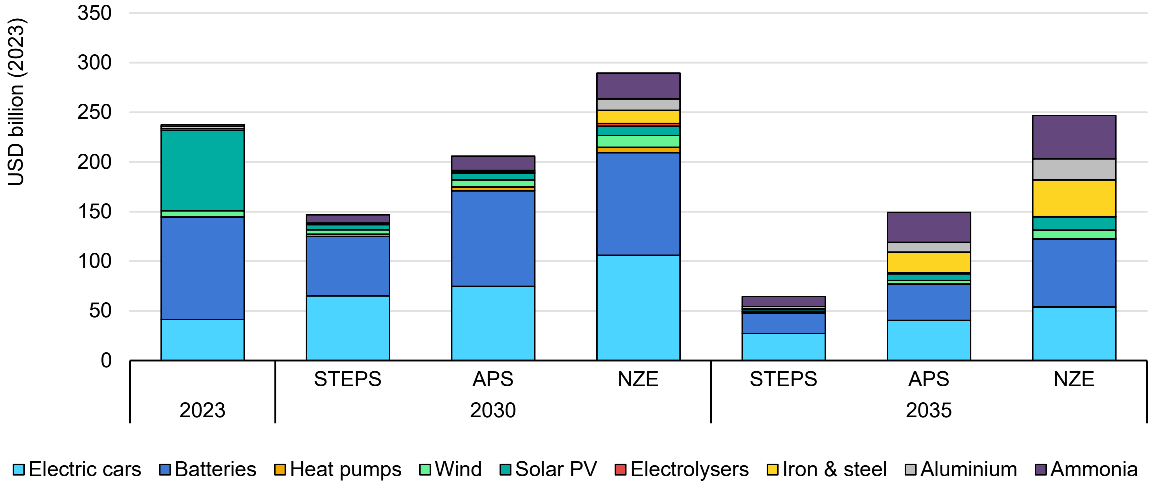
Lead times across clean energy supply chains vary widely, with mining projects generally taking the longest to bring onstream, accentuating the impact of underinvestment.

Monitoring the adequacy of investment

Industry stakeholders and policy makers will need to continue to monitor closely trends in investment along supply chains of all types of clean energy technology, as well as those of traditional forms of energy, to identify possible shortfalls in investment. The IEA has been systematically collecting data on and analysing global trends in investment on deployment for many years: with co-operation between governments and investors, this work could be expanded to include more detail on manufacturing as well as clean technology deployment. In the APS and NZE Scenario, global investment in clean technology manufacturing and near-zero emissions materials production remains elevated but, given the high level of investment in battery and solar PV manufacturing in 2023, only in the NZE

Scenario is it higher than today through 2035 (Figure 6.7). There is notable growth in investment in production capacity for near-zero emissions materials to 2035 in the APS and NZE Scenario. It is important that governments can track and update their expectations for investment in capacity to be aware of the risks of shortfalls in supply.

Figure 6.7 Average annual investment in selected clean technologies and near-zero emissions materials production by scenario, 2023-2035



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario. The values for 2030 are the averages of 2024-2030 and for 2035, of 2031-2035.

High levels of investment in clean energy technology value chains up to 2030 bring about lower investment needs by 2035, by when investment shifts towards material value chains.

Other important metrics for which data are often lacking concern project lead times and skills availability. Both factors influence the ability of manufacturers to respond promptly to increased demand through new investment. The impact of reducing lead times is hard to measure without a robust baseline and regular data collection. Data collection on skills and capacities relevant to the construction and operation of new clean energy technology and material manufacturing plants is very scarce today but could be collected as part of existing surveys. In order to improve market transparency, the IEA has since 2022 released the annual *World Energy Employment Report*, which tracks the size and distribution of the labour force across regions and energy technologies.

Examples of policy responses

Policy efforts to address the risk of underinvestment in clean energy technologies and associated materials need to focus on aggregating demand to send clear signals to investors, reducing project lead times and ensuring the availability of well-trained personnel.

Create demand

Private investment in new manufacturing facilities will not happen unless demand is expected to be high enough to absorb the output. Government-led demand creation is most critical for near-zero emissions materials such as steel, aluminium and ammonia, and low-emissions shipping fuels. This can take many forms, including performance-based payments, public procurement or helping to aggregate first-movers in the private sector. Examples include the following:

- The First Mover's Coalition, launched by the US government in 2021, co-ordinates private companies' pledges to obtain a proportion of their industrial materials from suppliers using near-zero emission production technologies (US Department of State, 2021).
- The US Federal Buy Clean Initiative aims to purchase lower-carbon steel, concrete, asphalt and flat glass for public and federally funded construction and infrastructure projects (US CSO, 2023).
- The Industrial Deep Decarbonisation Initiative (IDDI) member countries and Austria agreed in 2023 to adopt time-bound commitments to procure near-zero emissions steel, cement and concrete for public construction projects.[2]
- The European Hydrogen Bank runs auctions for hydrogen supply across Europe, awarding EUR 720 million to seven hydrogen projects in 2024 as a way of creating demand for hydrogen from renewable electricity at the lowest price (EC, 2022).
- Japan is co-operating with Brazil and the United Arab Emirates on building low-carbon iron supply chains by supplying high-grade iron ore from Brazil to the United Arab Emirates for processing into reduced iron (Nikkei Asia, 2024).

Reduce project lead times

Reducing lead times can play a major part in reducing the impact of poorly co-ordinated investment in clean energy supply chains. Policy options include clarifying regulations, streamlining permitting procedures and improving communication with private sector stakeholders. Examples include the following:

- The US IRA provides funding to various government agencies to hire new personnel and develop tools and guidance to strengthen and accelerate environmental reviews. The proposed US Critical Raw Materials Act would allow certain projects to be designated as "strategic", allowing them to benefit from a streamlined permitting process.

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[2] The members are the United Kingdom, India, Canada, Germany, Japan, the United Arab Emirates, Saudi Arabia, Sweden, the United States and Brazil.

- Under the NZIA, eligible European projects that manufacture clean energy technologies could be labelled “strategic projects" and benefit from faster permitting. The Act limits permitting windows for the manufacturing of clean energy technologies to 12 months for small projects of less than 1 GW and to 18 months for larger ones (EC, 2024a).

Ensure availability of personnel

The accelerated rollout of clean energy technologies needed to reach climate goals hinges on building up a skilled workforce, including for manufacturing and international shipping. Comprehensive workforce mapping exercises can help identify and foresee gaps between the type of skills and workers that will be needed and existing availability in specific locations. Examples of programmes to promote skills, retraining and labour opportunities are also presented below in Section 6.4.

6.3 Affordable technologies and materials

The affordability of clean energy technologies for end consumers is critical to the pace of clean energy transitions. For most households, energy represents a major part of their spending, especially since the energy crisis of 2022. Where they have the choice, households and businesses will only switch to clean technologies if they can afford to do so and if it makes financial sense. Higher prices could exclude some potential buyers from the market, whereas lower prices boost demand and bolster social and political support for clean energy transitions. It is, therefore, vital that governments act to make clean technologies as affordable as possible by reducing cost gaps with unabated use of fossil fuels.

Globally, continuing to pursue the energy path implied by current policies would be costly: in the NZE Scenario, the total cost of delivering energy – including operating expenses, the need to pay back previous investments and financing costs – is roughly 3% *lower* than in the Stated Policies Scenario (STEPS) on a cumulative basis to 2050 (IEA, 2024a). However, that requires production costs and prices to be minimised through the efficient allocation of resources worldwide, i.e. that fuels, materials and equipment are made in places where costs are lowest net of transportation costs to final consumers. All other things being equal, the cheaper the prices of clean energy goods and services, the faster they will be adopted and the faster those costs will continue to fall through learning effects.

Affordable technologies and materials

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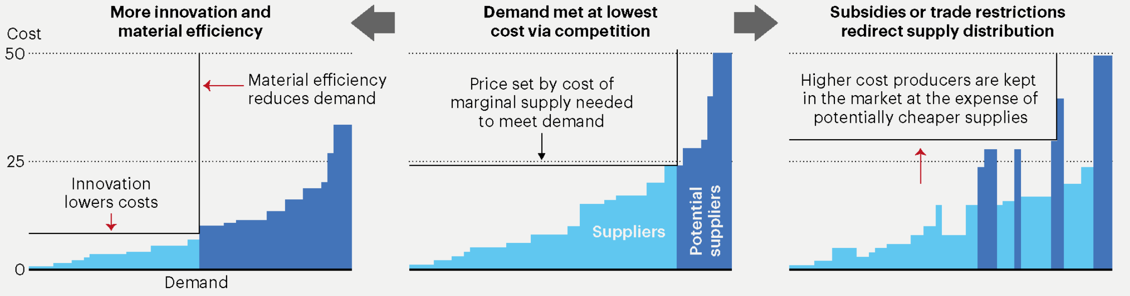
Key risks

- **Higher prices due to measures affecting trade or a lack of competition.** Firms compete to capture market share at the expense of competitors based on various factors, including labour, energy, transport, import-export and raw material costs, as well as product quality. The costs to technology manufacturers and materials producers may be distorted by various policy-related factors, notably measures that affect trade.

- **Higher costs due a lack of innovation.** Slow progress with developing and commercialising cheaper or higher performing clean energy technologies results in higher costs and slower uptake. A lack of innovation to lower costs and improve the performance of a company’s products and production processes risks leaving a region uncompetitive.

- **Higher costs due to inefficient use of materials and equipment.** If the need for a material or finished product to meet a given energy service is minimised, there will be no need for higher cost suppliers to enter the market and raise the marginal price. In addition, the fewer tonnes of materials, components and finished products that need to be shipped, the lower the severity of a trade disruption or increase in freight costs.

Archetypal supply curve and impacts of policy on price



Types of possible policy responses

- Co-ordinate with trading partners to facilitate trade
- Co-operate on standards to reduce non-tariff measures
- Provide timely and transparent cost and market data
- Co-operate internationally on priority innovation challenges
- Support demonstration projects and share the resulting knowledge
- Target support to emerging technology gaps
- Use performance-based regulation and other incentives for material efficiency
- Incentivise repairs and more durable products
- Boost re-use and recycling rates

Like any other good or service, each clean energy technology or near-zero emissions material has a supply curve that plots the cost of supplying that good (including production and transport costs) for different levels of output in order of cost. Market prices reflect the highest cost suppliers, i.e. the price is set by the point on the supply curve that intersects with demand. The relative competitiveness of different producing countries and regions in making a specific technology or material and, thus, their position on the supply curve, is driven by various factors, including labour, energy, transport, import-export and raw material costs, as well as product quality (see Chapter 1). Supply curves for manufactured goods are less physically limited and more dynamic than those for natural resources. For example, economies of scale can reshuffle cost rankings among producers during the scale-up of manufacturing capacity. In practice, there are very few manufacturing sectors where there is a lowest cost "winner takes all" because of product differentiation by suppliers, the contribution of transport costs and antitrust policies. As with other goods, the supply curves for all the clean energy technologies and associated materials assessed in this report are constantly shifting in response to various factors, including the potential for material efficiency gains, innovation and government regulations (Table 6.1).

Table 6.1 Ways in which prices can be influenced by supply curves

Factor	As a driver of higher prices	As a driver of lower prices
Rising demand	If demand rises and buyers are willing to pay higher prices, more expensive suppliers can enter the market, thereby raising prices.	If production expands with rising demand and producers can capture economies of scale, costs and prices fall. A larger market that can accommodate more producers is likely to be a more competitive one, which can squeeze margins and foster innovation.
Material efficiency	-	If the product can be used more efficiently to supply the same service, demand and prices would be reduced.
Innovation	-	If technologies for designing and manufacturing products improve through innovation, an individual producer may be able to move to a more competitive ranking in the supply curve, thereby reducing marginal costs and prices. Over time, the entire height of the supply curve would be expected to be lowered, further reducing prices.

Factor	As a driver of higher prices	As a driver of lower prices
Regulations and standards	If a region implements new regulations, such as emissions intensity standards, it effectively carves out a new, separate and smaller supply curve that only includes those suppliers able to meet the new standard. This curve will likely start at a higher cost but may not initially raise prices if the resulting supply curves can balance with demand at the same market-clearing price.	A global standard that implies costs for some or all producers may raise the height of the supply curve or reshuffle the rankings. However, in some cases regulation might stimulate innovation or changes that allow prices to remain the same.

There are opportunities for governments to work together through trade agreements and support for innovation to minimise the cost of supplying clean energy technologies and their material inputs, and ensure that they are as affordable as possible. These efforts have the potential to overcome risks relating to a lack of competition, trade measures and inefficient use of materials and equipment. Reducing restrictions on the flow of knowledge that prevent potential low-cost producers from accessing the most competitive technologies can also make clean energy technologies more affordable, as well as promoting the creation of a skilled labour force, enabling infrastructure and robust legal frameworks.

Risk of higher prices due to measures affecting trade or a lack of competition

As the market for an emerging technology grows, investors will typically seek to locate a new production facility in the location where costs are lowest to return the highest possible profit at the prevailing market price. However, the actual costs to technology manufacturers and materials producers may be distorted by various policy-related factors, notably measures that affect trade, including tariffs, NTMs and direct and embedded financial support (see Chapter 1).[3] Data is important too: for early-stage technologies, decisions about project location and timing can be undermined by misperceptions about equipment prices and their rate of change. Asymmetric access to information among project developers and suppliers can contribute to higher contract prices and higher costs than necessary.

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[3] Some of these measures are put in place to serve other compelling policy goals that can be in tension with lowest-cost production, such as supply diversity, support to disadvantaged communities or job protection. However, governments can seek to ensure that the policy environment encourages competition and keep prices as affordable as possible.

Monitoring prices and the factors that can raise them

With robust data, it is possible to measure the extent to which regional prices of clean technologies and materials are as low as possible and identify the contributing factors. Limited availability of data on clean technology manufacturing makes it hard to determine relative competitiveness between countries, hinders corporate decisions about where best to invest and complicates policy making. The impact of tariffs and NTMs on consumer prices is a good indicator of whether energy transitions are tending toward lower-cost outcomes. Their impact on the import prices of several clean technologies and associated materials has grown in recent years (see Chapter 1). This highlights the importance of international co-operation on measures that affect trade. There should be transparency about use of public funds to support domestic production of clean energy technologies.

Examples of policy responses

Policy support to clean energy technology manufacturing can promote affordability by rewarding the lowest-cost producers through financial incentives, auctions, contracts-for-difference pegged to price benchmarks, or equivalent measures. By co-operating with their trading partners, governments can work to create a more level playing field for clean energy investment and avoid an international “arms race” towards ever-higher financial support borne by taxpayers. The main policy responses include FTAs, international co-operation on standards and data gathering.

Co-ordinate with trading partners to facilitate trade

International trade is sustained by a wealth of policy efforts and international agreements that have been built up over many years and require continued attention to maintain and update. The World Trade Organization (WTO) works to reduce trade friction worldwide (see Chapter 1), while FTAs cover a smaller share of trade and are generally more specific about areas of co-operation. The WTO has provisions about environmental goods and services, as well as national security, and there remains considerable scope for harmonising definitions of what policy support is tolerated in these areas under existing trade rules. However, while WTO negotiations have been slow, the WTO remains an important forum to address possible disadvantages to WTO-compliant trading partners caused by unilateral measures that affect trade in clean energy technologies. Other multilateral and bilateral approaches include organising “clubs” of like-minded countries and FTAs.[4] Examples of recent moves in this area include the following:

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[4] Some of these approaches have been referred to as “friendshoring” or “nearshoring”.

- The Climate Club, launched in 2023, comprises 42 members that have agreed to work towards a high-ambition pathway for industry decarbonisation in their countries. This type of grouping has the potential to agree to mutually reduce measures that affect trade, giving preferential access to each other's markets for clean energy, materials and related technologies.
- The European Union and United States began in 2021 a process of removing the tariffs each partner imposed on their regional trade in aluminium and steel, in tandem with an ongoing negotiation of how materials with lower emissions intensities can receive preferential access to the two markets (EC, 2021).
- The United Kingdom-New Zealand FTA signed in 2022 requires both parties to eliminate customs duties on goods containing certain environmental goods, including materials used for solar PV panels and sustainably sourced construction materials (UK DBT, 2022; OECD, 2022).
- Parties to the EU trade agreement with the Andean Community signed in 2012 agree to facilitate more trade, investment, innovation and deployment of goods, services and technologies that can contribute to climate change mitigation (EU, 2022).
- The Singapore-Australia Green Economy Agreement, ratified in October 2022, establishes a framework for "green economy co-operation", containing a list of environmental goods and services, and establishes a mechanism to identify NTMs (Young & Clough, 2023).
- Unilateral measures can also give preference to selected trade relationships. Most of the tax incentives under the US IRA for EVs and batteries are also available to imports from other members of the USMCA trade bloc (US Department of the Treasury, 2023). They are also available for EVs with batteries utilising critical minerals extracted or processed in countries with which the United States has a FTA or has concluded a dedicated critical minerals agreement, such as Japan (USTR, 2023).

Co-operate on standards to reduce non-tariff measures

Standards that are not aligned or not recognised between regions can lead to higher costs for importers and exporters trying to enter new markets. This can be especially problematic for producers trying to establish large first-of-a-kind facilities to serve multiple markets and thus exploit economies of scale and reduce the risks associated with relying on a small number of buyers. This is the case for large facilities for low-emissions hydrogen and near-zero emissions steel and ammonia. In many cases, full harmonisation of technical standards and associated regulations between countries is not possible. Indeed, the European Union has been unable to fully achieve this after more than half a century of progress in various sectors. Yet there are very large potential benefits from mutual recognition of standards, electronic customs documentation, harmonised customs inspections and accelerated conformity assessment procedures, including testing methods (one of the more costly NTMs) for clean technologies and materials. Examples of recent efforts to reduce NTMs include the following:

- The Mutual Acceptance of Data system, managed by the OECD, helps governments to reduce administrative costs, facilitate trade and save industry time and money by co-operating on the testing of the safety of industrial chemicals and products of biotechnology (OECD, 2019a).[5]
- The World Forum for the Harmonization of Vehicle Regulations, operated by the United Nations Economic Commission for Europe (EC, 2012a; UNECE, 2024).
- Regional trade groupings, such as the Association of Southeast Asian Nations (ASEAN) and the Asia-Pacific Economic Co-operation (APEC), have established processes aiming to reduce the trade costs associated with regulations that differ between jurisdictions, including for EVs (APEC, 2024).
- The Comprehensive and Progressive Agreement for Trans-Pacific Partnership, which currently includes 11 countries, with the United Kingdom aiming to accede in 2024, has a strong focus on regulatory co-operation, conformity assessment and rule-making.
- Since 2021, the EU-US Trade and Technology Council aims to co-ordinate approaches to key global trade, economic and technology issues, including through mutual recognition agreements. The International Partnership for Hydrogen and Fuel Cells in the Economy on hydrogen, the Clean Energy Ministerial, IDDI, and the G7 Industrial Decarbonisation Agenda, and IEA Working Party on Industry Decarbonisation are all working on emissions intensity standards.

Provide timely and transparent cost data

Decision-making for clean technology investments is hampered by a lack of information that can lead to higher costs. Global exchanges like the London Metals Exchange play a pivotal role in data transparency for established commodities, by enforcing common standards and reporting, enabling cost-management instruments such as hedging and insurance. For products such as near-zero emissions steel and ammonia, there is not yet an international clearing house for tracking contracts and market data. Recent moves in this field include the following:

- For renewable energy deployment, an alliance of governments and project developers have shared anonymised data on costs as part of the International Renewable Energy Agency (IRENA) Renewable Costing Alliance since 2014 (IRENA, 2024).

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[5] This system has been estimated to save the sector more than USD 300 million per year (OECD, 2019a).

- The IEA and three partner organisations launched in 2023 the Cost of Capital Observatory to increase transparency in the renewable energy sector and encourage the introduction of measures that can lower costs in EMDEs (IEA, 2023b).
- The International Database of Efficient Appliances has been developed by Lawrence Berkeley National Laboratory to assist countries in developing regulations on product certification and labelling (Gerke, McNeil, & Tu, 2017).

Risk of a lack of innovation

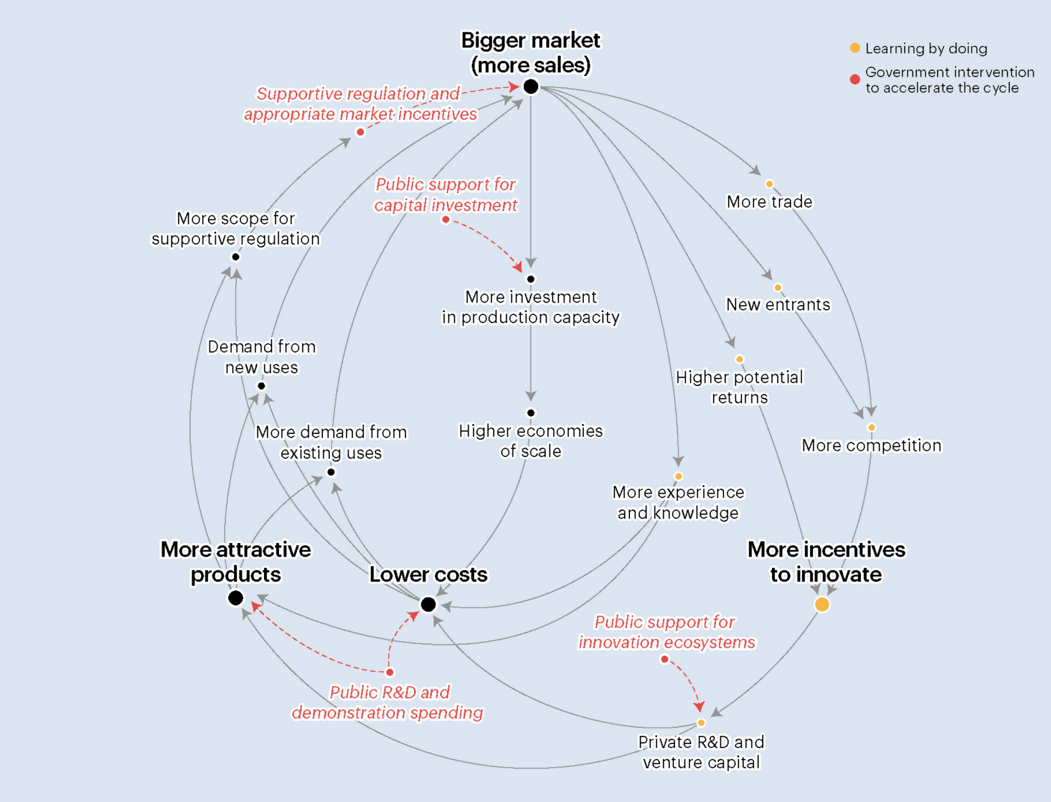
Slow progress with developing and commercialising cheaper or higher performing clean energy technologies results in higher costs and slower uptake. A lack of innovation to lower costs and improve the performance of a company's products and production processes risks leaving a region uncompetitive. However, if support measures are well calibrated then market growth can induce a virtuous cycle of technology improvements and improved competitiveness (Box 6.3). Innovation can also have a powerful effect on costs in regions that are already highly competitive if there is intense competition between domestic firms, such as in China's battery and solar PV supply chains.

Box 6.3 Innovation and learning curves for clean technology manufacturing

As costs and prices fall with innovation, clean technologies typically become more competitive in a wider range of applications and locations, increasing the size of the market (see Chapter 2). That enables new entrants and more competition, which raises the incentives for more innovation to reduce costs even more and further increase market share in a virtuous cycle. The resulting combination of lower costs and more opportunities for investment and employment in the technology value chain encourages governments to reduce non-price barriers and support market-led deployment. This phenomenon, known as "learning-by-doing", is a core dynamic in the scale-up of clean energy equipment (Figure 6.8).

Mass-manufactured goods typically have steep learning rates, because competing suppliers can integrate new generations of innovations much more quickly (IEA, 2020). The points reached along the learning curves for clean energy technologies – the cost of the output in relation to the cumulative number of units of the technology produced or installed – at any given time differ across the three scenarios presented in this report according to the different rates of deployment. Nevertheless, the shape of the curve is far from certain, due to uncertainties about future R&D and technology transfer. Around 30% of solar PV module cost reductions between 1980 and 2012 resulted from publicly funded R&D (Kavlak, McNerney, & Trancik, 2018) and, even after the technology was first widely commercialised in 2001, the role of public and private R&D in reducing costs was roughly equal to that of economies of scale.

Figure 6.8 Positive feedbacks between innovation and market growth in the early stages of technology deployment

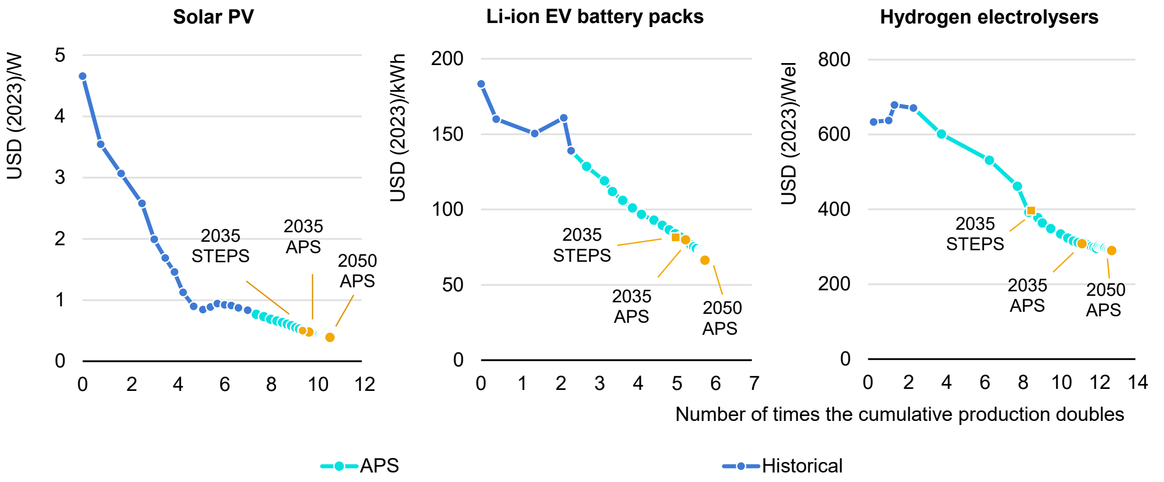


Free flow of knowledge about new techniques and ideas between companies and across borders, whether through trade, international co-operation or foreign direct investment by multinationals, is also an important factor, especially for pre-commercial technologies and demonstration projects. This is most critical for emerging near-zero emissions technologies in hard-to-abate sectors such as aluminium, cement and steel production. These channels of learning are at risk in a more protectionist world, which could lead to a significant slowdown in cost reductions and less affordable clean energy in the future. They are also at risk from market shocks: aviation, rail and shipping were badly hit by the Covid-19 crisis and R&D spending in those sectors has barely recovered since.

Monitoring innovation progress

Effective monitoring of learning rates and assessments of the effectiveness of support for innovation hinges on good data. Regular and co-operative monitoring at a global level will indicate whether cost declines are slowing down as a function of production. Normalising for factors such as inflation or rising input prices is likely to be a key element during periods of macroeconomic disruption. In the APS, learning rates, measured as cost declines per unit of cumulative deployment, follow a similar path to the recent past (Figure 6.9). The performance of clean energy technologies is also a key factor; and efforts to monitor changing efficiencies, durability or energy densities of products should also be enhanced.

Figure 6.9 Global average production cost by number of doublings of cumulative deployment of selected technologies by scenario



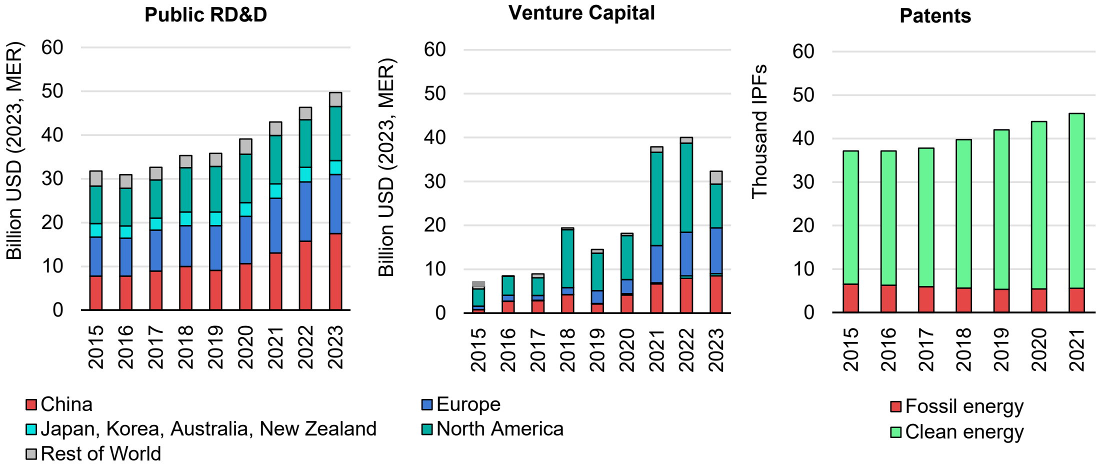
IEA. CC BY 4.0.

Notes: APS = Announced Pledges Scenario; STEPS = Stated Policies Scenario. W = Watt. kWh = kilowatt-hour. kWel = Watt of electrical input capacity. Li-ion = lithium-ion; EV = electric vehicle. The starting years for solar PV, battery packs and electrolysers are 2008, 2019 and 2019 respectively. Costs are annual sales-weighted averages.
Source: IEA analysis based on S&P, Bloomberg LP.

Rapid declines in the cost of mass-manufactured clean energy technologies over the last 15 years are projected to continue.

Various metrics can be used to track the level of support for innovators at different stages of the innovation process, as well as the outputs of R&D. These metrics include public and private spending on R&D related to clean energy technologies, venture capital flows to start-ups and patenting (Figure 6.10). The purpose of tracking these metrics is not because there is an optimal amount to aim for, but because any declines or sudden changes in the trends would warrant rapid investigation and corrective action if innovation ecosystems are underperforming.

Figure 6.10 Global public energy RD&D, energy-related venture capital and clean energy patents by country/region and type of energy, 2015-2023



Notes: RD&D = research, development and demonstration. IPF = international patent family.
Sources: IEA (2024b); patent data from European Patent Office based on IEA (2021a).

Indicators of clean energy innovation efforts have risen significantly since 2015, with public spending on RD&D holding up better than private venture capital.

Examples of policy responses

Governments take different approaches to supporting technology innovation. For energy technologies, they have typically directed resources to public research institutes and grant-funding of selected projects by consortia of researchers in academia or industry. In recent years, as the nature of energy technologies has changed and the pressure to develop them has intensified, a broader range of initiatives to support clean energy technology innovation has emerged. A selection of policies in a few key areas, such as international co-operation and technology demonstration, are described below.

Co-operate internationally on priority innovation challenges

There are many examples of the co-ordination of high-risk research among governments and companies, some of which have led to technological breakthroughs and major cost reductions, while others have broadened global participation in energy innovation efforts:

- Mission Innovation was launched in 2015 to provide a platform for energy R&D co-operation between its 24 government members (IEA, 2023c). Its Materials for Energy (M4E) Innovation Community is working to enable laboratories' databases of possible new catalyst materials to be digitally connected with standardised classifications for analysis by artificial intelligence (NRCan, 2021).

- Large-scale initiatives such as the International Thermonuclear Experimental Reactor for nuclear fusion, which draws on funding from multiple countries and researchers from around the world.
- The Technology Collaboration Programmes of the IEA have facilitated knowledge exchange and collaborative research across a wide variety of energy technology areas since the 1970s.
- The urgent need for Covid-19 vaccines spurred a sharp increase in 2020 of research partnerships, sharing know-how, intellectual property or technologies on favourable terms, many of which were international partnerships (Druedahl, Minssen, & Price, 2021). This was co-ordinated by the World Health Organization.
- After the relocation of most semiconductor chips away from Europe, Japan and the United States, US government-funded semiconductor R&D in collaboration with American and international companies enabled extreme ultraviolet lithography technology and a new business activity making the required machines (Hofman, 2022). Without this, the continued doubling every 2 years of the number of transistors in an integrated circuit (the infamous “Moore’s Law”) would have come to a halt.
- The European Union's R&D framework programmes fund energy R&D by researchers across the European Union and its partners, co-ordinated via the European Strategic Energy Technology Plan.
- Many countries have established bilateral programmes of energy R&D co-operation, including those between India and the United States, Germany and Morocco (via their public R&D agencies, Fraunhofer and IRESEN), and Australia and Japan. The UK Ayrton Fund supports clean energy RD&D projects in developing countries.

Support demonstration projects and share the resulting knowledge

For first-of-a-kind commercial-scale demonstrations, a large public grant in excess of USD 100 million is often needed to cover a share of the technology performance risk, as well as pay for testing the regulatory environment and learning about the technology’s performance. To ensure that project developers operate demonstration projects under commercial conditions and to spur follow-on investments if they are successful, it is often necessary to use offtake contracts or purchase obligations. However, not all countries have the resources to host multiple large demonstration projects, so sharing the costs between governments can enable faster progress:

- In Europe, the EU Innovation Fund provides grants to selected large-scale clean energy demonstrations using revenues from carbon pricing. In return for public funding, the project developers and European Commission commit to sharing knowledge from the project with peers and the public to help reduce the time to market (EC, 2024b).

- In Canada, investment tax credits for carbon capture, utilisation and storage (CCUS) projects that exceed specified cost thresholds are conditional on the developers making public regular “knowledge sharing reports” (NRCan, 2024). A similar requirement was also in place for CCUS demonstration projects built in Alberta, Canada (Alberta Government, 2023). To build institutional capacity for the management of such projects, the United States created an Office of Clean Energy Demonstrations in 2021. Part of its mandate is to execute a USD 6 billion Industrial Demonstrations Programme of grants (US DOE, 2024b).
- The US federal government offers large loan guarantees to first-of-a-kind projects that expect to generate enough revenue to cover costs but face a high cost of capital because first-movers are unfamiliar to banks.
- Japan has been actively developing demonstration projects overseas, with many of these related to hydrogen production that could be exported to Japan. Projects in Australia, Brunei and Saudi Arabia have received funding from a mixture of grants and export credits. Japan’s JPN 3 trillion (Japanese yen) (USD 21 billion) fund to cover 15 years of operational payments to clean hydrogen supply projects will be available to imports as well as domestic production (Nikkei Asia, 2023).

Target support to emerging technology gaps

The types of government measures used to target R&D in specific areas of emerging clean energy technologies have broadened considerably in recent years. For mass-manufactured technologies, private venture capital may be more appropriate than public grants, but public support can be crucial to help entrepreneurs access testing facilities or attract attention from customer and investors. Since 2015, the share of global energy-related venture capital from government-sponsored venture capital funds has nearly doubled, to almost 13%. In some cases, it is too early to evaluate the effectiveness of creative policy approaches, but they show that governments are identifying gaps in innovation ecosystems and taking steps to fill them. Examples that offer insights into the possibilities for policy design include:

- Technology-specific prizes, such as Canada’s Women in Cleantech Challenge, Germany’s Start-up Energy Transition and US American Made Challenges.
- Seed equity, such as Australia’s Clean Energy Innovation Fund, Finland’s Sitra and Korea’s Energy Innovation Companies.
- Business development services, such as Norway’s Advisory on Innovation and Development and South Africa’s Higher Education Innovation Fund.
- Laboratory access and vouchers, such as the EU Open Innovation Test Beds for Hydrogen, France’s Acceleration Strategies for Innovation (nuclear) and US Lab Vouchers.
- Networking, such as Brazil’s Systems of Hydrogen Laboratories, China’s National New Energy Vehicle Technology Innovation Center and Mexico’s Energy Innovation Centers.

- Living labs, such as the UK Energy Systems Catapult Living Lab.
- Regulatory sandboxes, such as Singapore's Regulatory Sandbox and the UK Ofgem Innovation Link, as well as enabling legal frameworks in Austria, Belgium, France, Norway and Spain.
- Corporate R&D loans, such as the EU Risk Sharing Finance Facility.
- Loan guarantees for innovation activities, including R&D, such as the InvestEU guarantees available from the EU budget.
- Technology- or sector-specific R&D tax breaks, such as Italy's Risk Sharing Finance Facility and Norway's SkatteFUNN R&D.
- Tax incentives for venture capital investments such as those in Italy's 2012 Startup Act and Spain's 2021 Startup Law.

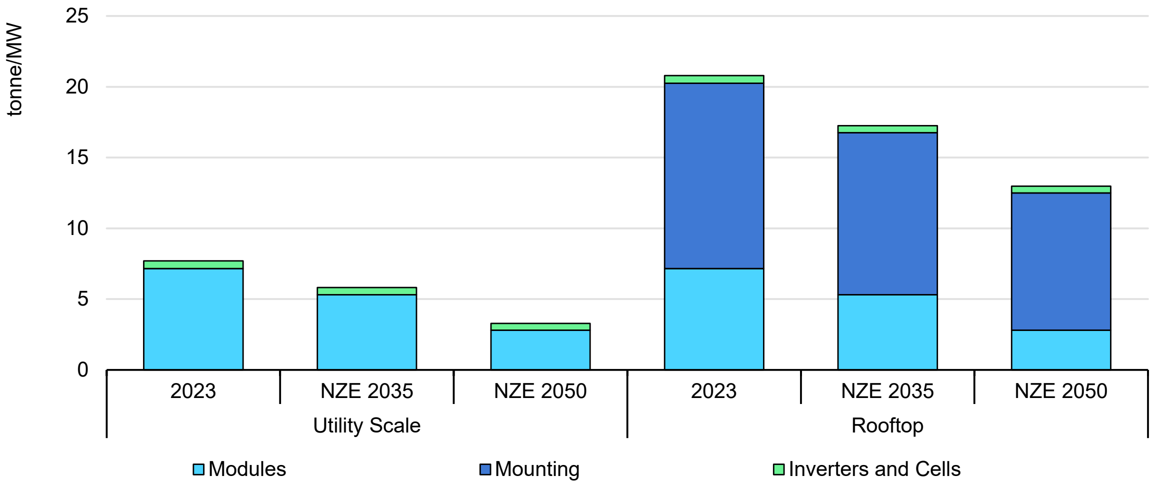
Risk of inefficient use of materials and equipment

Improving the affordability of clean energy technologies hinges in part on improving material efficiency. If the need for a material or finished product to meet a given energy service is minimised, there will be no need for higher cost suppliers to enter the market and raise the marginal price. In addition, the fewer tonnes of materials, components and finished products that need to be shipped, the lower the severity of a trade disruption or increase in freight costs. Material efficiency improvements make a significant contribution to reducing CO_2 emissions in all three scenarios in this report; for example, by 2050 in the NZE Scenario these improvements reduce steel and cement demand by 20% compared with in the STEPS.

Monitoring material efficiency

There are several categories of useful indicators that can be used to track progress in improving material efficiency, including demand for finished products, the material intensity of products, asset utilisation rates and recycling and re-use rates. For example, the material intensity of aluminium in solar PV can be reduced and tracked. In the STEPS, demand for aluminium to make solar PV modules increases by 26% between 2023 and 2050 (Figure 6.11). However, despite module production being higher in the NZE Scenario (in line with faster deployment), by 2050 aluminium demand for PV module manufacturing is 13% lower than today.

Figure 6.11 Global average aluminium intensity of solar PV manufacturing in the Net Zero Emissions by 2050 Scenario, 2023-2050

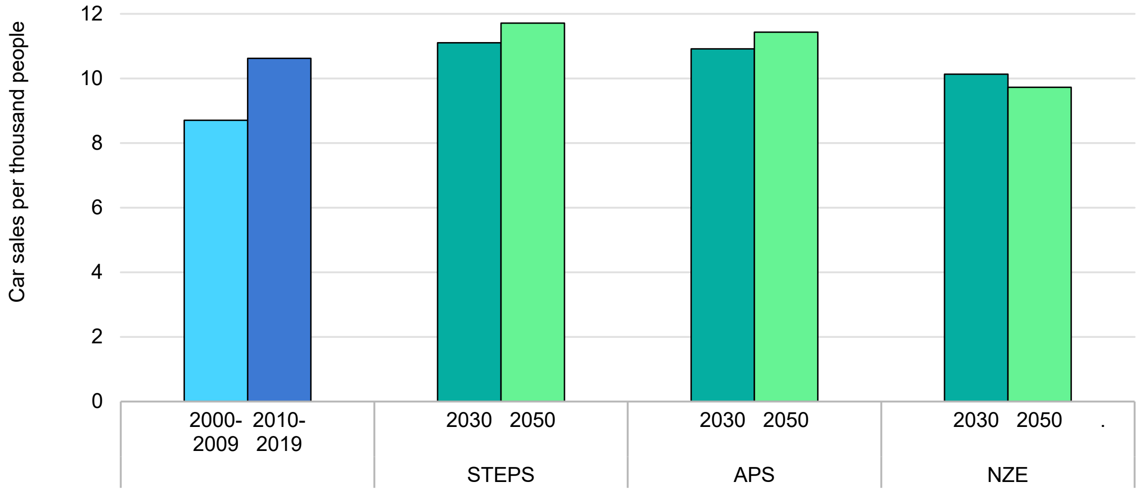


Notes: NZE = Net Zero Emissions by 2050 Scenario. Assumes utility-scale PV uses steel or other materials for mounting.
Sources: IEA analysis based on Lennon, Lunardi, Hallam, & Dias (2022) and Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020).

In the NZE Scenario, material efficiency gains result in lower total demand for aluminium, despite increased production of solar PV modules.

Sales data at national and global level is typically available for items such as vehicles, solar PV, wind turbines, electrolysers and heat pumps. Combined with data on usage, they can help tease out insights about utilisation rates, efficiency and durability. As an example of how trends might be benchmarked, in the NZE Scenario, total global car sales per capita fall faster than in the STEPS or APS (Figure 6.12).

Figure 6.12 Global car sales per capita, historical and by scenario, 2000-2050



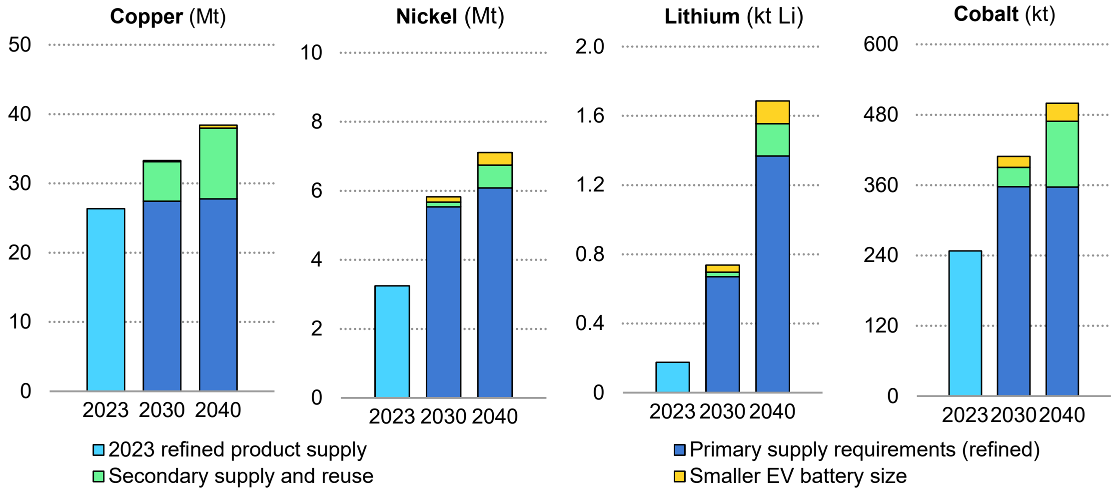
Notes: STEPS = Stated Policies Scenario. APS = Announced Pledges Scenario. NZE = Net Zero Emissions by 2050 Scenario.

The stronger climate ambitions reflected in the APS and NZE Scenario compared to the STEPS call for less demand for car journeys, reducing the number of cars made and traded.

The average material intensity of products can be tracked via surveys or sampling. Just as with life-cycle emissions or energy consumption analysis, the data would ideally also cover wastage in the supply chain. For example, substantial potential exists to reduce rates of metal waste at the semi-manufacturing (the process of converting crude metal into finished metal products like bars and sheets) and product manufacturing (the process of converting finished metal products into final end-user products like cars and appliances) stages.

Recycling and re-use are also important aspects of material efficiency. Recycling does not directly impact total demand for materials, but rather enables increased secondary production, which is expected to become one of the cheapest near-zero emissions options for material supply, thereby lowering prices, though this requires co-ordination of end-of-life collection. Steel recycling, which depends on available volumes and qualities of scrap, is already widespread: scrap currently accounts for 32% of global steel output, rising to over 45% by 2050 in the NZE Scenario. In the case of batteries, there is considerable potential to track progress in limiting demand for primary critical mineral supplies through battery re-use, recycling and better matching of battery sizes to needs (Figure 6.13).

Figure 6.13 Avoidance of primary critical mineral demand through battery re-use and recycling in the Net Zero Emissions by 2050 Scenario compared with the Stated Policies Scenario, 2023-2040



Notes: Mt = million tonnes. kt = kilotonnes.
Source: IEA (2024c).

Demand for primary critical minerals in the NZE Scenario is moderated by re-use, recycling, "right-sizing" and battery chemistry innovations.

Examples of policy responses

Governments and industry must work together to further develop policies, regulatory frameworks and business models that take a life-cycle approach to clean energy products. Policies need to focus on incentivising the re-use and recycling of materials and clean energy products to reduce the need for higher-emission primary materials production and on improving the integration of supply chains to facilitate these strategies. There are major risks that markets will not deliver these levels of material efficiency due to real and perceived investment risks, time constraints, the low cost of individual materials relative to other costs in many cases, fragmented supply chains, regulatory restrictions and lack of awareness.

Use performance-based regulation and other incentives for material efficiency

Regulatory standards and certification can be used to broaden efficiency assessments from energy efficiency to include materials efficiency. Examples include the following:

- The Netherlands has required life-cycle assessments of buildings at the permitting stage since 2013 with scheduled reductions in the maximum allowable score for new buildings over time (Klijn-Chevalerias & Javed, 2017; Rijksoverheid, 2021).
- Fuel economy regulations for vehicles intrinsically promote weight reductions. In the United States, new manufacturing processes, stronger alloys and computer-assisted vehicle design have delivered vehicles 5-15% lighter within 1-5 model years (IEA, 2019).
- In Paris, the cost of parking is based on vehicle weight, potentially incentivising less material use, which also reduces road maintenance costs and improves safety. Colombia, Hong Kong and South Africa have all used integrated transport planning to dampen car demand via active and public transport, or car-sharing, reducing the number of vehicles needed for the level of transport service (Rode, Heeckt, & de Cruz, 2019).
- To avoid the installation of over-sized heat pumps and other devices, Czechia offers a deep retrofit “bonus” subsidy for simultaneous renovations to several elements, such as the installation of a heat pump coupled with wall insulation or window replacement (New Green Savings Programme, 2024).
- The Dutch government’s home insulation standard, in place since 2021, encourages building owners to renovate their buildings to be suitable for the efficient use of a heat pump or a connection to low-temperature district heating rather than individual gas boilers (Tweede Kamer, 2024).
- In China, the central government sets a minimum utilisation rate for utility-scale solar PV installations (State Council, 2024). It also established an Action Plan for the Zero Increase of Fertiliser Use in 2015, since when the use of ammonia-based fertilisers has fallen (IEA, 2021b).

- India and Brazil have both taken measures to increase the efficiency of ammonia use in recent years, including regulations and finance for equipment (IEA, 2021b).
- Starting in the 1980s, China has steadily reduced the material intensity of energy exports from Shanxi Province. This started with efficiency requirements in importing provinces, backed with financial rewards, to alleviate rail network constraints that caused energy shortages (US CIA, 1983). The energy efficiency of coal-fired power generation in China rose by 40% from 1980 to 2000. From the early 2000s, environmental pollution concerns in importing regions spurred investment power plants in Shanxi and long-distance ultra-high voltage cables. Between 2015 and 2018 alone, Shanxi's electricity exports grew by 29% while its coal exports fell by 23%.

Incentivise repairs and more durable products

Several countries have introduced incentives to encourage consumers to repair rather than replace appliances:

- France introduced in 2020 a mandatory label to show the reparability of a range of appliances, including dishwashers, lawnmowers, and smartphones (MTE, 2024a).[6] In 2022, this was complemented by a scheme that entitles the owner to a discount on the cost of repairs (MTE, 2024b).
- The EU Ecodesign Directive, first passed in 2009 and updated in 2024, requires the producers of regulated products to consider the materials used, their weight, reparability, reusability and recyclability (EU, 2012; European Parliament, 2024).[7]

Boost re-use and recycling rates

A growing number of countries are adopting regulations governing end-of-life treatment for a particular product or technology and promoting re-use. For these policies, the timing of investment needs to take into account when sufficient volumes of end-of-life material are likely to become available for processing. For example, establishing appropriate requirements for recycled content in EV batteries must balance the need to incentivise investment in recycling infrastructure with the limited quantities of end-of-life batteries in the early stages of market creation. Example of policy measures include the following:

- In 2023, the Dutch government developed a technical agreement on the re-use of steel from buildings for similar uses (Nationale Milieu Database, 2023).

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[6] In 2025, this label will become a sustainability label, integrating additional information about durability and maintenance costs.

[7] In the Directive's first decade the related regulations largely focused on energy efficiency (EC, 2012b), leading to the proposal of an expanded Ecodesign for Sustainable Products Regulation, approved in 2024 (European Council, 2024). Depending on the product, this regulation foresees new requirements including product durability, reusability, upgradability, and reparability, as well as resource efficiency, recycled content and the introduction of a Digital Product Passport. Heat pumps may soon be covered by this regulation.

- Steel recycling is widely encouraged, including by measures such as Extended Producer Responsibility for facilitating materials recycling under India's 2019 Steel Scrap Recycling Policy.[8]
- India's 2022 Battery Waste Management Rules obliges producers to source 5% of the weight of an EV battery from recycled materials by 2028 and 20% by 2031 (Central Pollution Control Board, 2022). To enable compliance at lowest cost and encourage innovation, the rules allow producers to trade certificates with other recyclers to meet their obligation.
- China established in 2018 measures that designate vehicle manufacturers as responsible for battery end-of-life management and push battery manufacturers to design batteries in ways that facilitate recycling (IEA, 2021c).
- The EU Batteries Regulation, passed in 2023, sets thresholds for recycled content of batteries sold, as well as requirements for declaring their carbon intensity (EU, 2023a).
- The European Commission funded a project that explored the data requirements behind effective recycling of materials from end-of-life vehicles, electronic equipment, batteries and mining waste (Huisman, et al., 2017).
- Reporting on recyclability is now required under new rules in the EU Corporate Sustainability Reporting Directive, which came into force in 2023 (EU, 2023b).

6.4 People-centred transitions

People-centred transitions take account of the labour market changes associated with transitions to clean energy alongside broad concerns such as energy affordability, energy access and socio-economic development, and incorporate an inclusive approach to policy-making (IEA, 2021d). This is especially pertinent in EMDEs, which must be at the centre of global efforts to accelerate the clean energy transition given their growing share of energy needs and their resource endowments. As described in Chapter 4, there are major opportunities for some of these countries to manufacture clean energy technologies, components and near-zero emissions materials. In doing so, they can boost economic development and support deployment of these products in their own countries to meet their ambitious climate change mitigation goals.

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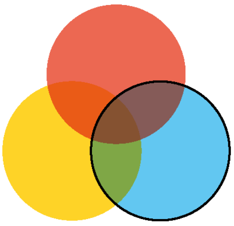
[8] Globally, the recycling rate for steel already stands at 80-90% (MoS, 2019). Governments nonetheless need to avoid introducing measures that might raise the price of recycled materials where recycling rates cannot easily be increased. In the case of steel, an obligation to source a certain percentage of material from recycled content would likely raise the price of scrap steel without increasing recycling rates and thereby increase the price of steel and steel-containing goods with no significant benefit.



People-centred transitions

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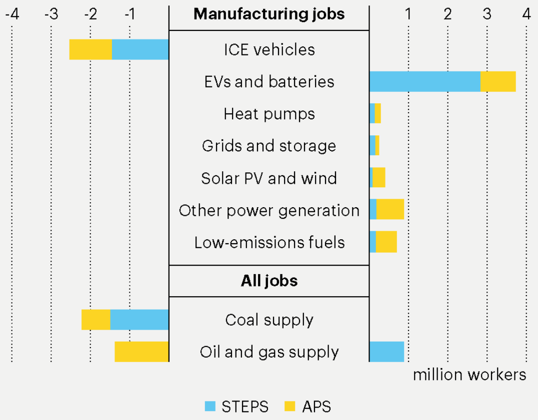
Key risks

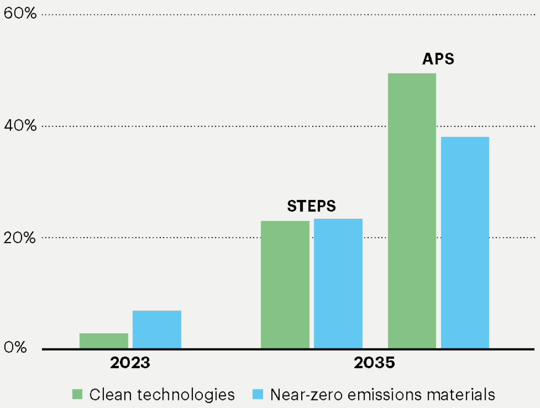
- **The benefits of clean energy supply chains are not shared globally due to low investment into EMDE supply chains.** Without dedicated actions and international co-operation there is a risk that investments in these countries will not proceed fast enough for the citizens of emerging and developing economies to benefit from clean energy-driven growth.

- **National transitions are not fair and inclusive.** The changes in employment ushered in by the clean energy transition need to be carefully managed to minimise the social costs, maintain a social licence for new projects and treat workers fairly, notably in communities intertwined with fossil fuel industries.

Net changes in employment, 2023 to 2030



Share of global manufacturing investment in EMDEs



Types of possible policy responses

- Design strategies to promote inward investment
- Agree and enshrine principles for responsible investment
- Provide regulatory assistance to emerging and developing economies
- Build strategic partnerships
- Support regional economic development
- Develop programmes to promote skills, retraining and job opportunities
- Support domestic manufacturing
- Create demand in the region
- Co-operate on standards to reduce non-tariff measures

Risk of low investment in emerging market supply chains

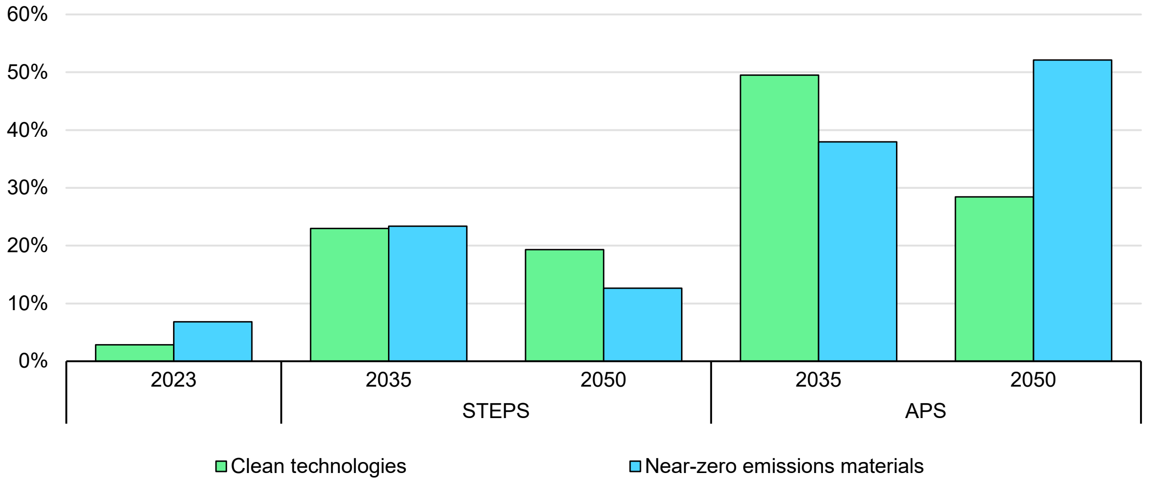
Clean energy technology supply chains, notably for batteries, solar panels and wind turbines, represent a growing opportunity for private sector investors in EMDEs. As energy transitions proceed, developing economies will encounter more opportunities to move up the value chain to capture more of the value added in clean energy technologies, especially those deployed in their own countries. Nearly 50% of the global annual investment in clean technology manufacturing over the period 2031-2035, takes place in EMDEs (excluding China) in the APS and nearly 60% in the NZE Scenario (see Chapter 4).

Policy action on the part of EMDE governments and the international community is required this decade to overcome the risk of a lack of investment due to weak institutional capacity, skills, infrastructure and high finance costs. It can be relatively costly today to establish a clean technology manufacturing facility in an EMDE, due to the need for parallel investments in infrastructure, the labour force and the provision of vital services that are taken for granted in advanced economies, as well as the relatively high cost of capital. Without strong measures to stimulate these investments, EMDEs risk pursuing unsustainable development pathways.

Monitoring clean energy investment in EMDEs

To monitor whether the world is making headway in supporting a shift towards clean technology manufacturing in EMDEs, several simple indicators can be used. These include the EMDE share of global investment in clean technology and material manufacturing capacity (Figure 6.14). The EMDE share of global clean technology and material exports can also be calculated with improvements in international customs data. The amount of foreign direct investment attracted by EMDEs for clean technology manufacturing and the total finance committed by multilateral development banks (MDBs) for this purpose are other potential indicators, along with the EMDE share of global production capacity.

Figure 6.14 EMDEs' share of global investment in clean technology manufacturing and near-zero emissions materials production by scenario, 2023-2050



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Notes: EMDEs = Emerging market and developing economies; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. The share of EMDEs for 2023 is estimated based on the average of investments between 2020 and 2023. The value for 2035 is the average of 2031-2035 and 2050 is the average of 2046-2050. China is not included.

The share of EMDEs in global investment in clean materials increases to 2050 in the APS.

Examples of policy responses

There are various examples of how EMDEs and other countries promote the development of clean energy technologies, which vary according to their circumstances and resources, and ways in which wealthier countries and international institutions can support them. Policy measures include those that seek to promote inward investment, improve regulatory capacity and encourage responsible investment practices.

Design strategies to promote inward investment

Attracting domestic and foreign investment in clean energy manufacturing calls for governments in EMDEs to develop well-designed industrial strategies, including strong regulatory and financial support. Above all, the domestic market must be stable, with dependable policies and potential for growth. China is the most obvious example of how crucial this is to success, but other countries are taking measures that offer insights for how such support can benefit from and contribute to trade:

- South Africa's Renewable Energy Independent Power Producer Procurement Programme includes criteria for projects to source inputs from local producers in line with the country's "just energy transition" philosophy (Department of Mineral Resources and Energy, 2024). Like similar criteria in other countries, they have been adjusted over time to balance different policy goals, illustrating the need for careful design and use of such policies (see Section 6.2).

- Viet Nam is currently the world's second-largest crystalline silicon solar module producer, mostly for export. In addition to low labour costs and political stability, it has created Special Economic Zones such as in Bac Giang and Quang Ninh, which have reformed administrative procedures related to land acquisition, construction, taxes and customs duties. The wave of solar-led foreign direct investment, which has built on existing manufacturing of electronics by foreign firms,[9] has recently been complemented by investment in batteries and EVs.

Agree and enshrine principles for responsible investment

For certain industrial activities, governments outline the efforts that investors and partners must make to ensure that a project is aligned with the interests of affected communities. This can involve establishing principles for consultations with certain groups and sometimes have legal provisions that empower the communities concerned to stop or suspend projects (IEA, 2023d):

- The Philippine Mining Act includes the right for communities to stop or suspend a project if they oppose it, and requires that where an agreement is entered into with a community or with artisanal miners, royalties must be paid into a trust fund for their socio-economic well-being.
- Sierra Leone has recently integrated Free, Prior and Informed Consent in its national mining legislation, allowing local communities to veto any project affecting them.
- Canada's Critical Minerals Strategy lays out the government's strategy for supporting the engagement of indigenous peoples in the country's critical minerals sector, which includes a commitment to uphold the duty to consult, with the aim of securing consent.[10]
- Proposed updates to Finland's mining code include a greater focus on the rights of the Sámi people. The amendments would require that protection and respect for the Sámi people and culture are taken into consideration more effectively during permit examination.
- In Mongolia, the Mineral Law requires licence holders to establish Local Co-operation Agreements with heads of local administrative units to outline the contributions made by companies to aspects such as environmental protection, local content, infrastructure investments and job creation. Similar provisions are found in Sierra Leone and Peru.

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[9] In 2023, Viet Nam's receipt of foreign direct investment rose 32% to more than USD 36 billion, two-thirds of which was for processing and manufacturing.

[10] The country is also developing a National Benefits Sharing Framework to help ensure indigenous peoples benefit directly from major resource projects in their territories.

- The Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) Framework and the Extractive Industries Transparency Initiative (EITI) Standard recommend that governments adopt financial transparency principles that can help to reduce corruption risks.
- The European Union has implemented Strategic Partnerships on Sustainable Raw Materials to allow resource-rich countries to co-design private investments as part of the EU Global Gateway strategy (Curtis, 2010; Findeisen, 2023; IEA, 2023e).

Provide regulatory assistance to EMDEs

Many EMDEs have weak institutions for managing the rapid introduction of a new industrial activity. This is especially hard for new activities with multiple intersecting elements, such as the production of steel from hydrogen made using renewable electricity, and where international standards and practices are in flux. Examples of regulatory assistance from advanced economies to EMDEs include the following:

- The IGF, the EITI, the Energy Resource Governance Initiative and the World Bank's Extractives Global Programmatic Support all seek to build regulatory capacity and enforcements in the area of critical minerals.
- Various technical assistance programmes have been announced to support EMDEs pursuing hydrogen-related investments. The World Bank is working with at least 14 different countries, the Inter-American Development Bank is working with six different Latin American countries, and the Asian Development Bank is supporting India, Georgia and seven South Asian countries. The European Investment Bank's Green Hydrogen Fund has raised EUR 459 million for such activities (EIB, 2024).
- The Regulatory Energy Transition Accelerator in the electricity sector, which has 54 participating regulators and involves 8 regulatory networks and several international organisations (RETA, 2024).

Build strategic partnerships

Future clean energy trading relationships will depend on trusted partnerships, especially during the early build-out of near-zero emissions materials and low-emissions fuels production. In some cases, countries may build on existing partnership frameworks, such as those that govern general policy and economic co-operation. In other cases, they may establish new partnerships as opportunities along clean energy supply chains emerge. There are several examples of countries working together to build trust and make complementary investments:

- In 2014, building on a long diplomatic history, Japan and Brazil established the Strategic and Global Partnership, and in May 2024 both partners expressed the intention to further strengthen the partnership, including through bilateral and multilateral agreements focusing on "sustainable fuels" as well as flex-fuel and hybrid vehicles (MOFA, 2024).
- In 2021, the United States and India formed a Strategic Clean Energy Partnership, a general framework for technical, financial and policy collaboration. The US International Development Finance Corporation has extended a USD 425 million loan to an Indian company (Tata Power Solar) and a USD 500 million loan to a US company (First Solar) to construct solar cell and solar module manufacturing facilities in India, respectively. In 2024 the two countries launched a roadmap initiative for safe and secure global clean energy supply chains (US DOE, 2024c).
- Since Russia's invasion of Ukraine in 2022, the European Commission and individual European countries have established strategic partnerships to reduce reliance on Russian natural gas and diversify energy supplies. In 2022, the European Union and Namibia signed a memorandum of understanding on clean energy supply chains for raw materials and low-emissions hydrogen. In October 2023, the European Union, its member states and European financial institutions, announced EUR 1 billion in investment in Namibia (EC, 2023a). Similar partnerships relating to hydrogen are being developed with South Africa and Mauritania. In 2022, Germany and Canada agreed a partnership on trade in low-emissions hydrogen from Canada (NRCan, 2022).

Risk that transitions are not fair and inclusive

The changes in employment ushered in by the clean energy transition need to be carefully managed to minimise the social costs, maintain a social licence for new projects and treat workers fairly, notably in communities intertwined with fossil fuel industries that are set to contract. The governments of countries around the world are paying close attention to ensuring that communities built around prosperous fossil fuel-related industries can benefit from clean energy transitions or other new economic opportunities.

Clean energy transitions will have profound implications for the citizens of countries dependent on oil and gas revenues to fund social services. The transition process for producer economies is much broader than energy; indeed, its purpose is to reduce the weight of energy in the economy, and to allow other industrial, manufacturing and service sectors to thrive. So far, most plans in this area target coal communities, but there is an increasing focus on how best to support the diversification of oil and gas producing companies and their workers (IEA, 2023f; IEA, 2022a). In some fossil fuel industries, workers already possess skillsets that can be highly applicable to other sectors (see Chapter 1). Approximately half of fossil fuel related job losses from 2022 to 2030 in the NZE Scenario are potentially transferable to other industries with retraining.

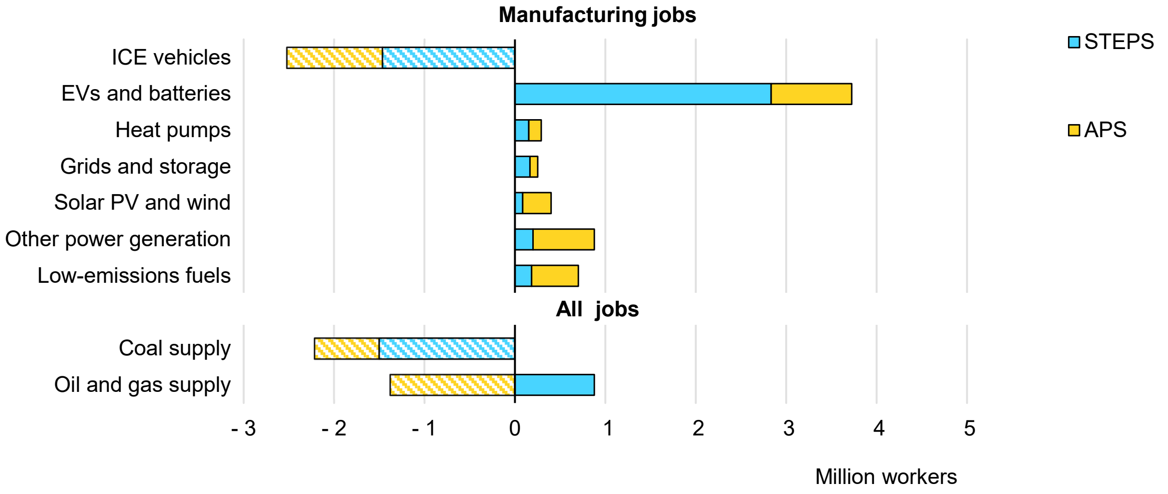
Up until now, the growth in battery manufacturing jobs has offset declines in other parts of the automotive manufacturing chain. However, firms that manufacture batteries for EVs may not be located in the same regions as those for ICE vehicles. For that reason, some regions with large employment bases focused on ICE manufacturing may lose jobs on a net basis from this sector unless large-scale investments in EV supply chains are made.

Monitoring changes in regional economic activity and employment

Employment data that is relevant to clean energy, and especially to manufacturing, are not readily available from official statistical sources. The IEA's *World Energy Employment report* presents the best available data each year and projects changes to manufacturing jobs in energy-related sectors (Figure 6.15). However, national governments could improve data availability by surveying employers directly or updating sectoral classifications. This should also be put in the context of overall employment in a sector or region. Around one-fifth of the jobs supported by a typical wind farm relate to manufacturing of the turbine, while the rest relates to services such as installation, grid connection, and operation and maintenance (OECD, 2021). Therefore, more than four-fifths of the jobs rely on the continuous deployment of wind energy and its improving cost-competitiveness for a wide range of end-uses.

Monitoring whether communities are thriving during energy transitions requires other indicators. Aggregate income tax receipts per capita in at-risk communities compared with national averages could provide valuable information and would capture their success in attracting investment in sectors unrelated to energy. Other economic metrics at a sub-national level could also help with monitoring success in managing this risk area, including the share of clean energy manufacturing in value added or total value added in sectors related to manufacturing.

Figure 6.15 Change in employment in selected energy-related sectors in the Stated Policies and Announced Pledges Scenarios, 2022 to 2030



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; ICE = internal combustion engine; EV = electric vehicle. Other power generation includes turbines, boilers and components for nuclear, bioenergy and fossil fuel power plants, with or without carbon capture, utilisation and storage. Low-emissions fuels includes electrolysers and other equipment for producing and delivering biofuels and low-emissions hydrogen, ammonia and synthetic fuels.

Source: Adapted from IEA (2023g).

Job creation is highest in the global EV supply chain in the STEPS, with job growth in manufacturing outpacing losses in fossil fuel supply and ICE vehicle manufacturing.

Examples of policy responses

There is no single blueprint for fortifying the economic resilience of communities whose businesses are facing the risk of being outcompeted by clean energy technologies and materials produced elsewhere. Much depends on local circumstances and priorities. In some cases, there is a good chance that timely investment and support for innovation help a region evolve from a producer of carbon-intensive products to a competitive producer of near-zero emissions steel, ammonia or clean energy technologies. In other cases, the changes required would be more disruptive, such as the transformation from being a manufacturer of ICE drivetrains to one of batteries, motors and other EV components. For advanced economies, the best opportunities are likely to be found in emerging technologies and supported by readily available low-emissions energy. Communities that wish to move away from dependence on extracting and refining fossil fuels to manufacturing clean technologies and materials face a different set of hurdles relating to skills and building entirely new supply chains. In all cases, regional economic development plans and training will play important roles.

Support regional economic development

Some governments have introduced measures that aim to guide investment in new and emerging industries to regions facing disruption from energy transitions. Effective economic development strategies need to pay careful attention to regional comparative advantages in order to develop realistic plans and projects, including infrastructure improvements. Examples include the following:

- The EU Just Transition Fund supports investments that improve digital and physical connectivity in order to facilitate economic diversification in the long run.
- Spain's Just Transition Strategy, which will be updated every 5 years, includes the negotiation of Just Transition Agreements, which serve as integrated regional action plans to support economic activity, diversification and employment in areas at risk from the phase-out of coal.
- The United States explicitly links its financial support for clean energy manufacturing to the policy goal of people-centred transitions. Recipients of IRA investment tax credits can claim ten percentage points more credit if their investment is in an "energy community" (NETL, 2024).[11]
- The US government launched in 2023 a programme to enhance clean energy innovation ecosystems in disadvantaged areas of the country (US DOE, 2023). In mid-2024, it awarded USD 1.7 billion for retooling 11 idle or at-risk automotive plants to make EVs or their components (US DOE, 2024d).

Develop programmes to promote skills, retraining and job opportunities

The public acceptability and justness of clean energy transitions depend on effective policy measures to ensure that workers have opportunities to move from fossil fuel-dependent activities to emerging new clean energy businesses or other quality jobs. These can also help locate clean manufacturing in regions that do not currently benefit from industrial opportunities, so as to avoid a situation in which new investments only repeat the geographical patterns of the past, and the inequalities associated with this. Examples of measures to promote opportunities for workers include:

- Under the EU NZIA, the Net-Zero Academy aims to train around 100,000 workers in the solar PV supply chain (EC, 2024c). The NZIA's Net-Zero Academies each focus on a specific technology and aim to ensure clean energy sectors are underpinned by a skilled workforce.

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[11] Defined as a brownfield site or an area with a high unemployment rate that has had significant employment or local tax revenues from the extraction, processing, transport, or storage of coal, oil, or natural gas since 2009.

- In October 2015, India's Ministry of New and Renewable Energy and the Confederation of Indian Industry established the Skill Council for Green Jobs to address skills requirements for emerging low-emissions sectors and manufacturing (SCGJ, 2024). In 2022, around half a million people received in-person training and a further 4 000 accessed online training (IEA, 2022b).
- The Canadian Coal Transition Initiative and the Spanish Plan Del Carbón offer education and training, career counselling and job search assistance to at-risk communities.
- The UK North Sea Transition Deal includes plans to retrain and shift personnel from the oil and gas industry to offshore wind and other clean energy sectors.
- The annual US Energy and Employment Jobs Report was first published in 2016 and is used by the US government to track and understand employment within key energy sectors (US DOE, 2024e).

6.5 Overarching strategic policy responses

The success of clean energy transitions will be strongly influenced by whether countries and regions successfully manage to balance supply chain security and resilience, affordability and inclusivity when developing their energy and climate policies, and industrial strategies. Our survey responses reaffirmed the central importance of policy to choices about where to make investments in new manufacturing assets (see Chapter 1). The previous sections of this chapter highlighted policy measures that have been used to address individual risks, but maximising the opportunities relating to clean technology manufacturing will require packages of measures that take a holistic approach to addressing the three key policy dimensions. Every country has a different starting point and different strengths, so policies and strategies will vary. However, at a global level, coherence between national approaches can facilitate trade and clean energy transitions.

Given that the competitiveness of each country in manufacturing clean technology is partly determined by the industrial policies of other countries, classic liberal policy packages based on free trade rules, harmonised regulation, innovation support, training and pricing of externalities appear insufficient. Many governments are adopting different industrial policies to promote competitiveness and co-operation with international partners. Even as countries build their domestic capabilities and strengthen their positions in the new global energy economy, there remain huge gains to be had from international co-operation as part of efforts to build a resilient foundation for the industries of tomorrow.

Effective policies and strategies will also require an all-of-government approach, closely co-ordinating climate and energy security imperatives with economic opportunities. Priority areas for policy action by governments include designing supportive industrial policy packages, enhancing competitiveness by fostering innovation ecosystems and clusters, supporting a broad diversification of manufacturing through effective partnerships, anticipating changes in the shipping sector and supporting the collection of better data (Table 6.2). Each of these actions are discussed in turn below.

Table 6.2 Priority policy actions for promoting investment in clean energy manufacturing and trade

Area	Action
Industrial support	Design industrial policy packages that are targeted, responsive and robust, and promote international competition.
Innovation	Enhance competitiveness by fostering innovation ecosystems and finance.
Co-location and integration	Enhance competitiveness by encouraging co-location and integration.
Supporting investment in EMDEs	Support a broad diversification of manufacturing, in particular to emerging and developing economies, through effective partnerships based on benefit-sharing and value addition.
Shipping	Anticipate changes that will reshape the relationship between energy and shipping, including different possible chokepoints for clean technology compared with fossil fuels, and surging low-emissions fuel demand.
Data	Support the collection of better data on trade, capacities and emissions to fill gaps and aid decision-making.

Well-designed industrial strategies

The results of our trade modelling show that the effects of industrial policies in the next 5 to 10 years will shape and constrain trade patterns as far into the future as the second half of this century. Trade in clean technologies and materials rises in all three scenarios we present in this report. This occurs in parallel with support in some countries for domestic manufacturing that dampens the total level of trade growth.[12] The speed with which some countries' policies lead to a ramp-up of domestic capacity by 2030 means that new plants in these countries, each with a typical lifetime of over 20 years, could occupy a preferential position in international production and trade until the middle of the century. For example, committed battery production projects in the European Union and the United States could satisfy much of the projected level of domestic demand needed to meet their climate goals through the 2030s (see Chapter 3).

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[12] Less trade can lower certain trade-related risks but can also diminish the resilience of supply chains to shocks and slow the speed at which new technologies and business models are replicated and improved around the world.

Promoting domestic and international competitiveness is key and this may require the strengthening of international coalitions of countries working towards common goals. At the same time, governments must be vigilant against the long-term impact on affordability. Given other competing priorities for public spending, governments cannot afford to tackle supply chain risks by each committing to long-term financial support to manufacturers. The ultimate aim should be to find the relationships and rules to which countries can agree to maximise the opportunities presented by exporting and importing clean technologies and materials with minimal trade friction, reflecting comparative advantages.

Industrial strategies can be designed according to seven principles that reinforce positive outcomes for the three main policy objectives described above, as well as the overarching goals of prosperity and tackling climate change: amplify local advantages, remain flexible and experiment, do not close off international competition, cultivate strategic partnerships, co-operate internationally to reduce tariffs and NTMs, consider the whole value chain and think long term. Each is discussed in turn below.

Amplify local advantages and reduce barriers to competitiveness

Every country needs to identify how it can benefit from the opportunities of the new energy economy, defining its industrial strategy according to its strengths and weaknesses. For most countries, it is not realistic or necessary to try to compete effectively across all parts of the relevant clean energy technology supply chains. As our analysis of production costs shows, the manufacturing of clean technologies and materials is most strongly influenced by operating costs such as energy and raw materials, and these are the factors that primarily shape the international competitive landscape. In the near term, policy measures that reduce or compensate for operational costs for manufacturers are most likely to boost their competitiveness. This does not need to involve full compensation, as other factors – proximity to markets and suppliers, local R&D strengths and familiarity with the regulatory environment – will compensate for some of the difference. Measures that only reduce capital costs for investors may not be sufficient to bridge competitiveness gaps. In the longer-term, investments in innovation to improve efficiency and reduce manufacturing costs can reap even greater rewards. In all cases, industrial support will be effective only if it is well-crafted for each sectoral objective, taking sectoral specificities into account in its design (Allen & Nahm, 2024).

Remain flexible and experiment to sharpen policies

Neither companies nor governments have perfect information about costs and benefits, or demand and supply, but they can learn and improve. Open markets are based on the principle of learning by trial and error, but governments tend to be less flexible. Industrial policy measures can and should incorporate flexibility to try different types of policy measures and adjust the levels of available support as more information becomes available. This learning process should be international as well as domestic: Policy makers can learn from the experiences of other jurisdictions.

Flexibility also means avoiding commitments to a fixed level of operational support for an unlimited number of projects over several decades. Sunset clauses can be especially helpful as each industrial policy measure creates a constituency of dependent businesses and investors, making it hard in many cases to unwind support schemes once they are in place.

Do not close off international competition

Some policy measures can support domestic production and preserve companies' incentives to minimise prices and continually innovate. To do so, they must not insulate manufacturers from the need to minimise costs and continually improve performance, so that domestic firms remain competitive once relevant policy measures expire.[13]

Perhaps the most effective approach is strong environmental regulations that can be met by a variety of technological solutions in which there is existing domestic leadership. Performance-based payments, such as tax credits, can incentivise cost minimisation to maximise profits and force recipients to compete for market share, but the level of the payment needs to be set carefully. If set near the level of the cost gap between domestic production and imports, recipients will need to innovate to stay competitive against imports. Auctions, for example for contracts-for-difference, encourage competition between applicants and lead to cost discovery, but have uncertain future budget implications and can reduce competition between market participants. Local content requirements can retain international competition when applied to access to concessional finance rather than access to markets. Requiring foreign operators of domestic manufacturing facilities to enter into joint ventures with local companies has been used by governments such as China to secure the flow of cutting-edge technologies and skills between regions. However, it is an approach that is generally unpopular with trading partners and only works for large markets. It can also be hard to enforce based on firms' headquarters, which may be relocated for strategic purposes.

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[13] China's EV market, for example, is fiercely competitive: since 2017 the number of registered EV makers in China has reduced by 90% from over 1 000 as hopeful newcomers went out of business or were acquired, including some that had raised billions of dollars (36Kr, 2024; OFweek, 2024).

Cultivate strategic partnerships

International co-operation is vital to accelerating the clean energy transition for the good of all. Strategic partnerships are a way for countries to increase resilience in areas of manufacturing supply chains where there is a case for sharing some of the supply chain risks based on comparative advantages and complementary goals that go beyond narrow economics. Good relations with trading partners also provide ways for domestic companies to access markets abroad, including by providing maintenance and other services that customers value having nearby.

The idea of co-operation among limited groups of countries seeking faster deployment of clean technologies, including by offering some preferential access to each other's markets to secure supply chain diversity, has gained interest recently with initiatives such as the Climate Club and the Global Arrangement on Sustainable Steel and Aluminium. These dedicated approaches could boost co-operation on climate and clean technology manufacturing more quickly than the negotiation of more wide-ranging FTAs. Strategic partnerships can facilitate investment in EMDEs and encourage clean energy transitions and socio-economic development in those countries. For near-zero emissions materials such as ammonia and steel, multi-year offtake agreements are likely to underpin the first major export projects this decade; they would benefit from robust international partnerships that spread manufacturing risks across multiple markets as they grow.

Potential strategic partners can be identified systematically. Core factors are likely to include cost, proximity and existing trade relations, but issues such as skills, regulatory frameworks and market similarities are likely to play a role too (IEA, 2024d).

International co-operation to reduce non-tariff measures

NTMs make up a significant proportion of the costs associated with trade in clean energy technologies and materials in particular. They mostly relate to inconsistencies of standards, testing, certification and other paperwork between regions. Another outcome of misaligned standards can be that suppliers in the more stringently regulated regions may invest in cleaner production for domestic markets but continue to produce comparatively "dirty" goods for export, undermining the goal of transforming the domestic sector. In many sectors, full harmonisation of standards may not be possible or desirable, but mutual recognition of standards in pursuit of common goals can reduce trade costs significantly. The most effective approaches are multilateral rather than bilateral, but they are also more complex. Consequently, interaction must start as early as possible for an emerging area of potential co-operation, where possible within existing fora.

Areas where structured dialogue will be of value in the near term include shipping fuel safety and handling; electrolyser performance testing; equipment emissions intensity calculations; near-zero emissions steel definitions; safety standards for battery trade, battery charging and safety testing protocols; heat pump refrigerant standards; cybersecurity protocols for connected devices; contract templates; and raw material critical mineral tracing. Greater standardisation in the wind supply chain to improve compatibility between components from different suppliers could reduce manufacturing investment risks for long lead-time items and could help manage policy risk in the case of local content requirements. The administrative capacity required to negotiate and implement standards in some of these areas should not be underestimated. Calculating and monitoring the equivalence of regulatory standards, as required by the EU Carbon Border Adjustment Mechanism, can be very complicated and administratively costly.

Consider the whole value chain, starting with end-user demand

Ensuring that there is robust end-user demand for clean technologies and materials is critically important. Strong demand signals for final products are essential, especially if a country's industrial policies support investment in, or production of, intermediate goods that are the most geographically concentrated in the value chain. Industrial policies that target manufacturing steps lower down a value chain weaken the demand signals for the finished goods and risk supporting overcapacity or stranded assets. For countries concerned about overcapacity, there is a clear case for boosting domestic demand and working with international partners, especially in EMDEs where consumers are less able to afford key technologies, to support their efforts to adopt cleaner energy as part of their industrialisation strategies.

Grants, tax incentives, performance-based payments, public procurement rules, regulations such as mandates and training can all drive consumers and suppliers to make cleaner choices, thereby pushing up utilisation rates of existing plants and keeping prices down. However, any industrial policy that seeks to improve the competitiveness of a specific sector must guard against unintended consequences in related sectors. For example, emissions intensity requirements for domestic aluminium production and imports could lead to increased production of higher emissions aluminium abroad for integration into final production overseas if imports of products such as solar PV do not face the same criteria.

While predictable end-user demand is essential, clean energy transitions will be more affordable and sustainable if recycling, re-use and other forms of material efficiency are given high priority within industrial strategies. Reducing material needs for clean energy services, including through innovation, can also ease trade-related risks.

Think long term

The transformation of the energy system needed to achieve net zero emissions, involving a broad portfolio of technologies, will not happen at the necessary scale or speed without clearly formulated long-term government strategies, integrated into overall energy, climate and industrial policy and system planning. Such long-term strategies need to be as clear and predictable as possible, including how they will be adjusted over time to incentivise continual improvement in, for example, environmental performance. Their progress needs to be tracked against medium-term milestones to make them credible and to secure buy-in from businesses and investors. Governments have a responsibility to ensure that the resulting investments are future-proofed against foreseeable market changes. When supporting investments in new plants in EMDEs, importing regions can help ensure that any financial support and offtake guarantees make it economically attractive to implement high standards for CO_2 emissions intensity and reducing water stress from the outset.

Innovation

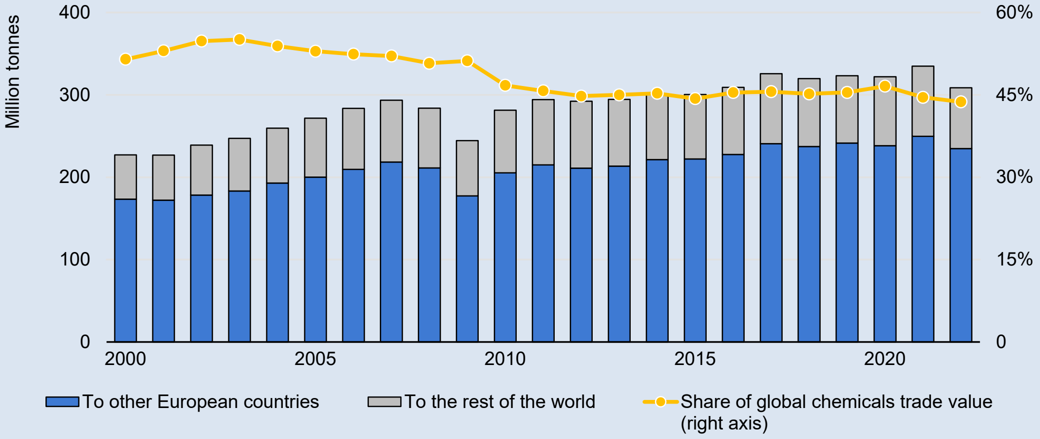
Technology innovation is an engine of economic growth, as investment flows to new or improved technologies that can outcompete incumbents or offer new value to consumers. Government spending on energy R&D is on the increase, aimed in part at raising competitiveness by reducing production costs, improving product quality and locking in an early comparative advantage in emerging technology areas. Most innovative companies stay close to where they were established and keep a share of their R&D and manufacturing there: international moves are rare (Lee, 2022; Shi, Sorenson, & Waguespack, 2024).

Innovation is also an important reason why countries with relatively high labour and energy costs continue to have factories that manufacture goods in trade-exposed sectors. One example is the European chemicals sector (Box 6.4). Others are automotive parts, engines, heating equipment and robotics, where firms have successfully operated manufacturing facilities in advanced economies over several decades, as they generally produce high-quality goods that can turn a profit. Some have opened factories in other regions – especially where these are close to new markets – but usually keep their R&D facilities in the country where they are headquartered (IEA, 2024c). Their spending at these R&D centres is often significant, representing 2% to 10% of their revenues (IEA, 2024c). For example, Valeo, an automotive parts supplier, spent over USD 2 billion, or 9% of total revenue, on R&D in 2023.

Box 6.4 European chemical industry competitiveness

It seems almost impossible to remain competitive in manufacturing in a region with high energy, labour and land costs without being innovative. Over several decades, however, the European chemical industry has managed to stay profitable by improving its products to maintain a comparative advantage over imports. Not all firms have weathered all storms, and the past few years have been especially tough for chemical producers. For bulk chemical producers, fossil fuel purchases already represented 60% to 80% of total costs before prices spiked since 2022 (IEA, 2018). As a share of total expenditure, operating expenses are higher for Europe's chemical industry than any other region (Figure 6.17). Yet the total mass of chemicals exported from Europe to other regions in 2021 was the highest on record, and Europe's share of global chemicals trade value has remained relatively constant since, at around 45% (Figure 6.16). The total market capitalisation of European chemical companies grew by nearly 50% between 2010 and 2023 in real terms. Nonetheless, the fortunes of the industry are threatened by energy prices that remain much higher than in other regions.

Figure 6.16 European chemical exports by mass and share of global trade value, 2000-2022



Note: Data shows exports from EU member states and the United Kingdom for HS codes 28 to 39.

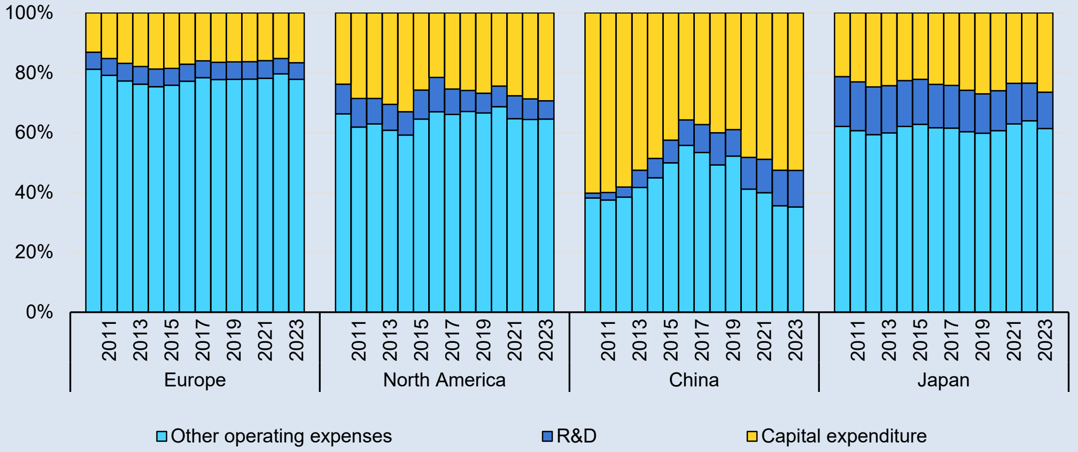
Source: IEA analysis based on Bloomberg terminal data.

There are several reasons why the European chemical industry has performed well despite high input costs, each of which holds lessons for clean technology manufacturers in such regions:

- Innovation in close co-operation with customers. European companies have generated competitive advantage for both parties by tailoring new products to consumer needs.

- Focus on products that are more technically complex, more valuable and more profitable. European chemicals producers have increased their focus on speciality chemicals, which now make up more than 40% of Europe's chemicals market (Erharter, 2019). Production of bulk and commodity chemicals are much less profitable, even though labour inputs per tonne of output are lower.
- Integration into networks of complementary businesses. The level of physical integration of processes and supply chains with nearby energy suppliers, steel suppliers, waste heat users and recyclers is very high, driven by environmental regulations and cost pressures. This significantly reduces the attractiveness for any single company to relocate abroad. These relationships have also reinforced the chemical industry’s role as an enabler of emissions reductions from its own processes and those of other sectors of the economy across the region. Synergies of energy use patterns can raise energy efficiency within chemical clusters (Janipour, Gooyert, Huijbregts, & Coninck, 2022).

Figure 6.17 Chemical industry expenditure by type in selected regions, 2011-2023



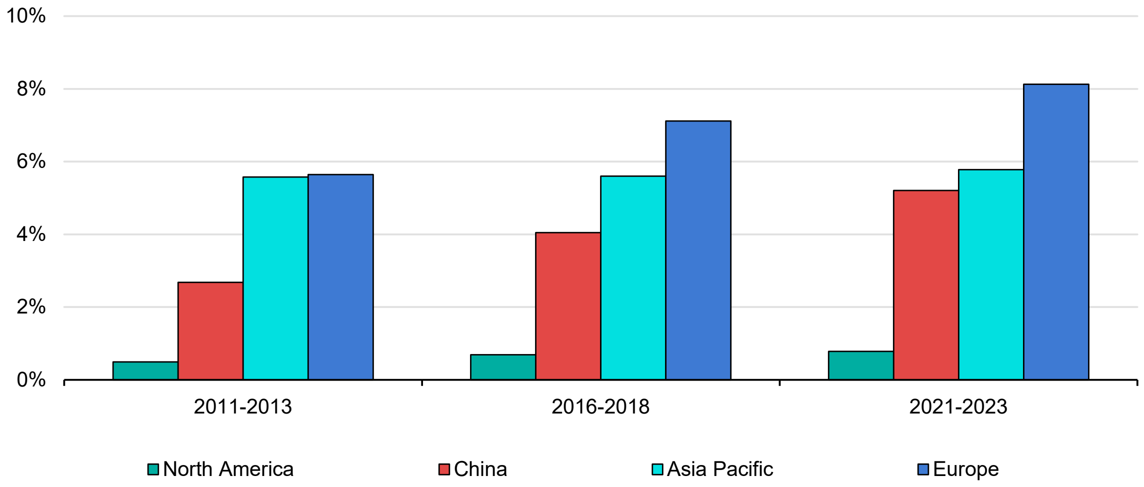
IEA. CC BY 4.0.

Notes: Regions represent country of headquarters. Other operating expenditures include energy, materials, labour, overheads, depreciation and amortisation.

Source: IEA analysis based on Bloomberg terminal data.

Private sector innovation is spurred by expectations of growing markets and the policies that support them. This dynamic can be seen in the increased spending on R&D by companies in the automotive parts sector since sales of EVs started in 2010 (Figure 6.18). Market support policies can be complemented by dedicated innovation policies, especially where it is not clear that private sector innovation will respond to market signals quickly or in line with policy goals. Innovation policies typically comprise a range of measures that boost R&D and create a supportive framework for taking the risks that move products stepwise towards commercial use or market scale-up.

Figure 6.18 Average R&D spending as share of total revenue for the largest automotive parts manufacturers in selected regions, 2011-2023



IEA. CC BY 4.0.

Notes: Chart shows arithmetic average over 3 years of the weighted average of the 20 largest firms by revenue in the automotive parts sector by location of headquarters.
Source: IEA analysis based on Bloomberg terminal data.

The share of R&D spending in total revenue for automotive parts manufacturers increased by about 2.5 percentage points in Europe and China between 2011-2013 and 2021-2023.

In most cases, there is scope to tailor this support selectively towards innovation challenges, such as reducing the cost of energy and material inputs to making batteries. Innovation programmes can support competing approaches, from reducing manufacturing waste to new designs that eliminate expensive material inputs while meeting minimum battery performance needs. Similarly, frameless solar PV modules could dramatically cut the need for aluminium and, therefore, costs. However, governments should not focus exclusively on radical, disruptive ideas, for which direct public funding is often critical. Continual, incremental innovation can be encouraged with targeted R&D loans and tax incentives for firms in relevant sectors (Breznitz, 2021). Over time, knowledge gained by manufacturers and innovators inevitably spreads to competitors via products, personnel or patents, but if the domestic market and innovation ecosystems are robust there will be strong incentives for competitive firms to keep a sizeable local presence. The most innovative countries and regions are often the ones with strong ecosystems of researchers and firms, good access to capital and relentless competition between leading companies.

Innovation policy for climate change mitigation has an inherently global dimension. Any technology improvement that can accelerate the uptake of clean energy is potentially of global importance if end-users around the world can benefit. Without international co-operation, it will not be possible for GHG emissions to fall to net zero by 2050, largely due to the importance of trade for enabling economies of scale and diffusing technological advances (IEA, 2021e). Trade in knowledge itself can also boost growth: for several G7 countries, net trade in intangible capital related to manufacturing exceeds 1% of GDP (IEA, 2024c). In manufacturing sectors such as wind energy it has become efficient for a small number of firms to compete to be contract manufacturers under licence for multiple major turbine designers from different regions. Across countries, intangible capital has been found to account for more than 50% more of the income in global value chains than returns to tangible capital, such as investments in factories, and to have a share that is half that of labour income (Alsamawi, et al., 2020).

Large-scale demonstration projects, especially for near-zero emissions steel, aluminium and low-emissions shipping fuels, represent a key focus area for international co-operation. A lack of finance and “pull” from the market for first-of-a-kind commercial projects can cause delays that prevent critical emerging technologies from being available for widespread investment (IEA, 2021d). For governments collectively to meet their climate pledges, it is essential that the demonstration period for near-zero emissions materials and low-emissions fuels is compressed to the next decade. This would require learning to be rapidly transferred between projects in different contexts to build confidence and experience, including among policy makers to inform more effective policies. International co-operation can also ensure that demonstration projects are located in the most appropriate locations for technology scale-up. Grants and tax incentives (including output-based payments), loan guarantees, advanced market commitments, emissions intensity standards and portfolio standards will all have a role to play in building a global technology portfolio.

Co-location and integration

The competitiveness of a manufacturing industry in a given country can be enhanced when different steps of a value chain are in proximity. In our industry survey, clean energy technology manufacturers and materials producers rated proximity to technology leaders, adjacent sectors, start-ups and potential partners among the most important factors for investment decisions (see Chapter 1). Co-location of suppliers and users of manufactured products raises competitiveness in three main ways:

- By reducing costs via shared inputs, lower transport costs and waste minimisation
- By tailoring products to consumers to increase added value
- By raising the rate of innovation through collaboration and knowledge spillovers.

Clustering of related activities within a region is a key strength of Chinese clean technology manufacturing, and will play an important role in making manufacturing competitive in other world regions. For example, the European Union’s large internal market helps to make the production of EVs and other clean technologies competitive in the APS. The full and successful implementation of the benchmark set in the NZIA of 40% or above of EU deployment coming from EU manufacturers (EC, 2024a) in that scenario boosts production of batteries and EVs. While the European Union can build on a large pipeline of projects to produce batteries, it will need to succeed in building up its domestic EV market to make use of those batteries and build an integrated, competitive EV supply chain. By doing so, its costs and specialisation improve, and dependency on Chinese EV imports is reduced to 20% by 2035, compared with 40% in the STEPS.

Geographic concentration can be a risk for clean energy supply chains (see Section 6.2), but industrial clusters can make supply chains more resilient. Access to localised supply chains helped the automotive sector to be more resilient to the Covid-19 pandemic in 2020 (Belhadi, et al., 2021). In the United States, industrial clusters have been shown to be more resilient to shocks (Cho, Lee, Yoo, Kim, and Park, 2024).

There are many examples of how co-location can reduce costs in clean technology manufacturing:

- Solar PV module assemblers commonly use just-in-time logistics and local sourcing of key components like glass and aluminium frames to lower inventory costs (US DOE, 2022a).
- JinkoSolar’s new fully vertically integrated solar PV plant in China is expected to have costs 25% below the national average, though the inflexibility of vertical integration carries some risks (IEA, 2024c)
- As recycling of solar panels becomes more commonplace, opportunities will arise for its integration into solar PV manufacturing, notably in recovering the aluminium in solar frames (Zante, Rivera, Hartley, & Abbott, 2022).
- The offshore wind sector has developed in partnership with ports and shipbuilders to help lower transport costs for components (US DOE, 2022b).
- In Europe, absorption heat pump supply chains are typically vertically integrated due to the need for specialist skills and inputs (EC, 2023b).
- Regulations and competitive funding programmes for hydrogen are pushing developers to find the cheapest ways to power electrolysers with renewable electricity and supply the hydrogen to end-users.
- Co-location with solar PV and wind, combined with short transport distances to multiple customers, is the most cost-effective option for low-emissions hydrogen production in many cases (IEA, 2022c).

Regions with co-located industrial firms tend to generate more new business than other regions, as well as higher incomes and employment growth (Feser, Renski, & Goldstein, 2008; Spencer, Vinodrai, Gertler, & Wolfe, 2010). One reason for this is the greater ease of creating and sharing new knowledge, leading to innovation (Xu, Li, Tao, & Zhou, 2022).

Governments use a range of measures to encourage firms to co-locate and benefit from synergies of physical flows and local knowledge. Some countries offer a package of measures to companies that invest in Special Economic Zones, including exemptions from certain export and import tariffs, subsidised land prices, special regulatory treatment and tax incentives (OECD, 2019b). Other governments use the eligibility criteria in clean energy funding programmes as a means of guiding investors to preferred locations. The US CHIPS and Science Act awarded grants to 31 technology hubs that were selected via competitive bidding, 11 of which are focused on technologies relevant to energy transitions (The White House, 2023b). India's Ministry of Ports, Shipping and Waterways is preferentially channelling funds to three ports to be developed in connection with low-emissions hydrogen projects in a bid for higher economies of scale (Rathi & Joshi, 2024). The United Kingdom has allocated GBP 210 million (around USD 270 million) in grants to the private sector to transform selected industrial hubs into one low-carbon cluster by 2030 and one net zero emissions cluster by 2040 (UKRI, 2024).

Close partnerships between clusters of manufacturers, on the one hand, and academic institutions and subsidised test beds for experimentations, on the other, can accelerate learning and help firms innovate with less risk. Co-location enables firms to obtain public and private support more readily, for example, through expedited permit processes, though it does not always guarantee that the final products will be competitive. Clusters can also boost local employment and bring local economic benefits, which can often make it more politically feasible to support certain technologies in specific geographic locations.

Box 6.5 Resilience of automotive industry clusters to supply disruptions

In principle, the EV market could be easier for newcomers to enter than the ICE vehicle market: EVs are simpler, with more standardised parts, fewer drivetrain components and a less customised assembly process. In practice, new companies launched in recent years have shown how hard it is to disrupt an existing sector that is characterised by highly integrated supply chains, diverse consumer tastes and labyrinthine regulatory hurdles. Creating a new EV company based on an innovative vehicle design is a highly capital-intensive process. Factories must be built alongside a sales and service network, and an array of contracts must be signed with suppliers with whom there is no existing relationship. Buyers must be found who are willing to commit to the high prices of the first output from a production line operating initially at low utilisation rates. Higher interest rates can cut off access to capital and slash margins.

Five new EV makers have gone bust since 2022, after raising over USD 6.5 billion between them. Lordstown Motors and Fisker were listed on the stock market in 2020 and went bankrupt in 2023 and 2024, respectively. Electric Last Mile went from listing in 2021 to bankruptcy in 2022, while Proterra went bankrupt in 2023. Arrival went bankrupt in 2024 after an aborted attempt to go public in 2021. The valuations of five other listed companies that have raised close to USD 50 billion between them – Canoo, Faraday Future, Lucid Motors, Nikola, and Rivian – are all significantly lower than a few years ago as they experience scale-up challenges. Tesla also grappled with existential supply chain and cashflow challenges throughout its scale-up journey.

Conversely, incumbent automakers are well-placed to capitalise on existing regional networks of suppliers, facilities and brand-loyal customers, as well as familiarity with the regulatory environment. While they cannot afford to be complacent, they can benefit from a legacy of co-location and can give longer commitments to trusted suppliers with whom they can collaborate to help smooth the transition to EV component manufacturing.

Supporting investment in emerging markets

Importers and exporters have common interests in successful projects and the realisation of clean manufacturing opportunities in EMDEs (see Chapter 4). For EMDEs, clean energy technology and near-zero emissions material manufacturing are possible pathways to attracting foreign direct investment and economic prosperity and can support their domestic decarbonisation goals. For wealthier importing regions, building capacity in EMDEs has been identified as a means of increasing supply diversity and resilience. Indeed, for many advanced economies, international co-operation is critical to achieve their net zero emissions goals. Furthermore, EMDEs offer some of the most competitive opportunities for clean technology and materials manufacturing in the long term, reducing the overall costs of energy transitions and creating trade and investment relationships that can underpin long-term geopolitical security. For example, Southeast Asia becomes the location with the most attractive enabling conditions to produce polysilicon and wafers for solar PV in the APS.

Major near-term obstacles to improving competitiveness and encouraging investment need to be overcome for the potential of EMDEs as clean energy manufacturers to be realised, calling for partnerships between potential trading partners and international co-operation more generally. For many EMDEs, building clean energy technology supply chains in the absence of international assistance, including sustained and active technical co-operation and support, will be very difficult. A variety of enabling factors are needed to attract investment in EMDEs (see Chapter 4), and both importers and exporters have responsibilities to ensure that the outcomes of such co-operation can meet the needs of all parties, recognising differences in the stages of development of different countries.

We have identified six principles that need to be integrated into partnerships by governments and other stakeholders in support of investment in EMDEs. These principles, the rationale behind them and the actions needed to implement them are outlined in Table 6.3

Table 6.3 Six principles for strategic partnerships in support of clean manufacturing investment in EMDEs

Principle	General activity	Possible action
Start consultation and dialogue as early as possible	• Build "win-win" socio-economic outcomes into the foundations of the partnership. • Enhance trust with a range of project stakeholders early in the process. • Share experiences to develop projects with most up-to-date information.	• Estimate the costs and benefits of different ways to split value chains and trade within them. • Establish bilateral, regional (including "south-south") and/or multilateral dialogues, involving international organisations and international financial institutions. • Develop common contractual templates and standards that can reduce project timelines and costs.
Ensure that institutional capacity and skills are part of the plan	• Proactively design programmes to plug skills gaps and address institutional weaknesses. • Build administrative knowledge to act as an "informed buyer" when selecting between technology options. • Build regulatory capacity to account for new approaches to permitting, grid connection and inspection for clean technology and materials manufacturing. • Protect intellectual property to allow project partners and suppliers to operate freely between different regions.	• Map capacities and identify obstacles to foreign direct investment in clean manufacturing. • Identify gaps in practical skills – electricians, machine operators, maintenance engineers and quality control specialists – as well as clean technology specialists. • Share capacity-building knowledge through multilateral financial institutions and bilateral development banks. • Support long-term vocational training.
Agree on standards for environmental performance	• Prevent "leakage" of emissions and water stress to countries with less stringent regulations. • Build material efficiency and recycling capacity in EMDEs.	• Develop import eligibility requirements that are contingent on environmental performance. • Jointly develop interoperable, environmental, social and governance (ESG) standards based on the common interests of long-term competitiveness and diversification.

Principle	General activity	Possible action
Design projects that contribute to meeting local climate goals	• Develop domestic manufacturing in EMDEs to lower prices of clean technologies and facilitate market growth domestically and in neighbouring countries. • Scale up renewable electricity capacity in ways that build credibility among lenders, lower financing costs for investors and provide low-cost manufacturing.	• Stipulate that clean energy needs for manufacturing projects should be provided from "additional" sources and not result in greater unabated fossil fuel use overall. • Co-ordinate the investment and infrastructure requirements for clean energy use in manufacturing and in the domestic market in ways that minimise total risks for investors (including governments) in energy transitions in the country. • Focus on long-term offtake contracts that facilitate access to lower-cost capital to crowd in funding for projects to serve local needs, especially for near-zero emissions materials.
Design projects as platforms for future prosperity	• Enable EMDEs to move up the value chain of clean energy technologies (from critical minerals to battery components and finished products, or from hydrogen to iron ore and steel), in line with developmental goals. • Realise local economic co-benefits from infrastructure requirements (roads, power grids, ports, desalination) of some manufacturing projects.	• Study options for the co-location of facilities in different value chains to optimise electricity consumption patterns. • Design projects to be able to meet anticipated changes in the environmental and social criteria of importers or other consumers, and not risk becoming uncompetitive due to focusing only on short-term drivers.
Build synergies and complementarity between finance, projects and programmes	• Leverage international financial assistance to play a catalytic role in project development. • Find opportunities to exploit synergies between the projects and programmes of different international partners. • Benefit from the comparative advantages of different countries to enhance complementarities.	• Apply well-tested policy tools, such as government-assisted site selection for renewable electricity generation, to newer technology areas. • Co-ordinate between programmes being implemented in the area of clean energy co-operation – from Just Energy Transition Partnerships to MDB-financed projects to bilateral capacity-building programmes. • Co-ordinate investments within a value chain across borders in a region to help manage scale-up risks. • Establish clear trading arrangements on favourable terms, priority treatment for these technologies and co-operation on quality, performance and innovation.

Shipping

As energy transitions proceed, seaborne trade in energy-related products will continue to be essential to the global economy, with clean energy technologies becoming a much more important part of this trade. Chokepoints such as the Strait of Malacca will not cease to be a concern for energy security and supply chain resilience, even if the direct repercussions of supply chains disruptions are likely to be different than for fossil fuels (see Chapter 5). Governments must ensure that shipping bottlenecks continue to be monitored and must support free passage under international conventions. The way that ships are powered is also set to change. To prevent international shipping and, therefore, trade becoming a stubborn source of emissions that prevents the achievement of overall climate goals, it is imperative that rapid progress is made towards a globally integrated system for producing and selling low-emissions maritime fuels.

Co-ordinating a common vision of the future fuel value chain

Given the international nature of shipping, it is not possible to plan for the introduction and ramp-up of low-emissions maritime fuels without multilateral co-operation. There are six main areas in which countries will need to work with each other and stakeholders from the port, fuel supply, shipbuilding, shipping operator, insurance and finance sectors:

- Harmonised fuel standards for quality, handling, refuelling and safety.
- Low-emissions fuel production capacity and bankable offtake contracts.
- Bunkering and fuel storage capacity.
- Port and refuelling infrastructure.
- Ship and drivetrain construction.
- Systems for monitoring interactions between fuel and food prices (see Box 6.6).

A common vision among international stakeholders will be essential. Interdependencies between the availability of fuels, infrastructure and ships means that the deployment of critical new assets for the delivery of low-emissions fuels must be achieved in a co-ordinated manner.

Involving a broad set of stakeholders

Existing institutions such as the International Maritime Organization (IMO) will continue to be at the heart of this process, along with key importing and exporting countries, and major shipping companies. These countries include those that are likely to host refuelling infrastructure and are already mostly identified, since major changes in the main bunkering and fuelling ports for the largest trade routes are not foreseen. They also include those whose policies will be central to driving up demand for cleaner shipping. A new set of stakeholders also need to come to the table, including large companies with net zero targets for their supply chain emissions and the capacity to commit to early contracts with shipping companies that can offer low-emissions services. The IMO GHG Strategy provides one basis for a common vision among stakeholders and it is reflected in the APS, while the milestones for fuel production, ship sales or emissions intensity in our NZE Scenario outline a complementary pathway if overall shipping activity is reduced in parallel.

Investing in an international bunkering system

The benefits of shipping with low-emissions fuels will be shared internationally. A transition away from the use of unabated fossil fuels will help countries and companies meet their climate pledges and will improve global climate security. However, the necessary investments will not be shared evenly around the world. Some countries have excellent resources for producing biofuels, ammonia or methanol with low emissions, and are also close to major ports. Capital for establishing new fuel production facilities needs to flow to these locations. Other countries that host large ports will need to invest in infrastructure for bunkering, refuelling and supplying low-emissions electricity to ships in port. Existing fuel storage capacity can be repurposed, but expansions will be necessary to account for the lower energy densities of ammonia and methanol. A third group of countries are those with the shipbuilding and manufacturing industries that are expected to invest in making efficient ships with engines adapted to the fuels that will be used on their specific routes.

Creating demand for low-emissions shipping fuels

The starting point for policy to unlock these investments in a co-ordinated manner is the creation of demand for low-emissions fuels such as ammonia and methanol. Emissions standards with stringencies that ratchet up over time, such as those in the FuelEU Maritime Initiative, will be important tools. Carbon pricing, such as the inclusion of maritime transport in the EU Emissions Trading System, can also play an important role. Additional demand will be fostered by measures that incentivise suppliers of traded goods to reduce the emissions intensities of their products, such as making access to financial support for clean technology deployment conditional on life-cycle emissions intensities. To manage risk for shipbuilders and fuel suppliers, this could start with just one type of ship or cargo, such as container shipping, which generally has the highest CO_2 emissions per tonne-kilometre within a size class and a greater ability to absorb higher fuel costs.

Funding complementary measures to manage early-stage risk

Additional measures will be essential to manage the risks of large investments in nascent shipping sectors. Concessional finance and funds for capacity building will be important for large infrastructure projects to produce low-emissions fuel for export from EMDEs. Finance packages to enable port expansion projects to account for changing patterns of refuelling, can also benefit the whole international community. Innovation policies, including grants for large-scale demonstration projects, will be needed to test and bring to maturity technologies for ship efficiency, including sails and new drivetrains. These demonstrations can be accelerated and made more effective through international co-operation to share costs and experiences, as well as reduce duplication. Guaranteed offtake contracts will also be key enablers of investment, just as they have been for the launch of other new capital-intensive transboundary fuel infrastructure, such as for LNG. Private sector mechanisms like "first-mover" coalitions of customers can help in this regard, alongside public tools such as the "double-sided" auctions for contracts-for difference that are currently under development to commit willing EU hydrogen importers to offtake from potential exporters.

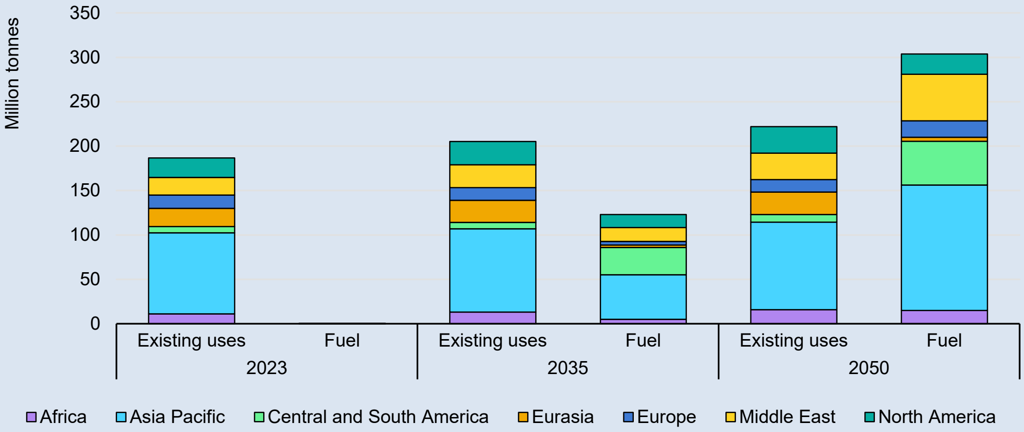
Developing clear and agreed international standards

It will be difficult to unlock the necessary investment in low-emissions fuels without clear and agreed standards in areas like fuel handling safety, fuel quality, environmental emissions and life-cycle emissions certification. Ongoing processes to reach international consensus within the IMO should be supported and expedited. While some of the necessary standardisation work is underway, less policy attention has so far been paid to the possible ramifications of increasing demand for ammonia, which much of the world relies on for making fertiliser, and which could push up its price. There are policy approaches that can be built into support for low-emissions shipping to mitigate risks in this area (Box 6.6).

Box 6.6 Managing the interactions between ammonia markets for food and fuel

Estimates suggest that around half the global population is sustained by food produced with nitrogen fertilisers derived from ammonia (Rosa & Gabrielli, 2023), which is almost exclusively made with unabated fossil fuels today. Roughly 70% of ammonia produced today is for fertiliser and the rest for chemical products. In the APS, the amount of ammonia used globally for shipping and other low-emissions fuels overtakes demand for fertilisers by 2050 (Figure 6.19). Adding fuel as a new source of ammonia demand to the market will, to some extent, push supplies up the supply curve and raise prices. There are valid concerns that if fuel buyers are willing to pay higher prices, some farmers will not be able to afford to buy all the fertiliser they need, especially in developing economies. However, this outcome depends on several conditions: that fuel purchasers are willing to pay higher prices, that ammonia is a single and integrated market; that switching to alternative fuels and fertilisers is unattractive; and that innovation cannot act quickly to bring costs back down.

Figure 6.19 Ammonia demand by use and region in the Announced Pledges Scenario, 2023-2050



IEA. CC BY 4.0.

Note: Existing uses includes fertilisers, explosives, plastics, textiles, pharmaceuticals and dyes.

The issue is reminiscent of the so-called food versus fuels debate that has helped shape biofuels policy over the past two decades. Numerous studies have looked at the impact of growing biofuels production on food availability, food prices and food security, with mixed findings. Some have found that biofuels expansion may have lowered food prices in some cases. To-date there is no body of evidence showing a strong causal relationship between biofuel production and food price increases (Janda & Kristoufek, 2019; Taheripour, Baumes, & Tyner, 2022; IEA Bioenergy, 2023).

There are some important differences between the case of biofuels and that of ammonia. Firstly, ammonia is an input to food production and is not itself food. There is evidence that nitrogen fertilisers are applied with low nutrient use efficiency in certain places today and there are ways to improve this without reducing food output. Governments can co-operate to improve the efficiency of ammonia use in food production, which will also have other environmental benefits. Secondly, it is possible to segregate the fuel and food markets for ammonia by applying stricter emissions intensity standards to ammonia production for fuel in the early stages of the low-emissions fuel market. In cases where low-emissions ammonia can be produced more cheaply than by traditional methods, which should represent more locations over time, fertiliser costs should fall too.

Experience with biofuels policy has shown that policy interventions can play an important role in mitigating food security concerns, especially where low-emissions fuels are blended. Governments can build in safety valves that allow for changes to fuel blending requirements (or encourage substitution between ammonia, biofuels and methanol) if there are food or price concerns, something that is built into India's Biofuel Policy (MOPNG, 2022). Governments can help to diversify feedstocks, which could mean supporting alternative fertilisers in the case of ammonia. The UN Food and Agriculture Organization (FAO) and IRENA recommend integrated food and energy planning to maximise the benefits of bioenergy for food security while mitigating negative outcomes (IRENA, FAO, 2021).

The possible effects of increased ammonia demand require careful consideration and tracking. If the downside risks are considered manageable with prudent policy, there remains a need to communicate the evidence to avoid the issue slowing the decarbonisation of shipping.

Data

Better public and private decisions will result from more transparent and equal access to up-to-date information, which will support faster, more orderly energy transitions. Over many years, the international community has developed standards and processes for collecting and tracking energy data. Global, coherent and detailed information about energy production, transformation, consumption and prices has facilitated a common understanding of how the energy system is evolving and has enabled early identification of potential weaknesses and imbalances. Without high-quality energy systems data shared by governments and aggregated by organisations such as the IEA, it would not be possible to accurately estimate energy-related GHG emissions or calibrate effective responses to energy security risks.

Robust energy policy-making must now take account of manufacturing and trade considerations. This includes monitoring the risks outlined in this chapter so that each country can forge a sustainable balance between security and resilience, affordability and inclusivity. However, the research carried out for this report has highlighted several important limitations to the data currently available for monitoring progress in addressing these risks. Issues relating to limited data availability are especially acute in many EMDEs, which struggle to identify their comparative advantages and obstacles to investment as a result.

In addition, today's weaknesses in data availability make some key markets opaque and less efficient, as they undermine sound decision-making by governments and companies. It is not in any country's interest to make important strategic decisions about taxes, fiscal spending, trade restrictions, regulatory stringency and international partnerships for clean technology manufacturing with partial knowledge and high uncertainty. There is a significant opportunity for the international community – including producers, importers and exporters – to unite around the standardisation, collection and sharing of data in the following areas:

- International classifications have not kept pace with the emergence of new clean technology sectors, hindering reliable tracking of metrics such as trade, investment and value added. Without these data it is nearly impossible to undertake consistent analyses of progress or assess the costs and benefits of policies. In the case of trade data, notable examples include the inability to separate trade in solar PV modules from that in other semiconductor devices, wind towers from communications masts, low-emissions methanol from fossil fuel-based methanol, or electrolysers from electroplating devices for printed circuits. For economic activity data, examples include the inability to separate the manufacture of heat pumps from that of air conditioners and other equipment, battery components from other electrical equipment, or wind nacelles from other motors and generators. Even if these issues are resolved, official customs data is reported in monetary or mass terms, rather than energy capacity, which is more informative for market tracking.
- Employment and skills data for clean energy and related manufacturing are scarce, which makes it hard for companies to identify the relative costs and risks of investing in different regions, and for policy makers to more identify where jobs are at risk, where training could have the biggest impact and with which countries strategic partnerships could be forged.
- Governments in many countries lack information about the full landscape of companies or skills in a sector, including on relevant intellectual property that is owned by entities within the country and the implications if it changed hands during a merger or acquisition. Mapping exercises can be undertaken to improve baseline data and monitor changes.
- Data on the life-cycle emissions intensity of traded goods are often inconsistent, if available at all. There has been considerable progress with traceability standards in some areas but differences in scope and methodology persist. This can become problematic when combining traded inputs from different sources in the production of a material that needs to be certified according to a specific protocol. These data gaps need to be addressed swiftly in each clean technology sector.
- There is a lack of transparency about prices, costs (including costs of capital) and contract terms, considering different grades or qualities of products like near-zero emissions steel or types of heat pumps. This makes it hard to determine the appropriate form and level of policy interventions and adjust them based on policy performance over time. Data on the level of public support are also often opaque. While it is usual for there to be limited data about costs in nascent industries, and private competitive advantage is to be respected, governments have an obligation

to collect and share more information about projects funded by taxpayers. Partnerships between the relatively small number of governments and multilateral banks engaged in funding many projects – such as the European Commission, the European Investment Bank, the Inter-American Development Bank, the World Bank and the governments of Germany and Japan – are well-placed to create such a platform and agree common data points.

- As with economic data, improved availability of information about technology performance, especially from taxpayer-funded R&D projects, offers a significant opportunity to improve decision-making.

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Annex A – IEA's Manufacturing and Trade model

Methodology

IEA's Manufacturing and Trade (MaT) Model was developed for the current edition of Energy Technology Perspectives (ETP) as a framework for projecting different metrics related to manufacturing and trade for six key clean energy technologies – electric cars, batteries, solar photovoltaics (PV), wind turbines, heat pumps and electrolysers. The modelling scope also includes the manufacturing and trade of the main components of these technologies, alongside three relevant materials – steel, aluminium and ammonia (both for industrial and fuel-related applications) – with a focus on near-zero emissions manufacturing processes. For each of the aforementioned technologies or materials, these metrics include capacity and production (both in physical units, such as GW, GWh or million tonnes, and monetary value), investments, energy consumption and CO_2 emissions associated with manufacturing, as well as bilateral trade flows (both in physical units and monetary value) per year.

Scope

For the purposes of *ETP-2024*, the following boundaries are considered in the modelling and analysis for clean energy technologies and components within each manufacturing supply chain in scope:

Batteries include the battery cells and any individual parts that are used to compose a battery cell. The cathodes and anodes are modelled explicitly, but not the electrolyte, separator, or any battery metals from upstream processes (even though they are considered when assessing material costs within production cost calculations, using global averages). If not stated otherwise, cathode and anode refer to their respective active materials.

Electric cars include battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) that belong to the passenger light-duty vehicles category such as cars and pick-up trucks.

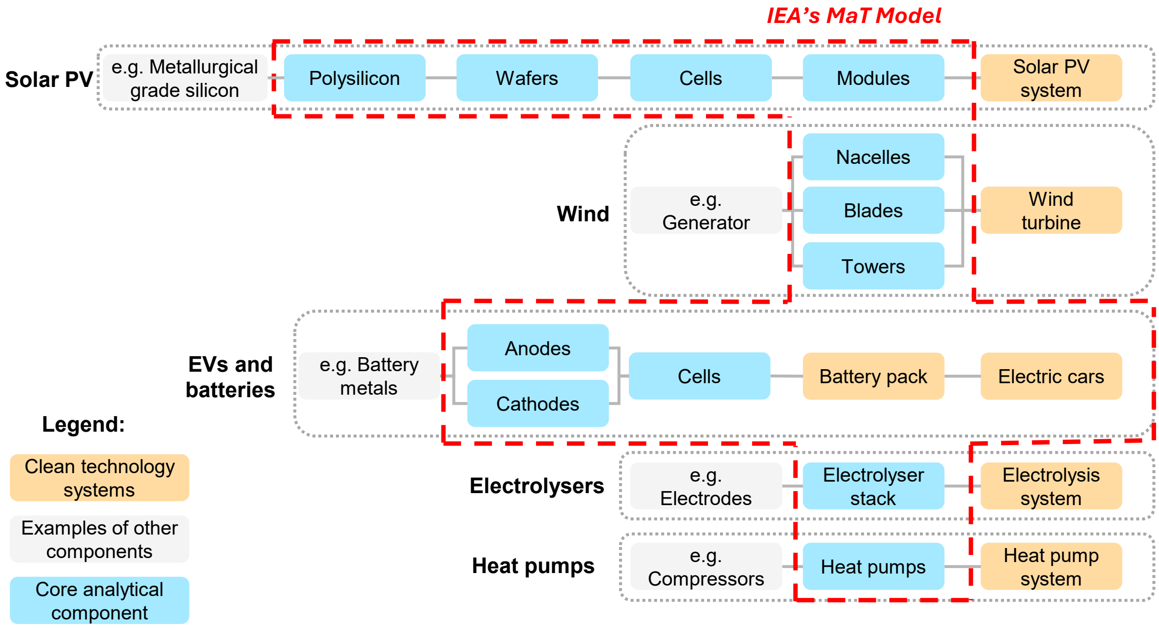
Solar PV includes the solar modules, solar cells, wafers and polysilicon, where all values are expressed in direct current (DC) terms. It does not include elements such as backsheets, encapsulants or any balance of system components, like inverters and racking. Metallurgical-grade silicon is out of scope, although considered as part of the production costs.

Wind includes wind nacelles, blades and towers. Manufacturing for nacelles includes only assembly and not the manufacturing of the downstream components such as the drive train and generator. Other wind components such as the foundation, yaw bearing, hub and power cables are not accounted for in the prementioned analysis but are assumed to be inputs to the production process. References to wind energy installation costs or turbine pricing by manufacturers include these products.

Electrolysers include all major electrolyser technologies (including alkaline, proton exchange membrane, solid oxide electrolysis and others) when displayed in manufacturing capacity and output figures. Only the final assembly step is considered for capacity. Any upstream components, such as electrodes, are outside the scope of capacity, output and trade considered here. For production cost, only the stack manufacturing is considered.

Heat pumps include in this analysis only heat pumps that deliver heat directly to residential and commercial buildings for space heating and/or hot water provision, whereas industrial heat pumps are excluded. It includes natural source heat pumps, including reversible air conditioners used as primary heating equipment. It excludes reversible air conditioners used only for cooling, or used as a complement to other heating equipment, such as a boiler. Any upstream components such as compressors are outside considerations for capacity, output and trade.

Figure A.1 Scope for clean energy technologies in IEA's MaT Model



IEA. CC BY 4.0.

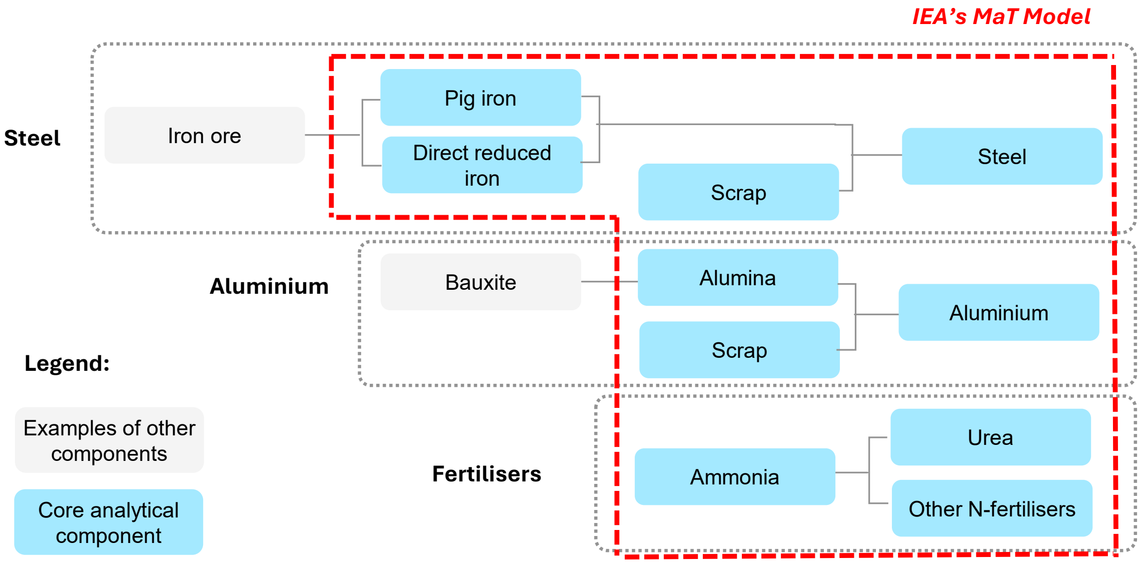
For the purposes of *ETP-2024*, the following boundaries are considered in the modelling and analysis for materials within each manufacturing supply chain in scope:

Iron and steel: Iron (pig iron and direct reduced iron), steel and steel scrap are considered. Steel production refers to crude steel. Steel trade refers to trade in ingots as well as in flat, long and tubular products (Harmonized System [HS] codes 7206 to 7307). Iron ore is outside the modelling boundary, although it is considered as a cost component in ironmaking.

Aluminium: Alumina, aluminium and aluminium scrap are considered. Aluminium trade refers to ingots and semifinished products (HS codes 7601 and 7603 to 7609). Only metallurgical alumina is modelled in the MaT Model. Bauxite is outside the modelling boundary, although it is considered as a cost component in alumina refining.

Ammonia and fertilisers: Ammonia, urea and other nitrogenous fertilisers are included. Other nitrogenous fertilisers include ammonium nitrate, calcium ammonium nitrate, urea ammonium nitrate and ammonium sulphate. Non-fertiliser applications of the products listed above are also considered within the scope (fuel and industrial applications for ammonia and industrial applications for fertilisers).

Figure A.2 Scope for materials in IEA's MaT Model



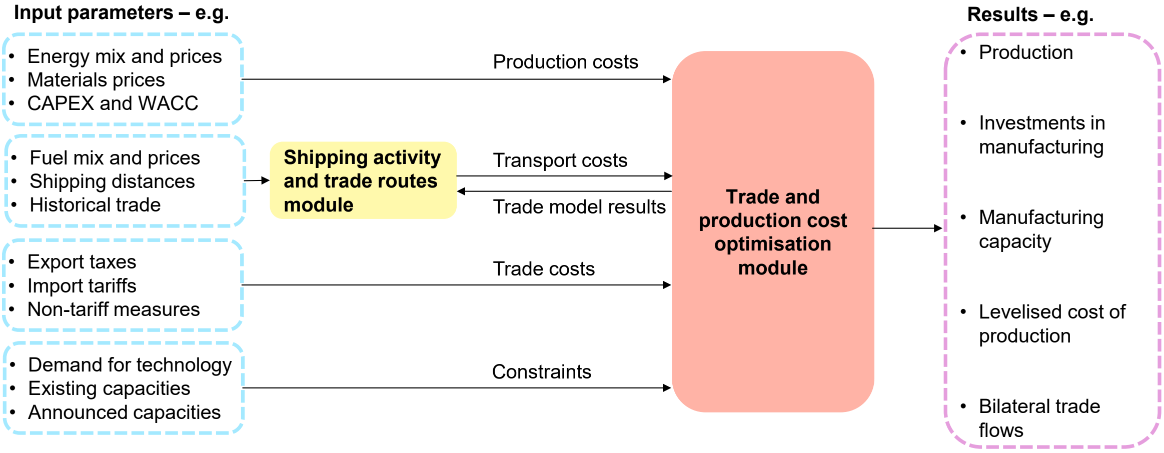
IEA. CC BY 4.0.

Note: Other N fertilisers = other nitrogenous fertilisers.

Framework description

The modelling framework is based on a least-cost bottom-up multiregional myopic optimisation approach, and consists of a set of models adapted to each clean technology, component and material production step, that are solved sequentially for 1-year periods. The modelling horizon spans from 2023 (base year) to 2050 with annual time steps. The model determines for given regional demands for clean energy technologies and materials the cost-optimal strategies for covering these regional demands with domestic manufacturing or imports from other model regions. Domestic manufacturing is influenced by domestic manufacturing capacity, which is also determined by existing and announced manufacturing capacities (see Table A.1). The modelling framework is informed by production costs, coming from the levelised cost of production (LCOP)[1] module, and trade costs, coming from the shipping activity and trade routes module, as well as by detailed regional information on industrial and trade policies (see section Industrial strategies and policy packages) and an assessment of current enabling conditions for manufacturing investments in emerging markets. Demand for clean energy technologies and materials produced and traded in the different scenarios is introduced exogenously to the MaT Model and taken from the outputs of the Global Energy and Climate (GEC) Model (IEA, 2024b).

Figure A.3 IEA's MaT Model schematic



IEA. CC BY 4.0.

Notes: CAPEX = capital expenditure; WACC = weighted average cost of capital. Inputs and results shown are non-exhaustive.

The objective function seeks to minimise the total global costs related to regional production and bilateral trade of clean energy technologies and materials, subject to constraints (see section Constraints) for the production taking place in each region *r* and trade between and trade between exporter *exp* and importer *imp* regions for each year *y*. The objective function includes the production costs for

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[1] As a convention, the acronym LCOP is used across the board even when referring to the levelised cost of manufacturing for clean energy technologies and materials. Similarly, 'production costs' also refer to the manufacturing costs of the technologies.

manufacturing clean energy technologies and materials, the transport costs for shipping them between model regions, and trade costs, reflecting costs incurred by trade policy measures and regulations:

$$Obj\colon min\ f(var\_production_{r,y}, var\_capacity_{r,y},\ \ var\_trade_{exp,imp,y}) = Production\_costs_y + Transport\_costs_y + Trade\_costs_y$$

Sets and indices

r: region ∊ modelling regions

exp: export region ∊ modelling regions

imp: import region ∊ modelling regions

y: year ∊ years within time horizon

m: material ∊ materials as input to the manufacturing process

f: fuel ∊ fuels used in the manufacturing process

Decision variables

$var\_production_{r,y}$:	production in region *r* and year *y*
$var\_capacity_{r,y}$:	manufacturing capacity in region *r* and year *y*
$var\_newcapacity_{r,y}$:	manufacturing capacity addition in region *r* and year *y*
$var\_trade_{exp,imp,y}$:	bilateral trade flow from region *exp* to region *imp* in year *y*

Inputs

Demand by clean energy technology and material

Demand for each of the finished technology products (the final step of a given manufacturing supply chain) is defined based on the results of the IEA's GEC Model per modelling scenario, while demand for intermediate technology components is determined by the MaT Model based on the production centres for the downstream steps in the manufacturing supply chain. For example, the model determines the location of manufacturing centres for electric cars, which influences the demand for battery cells in each region. Demand for materials is determined based on a set of macroeconomic drivers, including population and the value added of relevant economic subsectors, and integrates the impact of material efficiency measures derived from the GEC Model (IEA, 2024b). Unless explicitly mentioned, no stock changes have been considered as part of the demand.

Batteries: The demand for batteries is the sum of battery demands in each segment considered. The main source of battery demand is electric cars (over 70% of global demand for all years and scenarios considered), for which BEV production is modelled explicitly in the MaT Model and PHEV production considers 2023 trade patterns and BEV results (see “Electric cars: plug-in hybrid electric vehicles” in the Additional technical details section). For other non-passenger light-duty vehicle EVs (light commercial vehicles, trucks, buses), the 2023 import share and trade patterns are assumed to remain constant (regional sales from GEC 2024 model results). For electric two- and three-wheelers (2/3Ws), all demand is assumed to be supplied by local production without any trade. This assumption holds for the major markets such as China, India and Southeast Asia, together accounting for over 75% of global demand for all years and scenarios considered. For other markets, the electric 2/3Ws are a minor source of battery demand. The stationary storage battery demand is also taken into account and corresponds to the capacity additions (installations) per region per year.

Electric cars: The demand for electric cars aligns with regional new electric car sales for the same year.

Solar PV: The demand per modelling region for solar PV modules in each year corresponds to the average annual PV capacity additions between that same year and the following one, as a way to simulate time spent in stocks between production and use. The demand per modelling region for the immediate upstream component, solar PV cells, corresponds to the production of solar modules in the region within the same year. Similarly, the demand for wafers corresponds to the production of solar cells, and the demand for polysilicon to the production of wafers in the modelling region.

Wind: The demand per modelling region for any given year for all the wind components – nacelles, blades and towers – corresponds to the average annual wind capacity additions (i.e. installations) between the same year and the following one. This as a way to compensate for the fact that construction of a wind farm can take place over several years.

Electrolysers: Demand for electrolysers corresponds to electrolysis plant installations in the same year.

Heat pumps: Demand for heat pumps corresponds to heat pump sales and installations in the same year measured in GW, and not individual units.

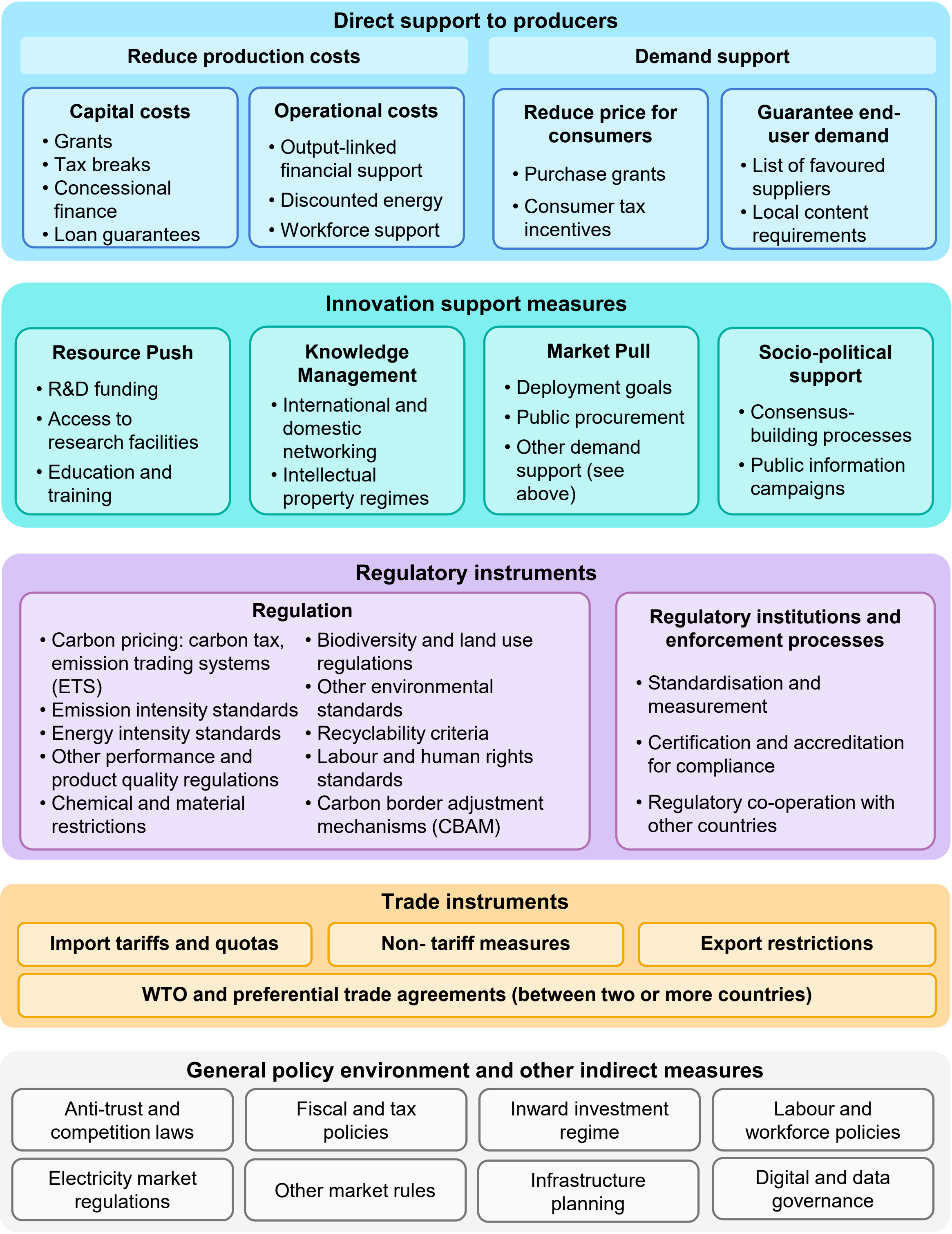
Materials: The demand for steel and aluminium corresponds to the demand for semi-finished steel and aluminium, measured in Mt. The demand for fertilisers is a composite of demand for different fertiliser types (see Scope section above) to allow for production and trade to be modelled. Ammonia demand for existing applications is partially endogenously determined by where fertilisers are produced, and partially exogenously determined when used for other industrial applications. Ammonia demand for fuel applications corresponds to ammonia use for shipping, power and as a hydrogen carrier in the GEC Model.

The projected demand share of near-zero emissions materials (compared to conventionally produced materials) at a global level comes from the projections of production technology shares modelled in the GEC Model. Ammonia for fuel applications is assumed to be only near-zero emissions (as it is in the GEC Model).

Industrial strategies and policies

A wide range of policies can affect industrial manufacturing, often guided by overarching industrial strategies. The figure below illustrates the main policy instruments that could potentially affect the manufacturing of clean energy technologies and materials. Some of these direct measures are explicitly modelled, such as import tariffs, export restrictions, non-tariff measures and production-linked financial support (if part of an announced policy programme). However, other measures, such as ad hoc incentives granted on a project-by-project basis, innovation policies with long-term effects and horizontal policies with indirect effects on the wider economy, are not modelled with exogenous parameters, but are considered part of the enabling conditions (e.g. the possibility to increase the manufacturing capacity). This is because their direct impact on industrial manufacturing is difficult to quantify.

Figure A.4 Industrial strategy policy instruments



Direct support to producers

Reduce production costs

Capital costs
- Grants
- Tax breaks
- Concessional finance
- Loan guarantees

Operational costs
- Output-linked financial support
- Discounted energy
- Workforce support

Demand support

Reduce price for consumers
- Purchase grants
- Consumer tax incentives

Guarantee end-user demand
- List of favoured suppliers
- Local content requirements

Innovation support measures

Resource Push
- R&D funding
- Access to research facilities
- Education and training

Knowledge Management
- International and domestic networking
- Intellectual property regimes

Market Pull
- Deployment goals
- Public procurement
- Other demand support (see above)

Socio-political support
- Consensus-building processes
- Public information campaigns

Regulatory instruments

Regulation
- Carbon pricing: carbon tax, emission trading systems (ETS)
- Emission intensity standards
- Energy intensity standards
- Other performance and product quality regulations
- Chemical and material restrictions
- Biodiversity and land use regulations
- Other environmental standards
- Recyclability criteria
- Labour and human rights standards
- Carbon border adjustment mechanisms (CBAM)

Regulatory institutions and enforcement processes
- Standardisation and measurement
- Certification and accreditation for compliance
- Regulatory co-operation with other countries

Trade instruments

Import tariffs and quotas

Non- tariff measures

Export restrictions

WTO and preferential trade agreements (between two or more countries)

General policy environment and other indirect measures

Anti-trust and competition laws

Fiscal and tax policies

Inward investment regime

Labour and workforce policies

Electricity market regulations

Other market rules

Infrastructure planning

Digital and data governance

IEA. CC BY 4.0.

Note: WTO = World Trade Organization.

Trade databases

Ad valorem and specific tariffs per region and HS codes are taken from (WTO, 2024a), using applied tariff rates at six-digit HS code level for 2023. These tariffs are aggregated by modelling region and clean energy technology or material using the following methodology:

- Aggregation of countries into regions: Where a modelling region includes more than one country, the tariffs of each country are aggregated to a single tariff for the entire modelling region.
- Aggregation of HS codes into products: Multiple line tariffs at the six-digit HS code level are aggregated into a single clean energy technology or material.
- Weighted average calculation: Aggregation is performed using a weighted average approach, with weights based on actual trade flows (in economic terms) between countries and at the six-digit HS code level. The trade flow data used for weighting are taken from (CEPII, 2024) for the year 2022, as 2023 data were not yet available.
- Special, temporary and newly announced tariffs: Special tariffs, such as the Section 301 tariffs applied by the United States to imports of certain products from China, and temporary tariffs or exemptions are added to the tariff database on a rolling basis. These tariffs are applied according to their scheduled start and end dates when this information is published. As the WTO data reflect applied tariffs in 2023, updated tariffs during 2024 are also included in our tariff database and become applied tariffs from their implementation dates.

Export restrictions impacting any of the products modelled are taken from the OECD Inventory on Export Restrictions on Industrial Raw Materials (2024a).

IEA’s MaT Model uses ad valorem equivalents (AVEs) to quantify non-tariff measures (NTMs). The AVE of an NTM represents the equivalent uniform tariff that would produce the same trade effect as the NTM, capturing the additional costs that NTMs impose on imports. The estimation of AVEs in the ETP-2024 is based on Kravchenko, Strutt, Utoktham, & Duval (2022).

The study by Kravchenko et al. estimates the AVEs of NTMs using a price-based approach at the six-digit HS code level. AVEs are derived as the percentage increase in import prices attributable to NTMs, calculated by comparing price differences between markets with and without these measures. The study uses data on bilateral import flows, which serve as a proxy for import prices and are obtained by dividing trade values by volumes, from the World Bank's World Integrated Trade Solution (WITS) platform for 2015. NTM data are taken from the United Nations Conference on Trade and Development (UNCTAD) TRAINS database, using records closest to 2015. In their modelling process, the six-digit

HS-level AVEs are transformed into Global Trade Analysis Project (GTAP) sectors.

These NTM AVEs are then aggregated by modelling region and clean energy technology or product through the following process:

- Aggregation into modelling regions: Country-specific AVEs are aggregated into five modelling regions: Advanced Economies, China, India, Other Emerging Economies and Least Developed Countries. Least Developed Countries are those listed by the United Nations (UN, 2024).
- Assignment to GTAP sectors: Each clean energy technology or product is assigned to one or more GTAP sectors.
- Weighted averaging: Aggregation is done using a weighted average approach, with weights based on actual trade flows (CEPII, 2024).

It should be noted that the study by Kravchenko et al. considers bilateral flows and classifies NTMs into technical and non-technical types, but excludes zero-trade flows, potentially missing prohibitive NTMs. It also relies on aggregate NTM counts without isolating individual effects. The 2015 data used to estimate the AVEs of NTMs should be considered as a proxy, given the significant increase in clean technology trade volumes and the evolving nature of regulatory frameworks since then.

Industrial strategies and policy packages

A list of main policies included in the report are available in Tables 2.1, 3.1 (United States), 3.3 (European Union), 3.5 (China) and 3.6 (India). Additional industrial strategies and policy packages in other emerging markets and developing economies (EMDEs) are also shown in the Table A.1 below. These strategies and policy packages have an impact on the greater diversification of supply in the NZE Scenario.

Table A.1 Industrial strategies and policy packages targeting clean energy technologies or materials manufacturing in EMDEs other than China and India

Country	Key Policies
Brazil	Support from the National Bank for Economic and Social Development (BNDES); New Industry Brazil (*Nova Indústria Brasil*); and MOVER (Green Mobility and Innovation Program)
Chile	Electromobility Strategy Hydrogen Strategy, CORFO's call to establish electrolyser manufacturing in the country
Colombia	High-level document on Re-industrialisation Policy (*Política de Reindustrialización*), including a priority line on the energy transition

Country	Key Policies
Egypt	National Automotive Industry Development Program
Indonesia	Export restrictions on raw materials that can be used for batteries in the EV supply chain
Kazakhstan	Third Modernization of Kazakhstan: Global Competitiveness
Kenya	4th medium term plan programme and projects (2023-2027)
Malaysia	New Industrial Master Plan 2030
Morocco	Integrated Wind Energy Plan for Morocco (PMIEE); Financial incentives for battery manufacturers
Nigeria	Nigeria Energy Transition Plan
Saudi Arabia	Vision 2030
South Africa	Just Energy Transition Plan; South African Renewable Energy Masterplan (SAREM)

Note: Financial support policies for energy inputs are not included in this table.

Cost data

The cost data used as inputs for the MaT Model can be separated into production costs, transport costs and trade costs associated with the domestic production or import of a clean energy technology or a material.

Production costs

These come from the levelised cost of production (LCOP) module, which is used to estimate the annualised CAPEX ($annualised\_CAPEX_{r,y}$), the fixed OPEX ($fixed\_OPEX_{r,y}$) and variable OPEX ($variable\_OPEX_{r,y}$) costs per unit of output over the lifetime of a production asset for the clean energy technologies and materials featured in *ETP-2024*. It accounts for all the costs associated with producing a product and is used to assess the competitiveness of outputs produced within a specific region. In the case of materials, different cost components have been considered for conventional and near-zero emissions production.

Annualised CAPEX: This refers to the costs an organisation bears in acquiring, upgrading, or maintaining physical assets of a manufacturing facility, and is typically a one-time, upfront investment. It is calculated by taking into account the overnight value of the CAPEX ($overnight\_CAPEX_{r,y}$) minus the financial support ($CAPEX\_FinSupport_{r,y}$) available to manufacturing investors per region and year, and annualised using the capital recovery factor ($CRF_{r,y}$). The CRF is calculated based on the weighted average cost of capital ($WACC_{r,y}$) for each modelling region and by assuming a useful economic lifetime for each clean technology or material.

$$annualised\_CAPEX_{r,y} = \left(overnight\_CAPEX_{r,y} - CAPEX\_FinSupport_{r,y}\right) * CRF_{r,y}$$

$$CRF_{r,y} = \frac{WACC_{r,y}}{1-(1+WACC_{r,y})^{-Lifetime}}$$

Fixed OPEX: This refers to the ongoing, regular costs required to operate a manufacturing facility that do not vary with the level of output and therefore remain constant regardless of the operational activity level. Annual fixed operational expenditure is assumed to be proportional to the overnight capital expenditure at a ratio ($fixed\_OPEX\_ratio_{r,y}$) for each region *r* and year *y*.

$$fixed\_OPEX_{r,y} = overnight\_CAPEX_{r,y} * fixed\_OPEX\_ratio_{r,y}$$

Variable OPEX: This refers to the operational costs that vary proportionally to the level of output of a facility, such as material inputs ($material\_costs_{r,y}$), energy consumption costs ($energy\_costs_{r,y}$), and emissions costs ($emissions\_costs_{r,y}$). For manufacturing of clean energy technologies, variable OPEX also include labour costs ($labour\_costs_{r,y}$), while for material manufacturing labour costs are accounted as fixed OPEX. For this calculation, any grouped other OPEX costs ($other\_OPEX_{r,y}$) have been included in the variable OPEX for clean energy technologies, as well as any costs stemming from the use of upstream components ($components\_costs_{r,y}$), where applicable, that are inputs of another product within the MaT Model, such as the solar PV cells which are inputs for the production of solar PV modules, or the cathode active material for the production of battery cells. The total variable OPEX is reduced by the amount of output-linked financial support available for a product in each region *r* and year *y* ($OPEX\_FinSupport_{r,y}$).

[2] $$variable\_OPEX_{r,y} = material\_costs_{r,y} + energy\_costs_{r,y} + emissions\_costs_{r,y} + components\_costs_{r,y} + labour\_costs_{r,y} + other\_OPEX_{r,y} - OPEX\_FinSupport_{r,y}$$

The material, energy and emissions costs are calculated based on the energy[3] and emissions prices ($energy\_prices_{r,y,f}, CO2\_prices_{r,y}$), the material ($material\_intensity_{r,y,m}$), energy ($energy\_intensity_{r,y,f}$), and emissions intensities, ($emission\_intensity_{r,y,f}$) and the process emissions ($process\_emissions_{r,y}$). These come from IEA's GEC Model (IEA, 2024b),

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[2] The expression presents the comprehensive list of elements taken into account; however, depending on the clean technology component or material, certain terms might be accounted for elsewhere, such as components costs for clean technologies without upstream components in scope or labour costs for materials.

[3] The energy prices correspond to the average national prices for industrial consumers and do not capture any sub-national prices (e.g. province level for China), individual contracts between large consumers and producers or effective costs for auto-producers.

complemented by additional research. The exact formulas are as follows for each region *r*, year *y* and material *m* or energy input *f*.

$$material\_costs_{r,y} = \sum_{m} material\_intensity_{r,y,m} * materials\_prices_{r,y,m}$$

$$energy\_costs_{r,y} = \sum_{f} energy\_intensity_{r,y,f} * energy\_prices_{r,y,\mathrm{f}}$$

$$\begin{aligned} CO2\_costs_{r,y} = (&process_{emissions_{r,y}} \\ &+ \sum_{f} energy\_intensity_{r,y,f} * emission_{intensity_{r,y,f}}) \\ &* CO2\_prices_{r,y} \end{aligned}$$

For material prices, Bloomberg data are used for historical values (BNEF, 2024a), whereas price signals are projected forward using different methods for bulk materials and critical minerals:

For bulk materials, demand and LCOP projections from the GEC Model $(bulk\_materials\_demand_y, bulk\_materials\_LCOP_y)$ are used to generate price signal projections $(bulk\_materials\_prices_y)$ specific to each scenario, based on the multi-linear regression between historical prices, demand and LCOP.

$$\begin{aligned} &bulk\_materials\_prices_y \\ &\quad = \beta 0 + bulk\_materials\_demand_y * \beta 1 + \ bulk\_materials\_LCOP_y * \beta 2 \end{aligned}$$

For critical minerals, historical prices and changes in annual demand are compared to get the elasticity $(elasticity)$. This ratio is then applied to critical mineral demand projection $(critical\_minerals\_demand_y)$ from the GEC Model to generate price signal projections $(critical\_mineral\_price_y)$.

$$\begin{aligned} &critical\_mineral\_price_{y+1} \\ &\quad = \left(\left(\frac{1}{elasticity} \right.\right. \\ &\quad \left.\left. * \frac{critical\_minerals\_demand_{y+1} - critical\_minerals\_demand_y}{critical\_minerals\_demand_y}\right) + 1\right) \\ &\quad * critical\_mineral\_price_y \end{aligned}$$

The costs of upstream components that are used as inputs in multi-step supply chains are estimated by considering their respective LCOP increased by a profit margin and based on the composition of their origins, where for imported ones the eventual trade and transport costs are also added.

Overall production costs are expressed as in the equation below:

$$Production\_costs_y = \sum_r ((annualised\_CAPEX_{r,y} + fixed\_OPEX_{r,y}) * var\_capacity_{r,y} + variable\_OPEX_{r,y} * var\_production_{r,y})$$

Transport costs

These refer to the cost of transporting a given commodity between modelled countries and regions and include freight and insurance costs. The shipping costs ($shipping\_costs_{exp,imp,y}$) are linked to the shipping model embedded in the IEA's GEC Model (IEA, 2024b), which projects energy demand by fuel for international and domestic shipping operations by vessel type and scenario. Costs coming from other means of transport are considered to be growing or decreasing proportionally to shipping. Insurance costs are expressed as a percentage ($insurance_y$) of the value of the exported product ($export\_price_{exp,imp,y}$), that varies across clean technologies and materials. Overall transport costs are expressed as in the equation below:

$$Transport\_costs_y = \sum_{exp}\sum_{imp}((shipping\_costs_{exp,imp,y} + export\_price_{exp,imp,y} * insurance_y) * var\_trade_{exp,imp,y})$$

Trade costs

The trade costs are all the costs incurred when bringing a product from a country to another country. These costs include, among others, direct duties, such as export taxes, import tariffs or the impact of carbon border adjustment mechanisms (CBAM), and some indirect costs, such as NTMs, whose quantification is based on AVEs (see previous section).

To calculate the domestic price of a product in the country where it is manufactured ($domestic\_production\_price_{r,y}$) an assumed profit margin ($profit\_margin_y$) is added to its production cost ($LCOP_{r,y}$):

$$domestic\_production\_price_{r,y} = LCOP_{r,y} * (1 + profit\_margin_y)$$

The export cost of a product ($export\_cost_{exp,imp,y}$) considers the costs incurred by potential ad valorem ($exptax\_advalorem_{exp,imp,y}$) and specific taxes ($exptax\_specific_{exp,imp,y}$):

$$export\_cost_{exp,imp,y} = domestic\_production\_price_{exp,y} * exptax\_advalorem_{exp,imp,y} + exptax\_specific_{exp,imp,y}$$

$$export\_price_{exp,imp,y} = domestic\_production\_price_{exp,y} + export\_cost_{exp,imp,y}$$

The import cost of a product ($import\_cost_{exp,imp,y}$) considers the costs incurred by ad valorem ($tariffs\_advalorem_{exp,imp,y}$) and specific tariffs ($tariffs\_specific_{exp,imp,y}$), as well as the estimated impact on costs of NTMs using AVEs ($ntm\_ave_{exp,imp,y}$).

$$import\_cost_{exp,imp,y} = \left[export\_price_{exp,imp,y} * (1 + insurance_y) + shipping\_cost_{exp,imp,y}\right] * (tariffs\_advalorem_{exp,imp,y} + ntm\_ave_{exp,imp,y}) + tariffs\_specific_{exp,imp,y}$$

Overall trade costs are expressed as in the equation below:

$$Trade\_costs_y = \sum_{exp}\sum_{imp}\left[(import\_cost_{exp,imp,y} + export\_cost_{exp,imp,y} + CBAM\_cost_{exp,imp,y}) * var\_trade_{exp,imp,y}\right]$$

Other inputs

Existing manufacturing capacity

Information on existing manufacturing capacity for clean energy technologies and materials related to 2023 is based on various data sources (see Data sources) and is aggregated by model region. If no information on the remaining lifetime of existing manufacturing plants was available, it was assumed that the existing capacity linearly declines to zero over a period that is equal to their lifetime. Capacity represents the amount a facility is nominally able to produce, i.e. not taking into account utilisation rates, and is measured in the physical units.

Announced manufacturing capacity

Announced manufacturing capacity by companies for the production of clean energy technologies or materials includes both new facilities and capacity expansions of already existing plants. Announced manufacturing capacity is based on various data sources, including external data providers (see Data sources section) and on desk research. Like existing manufacturing capacity, announced capacity represents the amount a facility would nominally be able to produce in 1 year and is measured in physical units. Announcements on increased manufacturing capacity are categorised by committed (i.e. those under construction or that have reached final investment decision) and preliminary announcements (i.e. those that have not reached final investment decision). Unless otherwise stated, the announced projects dataset assembled for *ETP-2024* comprises announcements dated up to end of June 2024.

Announced capacity data is used as a model input to inform capacity developments up to the year 2030. In the Stated Policies Scenario (STEPS), committed announced capacity is assumed to be built for clean energy technologies and any near-zero emissions capable facilities for materials. Preliminary announced capacity is considered in the Announced Pledges Scenario (APS), on top of committed announced capacity (see Constraints section).

To derive forward-looking benchmark quantities of output from existing and announced projects such that a comparison can be made with deployment levels in IEA scenarios (see Chapter 2), utilisation rates of 85% are applied as an assumption.

Results

The IEA's MaT Model determines based on global least-cost optimisation the manufacturing locations and trade patterns within a set of constraints for each year in the modelling horizon 2023-2050, for different scenarios, and produces the following results:

Manufacturing results

- **Production** of each technology component or material per region and production technology for each annual period. This is calculated in the physical units for each product, as well as monetary values based on relevant price projections.
- **Manufacturing capacity** per region and production technology for each year of the model horizon.
- **Investments in manufacturing** which are derived from the capacity expansions per period and the CAPEX for each facility.
- **Energy consumption** and **CO_2 emissions** related to the manufacturing of clean energy technologies and components.[4]

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[4] The respective results for materials come from the GEC Model.

Inter-regional trade results

- **Bilateral trade flows** between pairs of modelling regions.[5] These are calculated in physical units for each product, as well as monetary values based on relevant price projections.

Levelised cost of production

The LCOP values resulting from the respective modules concern the total costs coming from CAPEX, fixed OPEX and variable OPEX. The LCOP annualises and sums up all costs incurred throughout the economic lifetime of the manufacturing facility, using an assumed high but feasible utilisation rate (UR) of 85% for clean energy technology manufacturing. Early retirements of manufacturing capacity and related savings in fixed OPEX are not considered in the model. The LCOP costs ($LCOP_{r,y}$) include the annualised CAPEX ($annualised\_CAPEX_{r,y}$), the fixed OPEX ($fixed\_OPEX_{r,y}$) and the variable OPEX ($variable\_OPEX_{r,y}$) according to the following formula applied per individual product for each region *r* and year *y*:

$$LCOP_{r,y} = \frac{annualised\_CAPEX_{r,y} + fixed\_OPEX_{r,y}}{UR} + variable\_OPEX_{r,y}$$

Other results

- Other outputs which are calculated in the context of the manufacturing and trade modelling include market sizes, which are derived from the demand for a product and its global price.
- LCOP without financial support, which excludes any kind of financial support from the calculations.
- Imported product prices for each importing region depending on the exporting region, which reflect the per-unit costs of production of the exporting region with an additional profit margin, together with the transport costs and trade costs associated with each pair of exporters-importers.

Constraints

A set of constraints are incorporated into IEA's MaT Model to reflect technical and practical considerations. They can be divided into three categories:

Balance constraints: these ensure that fundamental balancing rules are respected, such as supply-demand balances that ensure that domestic production

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[5] The bilateral trade flows are effectively an approximation of net trade flows between the regions, as any backflows do not get estimated.

plus imports and minus exports meets domestic demand. A capacity balance constraint requires that installed capacity in year *y* equals the installed capacity in the previous year *y-1* plus new capacity additions and minus capacity retirements from plants reaching the end of their technical lifetime. Production-capacity balance constraints are also included, ensuring that production cannot exceed the available installed manufacturing capacity, taking into account typical maximum utilisation rates for manufacturing facilities. An example of a demand-supply balance constraint is shown below, valid for each region *r,* and each year *y*, where *imp* and *exp* belong to the full set of regions:

$$var\_production_{r,y} \geq demand_{r,y} + \sum_{imp} var\_trade_{r,imp,y} - \sum_{exp} var\_trade_{exp,r,y}$$

Policy constraints: these allow representation of government policies and regulations such as local content requirements and import quotas, among others. An example of local content requirements is shown below, for each region *r*, and each year *y*, where *imp* belongs to the full set of regions and local requirements ($local\_requirement_{r,y}$) is an exogenous input parameter, describing the share of domestic demand that needs to be covered by domestic production:

$$var\_production_{r,y} - \sum_{imp} var\_trade_{r,imp,y} \geq demand_{r,y} * local\_requirement_{r,y}$$

Calibration constraints: these constraints limit the rate at which production can be ramped up or down and the rate at which bilateral trade flows can change from year to year. This category also includes constraints that take account of a detailed assessment of current enabling conditions for manufacturing investments in emerging markets and that ensure that project announcements for future clean energy technology manufacturing and for near-zero emissions production of materials are reflected in installed manufacturing capacity, as relevant. For example, up to 2030 inclusive, the announced manufacturing capacity ($announced\_projects_{r,y}$) for future clean energy technology manufacturing in each region *r*, and year *y*, which are exogenous inputs as observations based on research, can serve as lower and upper bounds within a relaxed corridor by applying lower ($lower\_bound_{r,y}$) and upper ($upper\_bound_{r,y}$) factors of a few percentage points (e.g. 1-2%) for manufacturing capacity additions ($var\_newcapacity_{r,y}$) which are the change in capacity ($var\_capacity_{r,y}$) between year y and y-1 by considering also the retired capacity on that year ($retirements_{r,y}$):

$$var\_newcapacity_{r,y} \leq announced\_projects_{r,y} * \left(1 + upper\_bound_{r,y}\right)$$

$$announced\_projects_{r,y} * \left(1 - lower\_bound_{r,y}\right) \leq var\_newcapacity_{r,y}$$

$$var\_newcapacity_{r,y} = var\_capacity_{r,y} - var\_capacity_{r,y-1} + retirements_{r,y}$$

For any regions r and years y where the upper (or lower) bound contradicts with the application of policies and/or strategic ambitions depending on the scenario (e.g. 40% of domestic EU production in the Net-Zero Industry Act) or the total global demand coverage, the bound limits have been relaxed, giving priority to policies and the scenario narrative.

Additional technical details

Batteries

Battery manufacturing capacity refers to 2023 and announced lithium-ion battery (cell) manufacturing capacity to 2030. The analysis includes all Tiers (I, II, III), where Tier I is defined as a manufacturer qualified to supply multinational EV producers in China and outside of China, Tier II are not yet qualified to serve EV producers outside of China, and Tier III are producers that are not yet qualified to supply EV markets, but that might be able to serve smaller markets like electric two- and three-wheelers and stationary storage, or be certified to serve the more valuable EV market in the future.

Differences in battery chemistry are not considered explicitly in the modelling and analysis, but different chemistry choices (as the predominant use of lithium iron phosphate [LFP] rather than lithium nickel manganese cobalt oxides [NMC] batteries or vice versa) are considered exogenously during the model calibration based on IEA analysis. The 2023 and projected world capacity-weighted battery chemistry is used to calculate the battery cell and cathode LCOP (e.g. about 40% LFP and 60% nickel-based (NMC and lithium nickel cobalt aluminium oxide [NCA]) chemistries in 2023) (IEA, 2024d).

For the conversion from tonnes to GWh of cathode and anode active materials, a material energy density of around 670 Wh/kg (NMC and NCA cathode active material), 465 Wh/kg (LFP cathode active material) and 1 500 Wh/kg (graphite-silicon blended anode active material) is assumed. A negative (anode) to positive (cathode) electrode ratio of 1.05 is assumed for the final cells, which implies 5% more anode capacity than cathode capacity per cell.

Battery and battery components trade flows in the base year are estimated by combining manufacturing capacity (see Data sources section), data on production of the final product (e.g. of EVs using data from EV Volumes), and the battery cell supplier.

For any upstream components incorporated in the calculation of the LCOP of EVs and battery cells, the origin-dependent prices have been considered based on the shares of domestic production and imports by trade partners.

Electric cars: plug-in hybrid electric vehicles

PHEV car trade is estimated using 2023 trade patterns and BEV MaT Model results. It is assumed that PHEV trade is likely to mirror BEV trade, as the factors that influence the cost-effectiveness of BEV and PHEV manufacturing are generally similar. After 2040, PHEV import shares are assumed to match those of BEVs. As with other vehicle types, PHEV demand is taken from GEC Model demand projections, and this is used in conjunction with the share of imports in regional demand to determine final PHEV trade flows.

Solar PV

Due to the significant amount of stockpiling of modules in 2023 (base year), the amount of PV modules ending up in inventories has been taken into account when modelling historical trade for PV modules. This is reflected in the production volumes and global trade volumes for that year. In the long run, it has been assumed that the global production and demand for installations will be balanced and therefore any results from 2030 onwards do not consider any inventory changes. No inventory changes have been considered for PV cells, wafers and polysilicon.

For PV modules, the base year trade comes from IEA analysis. This takes into account production that has ended up in inventories of the importing countries, as well as inventory increases in the producing country (generally China). The sources for this analysis are InfoLink (2024), BNEF (2024a), SPV Market Research (2024) and UN Comtrade (2024). The same sources have been considered for the trade of PV cells, whereas the analysis of trade of wafers and polysilicon was based primarily on InfoLink (2024) and BNEF (2024a).

The LCOP calculations for PV modules and PV cells assume mono passivated emitter rear cells (PERC) c-Si cells. For any upstream components incorporated in the calculation of modules, cells and wafers, the origin-dependent prices have been considered based on the shares of domestic production and imports by trade partners. The polysilicon prices include the processing of metallurgical-grade silicon, assuming this is domestically produced. When comparing the LCOP of PV modules between regions, this does not refer to start-to-end domestic production of all the components, as it may be more cost competitive to import certain components.

Wind

Trade flows for wind components were modelled without differentiating between onshore and offshore. This is because facilities dedicated to manufacturing wind components can generally serve both sectors. However, regional transport costs, production costs and capital costs for factories (used in investment calculations) were calculated separately for offshore and onshore. To determine the final costs, the global split between offshore and onshore derived from GEC Model results was used (which show a growing share of offshore over time).

Global trade for wind components can be difficult to track, as the components often fall under different sets of HS codes. Furthermore, the many means of transporting them, and the fact that downstream components are frequently shipped in between facilities makes it difficult to acquire official data on this. To estimate the trade situation for 2023 a combination of resources was used. At the basic level, two databases were combined: the manufacturing database (see the Data sources section), and the installation of turbines per original equipment manufacturer (OEM) database. For each OEM, trade was modelled to take place between the regions where final installation took place and the regions where its manufacturing hubs are located. As an initial assumption, these trade links were based on weighted averages of where production and installation take place. However, when more sources were available, as in the case of the United States, which tracks imports of nacelles, blades and towers (Harmonised Tariff Schedule [HTS] codes: 85023100, 8412909081 and 7308200020, respectively), or published articles on shipments of components to wind farms, these initial assumptions were slightly altered. In case of blades, manufacturing capacities were also adjusted, as some OEMs use other companies’ blades.

Electrolysers

The trade flows in the base year are estimated by combining capacity and location of installed and planned electrolyser projects from the IEA Hydrogen Production Projects database (IEA, 2024f), with the location of electrolyser manufacturing facilities based on internal research, taking into account information on electrolyser shipments of manufacturers to specific projects where available.

Heat pumps

Trade flows in the base year are estimated by aggregating trade values of HS codes 841581 (Air conditioning machines; containing a motor driven fan, other than window or wall types, incorporating a refrigerating unit and a valve for reversal of the cooling/heat cycle (reversible heat pumps)) and 841861 (Heat pumps; other than air conditioning machines of heading no. 8415). Trade for these two 6-digit HS codes are estimated using data from Oxford Economics (2024b) available for the parent 4-digit codes and then disaggregating them to 6-digit level codes based on the CEPII/BACI (CEPII, 2024) trade flows for 2022 values within each 4-digit code. The trade flows are weighted based on the relative sales of the different types of equipment, specifically to exclude air-to-air heat pumps not used as primary heating equipment. Future trade flows in the MaT Model are also aggregated and include these two HS categories.

Trade shipping routes modelling

Trade shipping routes modelling was developed to inform shipping activity assessment, shipping energy demand modelling in the GEC Model, the chokepoint analysis (see section 5.2) and to calculate the cost of shipping clean energy technologies, materials and fuels. Shipping costs were also used in the alternative fuel refuelling infrastructure analysis (see section 5.3). Historical trade between countries was estimated using a range of data sources (see “International trade” in the Data sources section). The share of total trade being allocated to maritime shipping was determined using a dataset underlying work by Vershuur et al. (2022) which includes estimates of maritime trade shares between individual countries for specific product groups.

Bilateral seaborne traded quantities were then allocated to individual ports using import and export shares for each port provided by Ports Watch (IMF, 2024). Trade between individual ports was assumed to be proportional to their respective share of a country’s imports and exports.

To model the **distance and specific route between two ports**, given the co-ordinates, the python package “searoute” was used (Halili, 2024), which generates the shortest sea route between two points. It offers the possibility of blocking certain maritime chokepoints; this feature was used to close the Northwest Passage and Sunda Strait on the assumption that they represent only a minor share of trade.

For the **shipping routes** displayed on the world map (see section 5.1) Automatic Identification System (AIS) data have been used (UN Global Platform, 2024), as they reflect a more realistic picture: the load factor was estimated for each ship and each point in time from the reported draught, and then multiplied by the ship deadweight tonnage to estimate the mass of cargo transported. This dataset could not be used for the chokepoint analysis because it does not give precise information on the type of goods transported.

For the **maritime chokepoints analysis**, the coordinates of the route generated between two ports were intersected with a buffer around each chokepoint, and the sum of the trade routes intercepting the defined buffer zone determined the amount of maritime traffic passing through said chokepoint. The results were calibrated against external sources tracking traffic through chokepoints (EIA, 2024).

For the **alternative fuel refuelling infrastructure analysis**, the distance between the supplier ports and the receivers was obtained with the “searoute” package and then multiplied by the transport cost per unit of energy and distance as per Table 5.6.

Shipping activity

Shipping activity was calculated by multiplying the seaborne traded quantities for each port-to-port combination by the distances involved. Base year (2023) estimates were then reconciled with UNCTAD’s shipping work estimate (2023). Trade by commodity was allocated to ship types based on the classification from the International Maritime Organization’s Fourth GHG study (2020).

For projections, it was first necessary to establish the evolution of traded quantities in different scenarios. These quantities were derived using two methods:

1. Products explicitly modelled within the IEA’s GEC and MaT Model: For these products, trade results are differentiated by scenario. Trade was modelled at a regional level and then re-allocated to individual countries based on a combination of historic indicators and macroeconomic indicators from the GEC-Model.
2. Other products: For products that do not fall within our modelling scope, we relied on trade projections from Oxford Economics’ Trade Prism (2024b).

The modal share of maritime trade between individual countries, as well as the share of each port in their country’s imports and exports, was assumed to remain unchanged over time and scenarios. Projected bilateral traded quantities by scenario were then used for projections in the chokepoint analysis, and to determine projected shipping activity.

Data sources

The table below summarises the main external data sources used in this report, which are supplemented by desk research and personal communications with manufacturers, project developers and other technology experts. IEA scenario and modelling data from IEA’s Global Energy and Climate Model (IEA, 2024a) are used in conjunction with the data below for the MaT Model.

Table A.2 Description of the main data sources used in this report

Technology	Data on manufacturing and trade	Data sources	Description
Solar PV	• Existing capacity • Announced capacity • Energy and material intensity • Capital costs • Historic output • Historic component prices • Historical trade	InfoLink (InfoLink, 2024), BNEF (BNEF, 2024a), IEA PVPS (IEA PVPS, 2024), SPV Market Research (SPV Market Research, 2024), RTS Corporation (RTS Corporation, 2024), NREL (NREL, 2023), (UN Comtrade, 2024)	InfoLink data is the primary source for capacity and output data, supplemented by BNEF and SPV Market Research for cross-checking and details for certain regions. Trade data come from a compilation of sources including the list of sources above used for output and UN Comtrade. PV components' prices timeseries come from BNEF, whereas NREL and IEA PVPS studies have been used for the intensities of LCOP. CAPEX data come from IEA desk research on investments, in conjunction with the capacity data above.
Wind	• Existing capacity • Announced capacity • Energy and material intensity • Capital costs • Wind components prices • Historical output • Historical trade	S&P Global Commodity Insights (S&P Global, 2024a), BNEF (BNEF, 2024a), GWEC (GWEC, 2023), WindEurope (WindEurope, 2023), Wood Mackenzie (WoodMackenzie, 2024) and NREL (NREL, 2019)	S&P Global Commodity Insights is the primary data source for capacity and output data, which are supplemented with data from WindEurope, BNEF, GWEC and Wood Mackenzie. The Wind Supply Chain series from Wood Mackenzie and NREL studies were used to inform the assessment of levelised costs. Blades and nacelles trade estimates for 2023 are done based on manufacturing capacities per country and OEM from S&P and deployment per country and OEM, assuming that each OEM will deploy first locally and then ship components to other sites; in this context demand for components is calculated as the average between the current and next year. CAPEX data are based on analysis drawing from S&P Global Commodity Insights data.
Batteries	• Existing capacity • Announced capacity • Battery sizes • Active material conversion factors • Energy and material intensity • Capital costs • Battery components prices • Historical output • Historical trade	Benchmark Mineral Intelligence (BMI, 2024), EV Volumes (EV Volumes, 2024), BNEF (BNEF, 2024b), (Dai et al., 2019), (Argonne, 2024), (Frith, Lacey, & Ulissi, 2023)	Benchmark Mineral Intelligence (BMI) is the primary data source for current and projected battery cell manufacturing capacity and for classifying announcements as committed or preliminary. EV Volumes is used for historical average EV battery sizes (kWh). BNEF is used as a supplementary source for battery cell manufacturing status (committed or preliminary) and as the primary source for cathodes and anodes active material manufacturing capacity and plants' status

Technology	Data on manufacturing and trade	Data sources	Description
			(committed or preliminary). CAPEX data come from IEA desk research on investments in conjunction with the capacity data above. GREET and Dai et al. are used, together with IEA analysis, for battery and components material and energy intensities. Frith et al. is used for the conversion factors between battery cells and battery pack and other technical specifications like the anode to cathode ratio.
Electric cars	● Electric car sales ● Car manufacturing capacity ● Energy and material intensity ● Capital costs ● Electric car prices ● Historical output ● Historical trade	EV Volumes (EV Volumes, 2024), Marklines (Marklines, 2024), Atlas EV Hub (Atlas EV hub, 2024), ICCT, S&P Global Mobility (S&P Global Mobility, 2024), BNEF (BNEF, 2024d), Transport & Environment (BNEF, T&E, 2021), UBS (UBS, 2017)	EV Volumes is the primary source used for historical sales and trade of electric cars (including electric commercial vehicles and buses). Marklines' OEM plant dataset is used to inform the car regional manufacturing capacity estimates. Atlas EV hubs is used to inform the historical EV manufacturing investment analysis. Historical purchase price values of electric car are taken from S&P Global Mobility. BNEF, ICCT, T&E and UBS all published studies that helped inform the LCOP estimates for electric cars in China, Europe and the United States.
Electrolysers	● Existing capacities ● Announced capacity ● Energy and material intensity ● Capital costs ● Electrolyser prices ● Historical output ● Historical trade	Primary research, IEA Hydrogen Projects database (IEA, 2024f)	Manufacturing capacity data are based on announcements by manufacturers and personal communications gathered by the IEA. Historic trade data are derived from the IEA Hydrogen Projects database. CAPEX data are coming from desk research and communication with manufacturers.
Heat pumps	● Existing capacity ● Announced capacity ● Energy and material intensity ● Capital costs ● Heat pump prices ● Historical output ● Historical trade	CEPII (CEPII, 2024), Oxford Economics Trade Prism (Oxford Economics, 2024b), JETRO (JETRO, 2024)	Manufacturing capacities are derived by combining heat pump sales in different regions and trade flows based on Oxford Economics and CEPII. Manufacturing capacity additions and expansion plans are based on public announcements by manufacturers, whereas CAPEX data are based on analysis of JETRO data.
Other	● Material prices ● Energy prices ● Labour prices ● Energy and material intensity ● WACC	Bloomberg (Bloomberg, 2024), IEA World Energy Prices (IEA, 2024c), ILOSTAT (ILO, 2024), JETRO (JETRO,	Bloomberg is the primary source for information on material prices; IEA data are used for end-user prices for energy and ILOSTAT data are used to calculate labour costs. Academic literature is consulted to derive

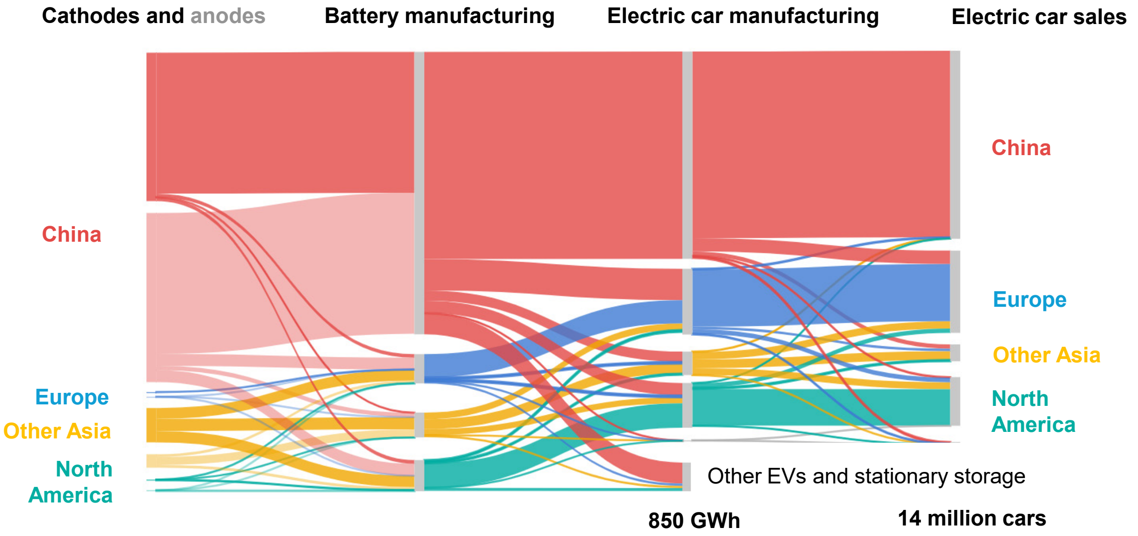
Technology	Data on manufacturing and trade	Data sources	Description
		2024), (Damodaran, 2024)	material, labour and energy intensities and to benchmark results for levelised cost. The weighted average cost of capital is based on data from Damodaran.
Materials (capacity data)	● Existing capacity ● Announced capacity	(IFA, 2024a), (CRU, 2024), (GEM, 2024), (OECD, 2024b), (IEA, 2024f)	For conventional production capacity, steel numbers are sourced from OECD; iron from CRU; alumina and ammonia from CRU; ammonia from the IFA. For near-zero emissions capacity, the IEA Hydrogen Production and Infrastructure Projects Database is used for ammonia while data for other materials rely on announcements by manufacturers, gathered by the IEA.
International trade	● Historical trade in physical and monetary values	(Oxford Economics, 2024b), (CEPII, 2024), (EV Volumes, 2024), (InfoLink, 2024), (IEA, 2024j), (IEA, 2024h)	Oxford Economics and CEPII data are used to estimate the trade for most commodities. Exceptions being: EVs relying on EV Volumes; Solar PV on InfoLink; Fossil fuels on IEA data.
Trade routes	● Port capacity ● Maritime trade ● Historical shipping routes ● Shipping activity	(Lloyd's List, 2023b) (Verschuur et al., 2022) Ports Watch (IMF, 2024), (UNCTAD, 2022)	Lloyd’s List is used for the size of the ports for containers; Verschuur is used for the tankers and dry bulk port capacities, maritime share of trade; Ports Watch to select relevant ports for the chokepoint analysis; and for their share in their country’s imports/exports; Global Hydrogen Review 2024 for hydrogen, ammonia and methanol projects and assumptions; UNCTAD shipping activity data for calibration in the base year.

Note: Many of the data sources are only accessible via subscription – in these instances a link to the data provider’s website is provided in the Reference list.

Current and future trade flows by clean energy technology

Electric cars and batteries

Figure A.5 Global manufacturing and trade flows of electric cars and lithium-ion batteries, 2023

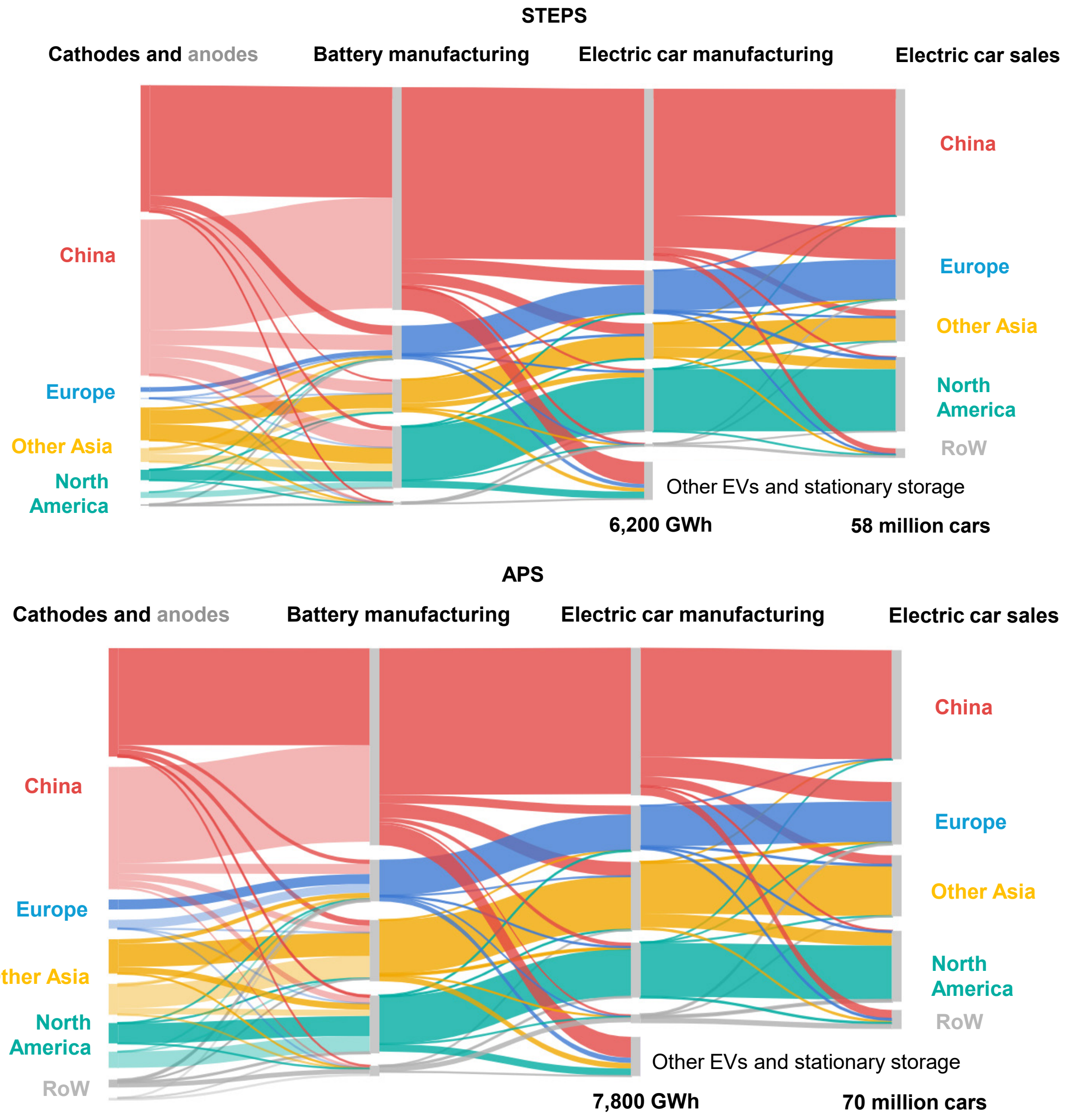


IEA. CC BY 4.0.

Notes: Flows are normalised to the battery (cell) manufacturing step, with cathodes and anodes normalised such their sum is scaled to the battery cell volume. Numbers below the charts refer to the total demand, not only the traded volume. The lighter-colour version of the flows going to battery manufacturing represents the anodes.

Sources: IEA analysis based on EV Volumes and Benchmark Mineral Intelligence for the 2023 trade flows.

Figure A.6 **Global manufacturing and trade flows of electric cars and lithium-ion batteries in the Stated Policies Scenario and Announced Pledges Scenario, 2035**



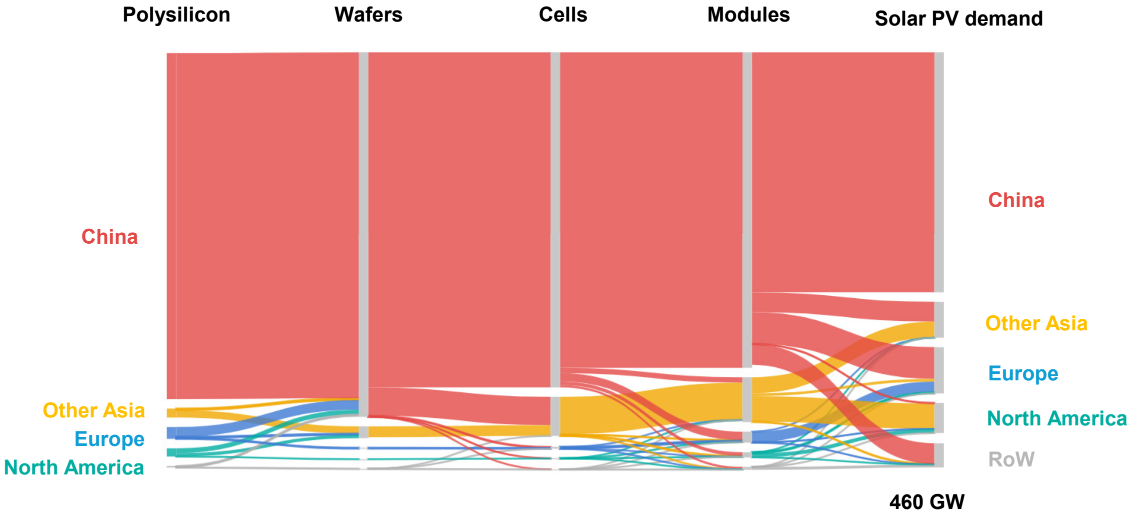
Notes: RoW = Rest of World, STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario. Flows are normalised to the battery (cell) manufacturing step, with cathodes and anodes normalised such their sum is scaled to the battery cell volume. Numbers below the charts refer to the total demand, not only the traded volume.

The lighter-colour version of the flows going to battery manufacturing represents the anodes.

Sources: IEA analysis based on EV Volumes and Benchmark Mineral Intelligence for the 2023 trade flows.

Solar PV

Figure A.7 Global manufacturing and trade flows of solar PV modules and components, 2023

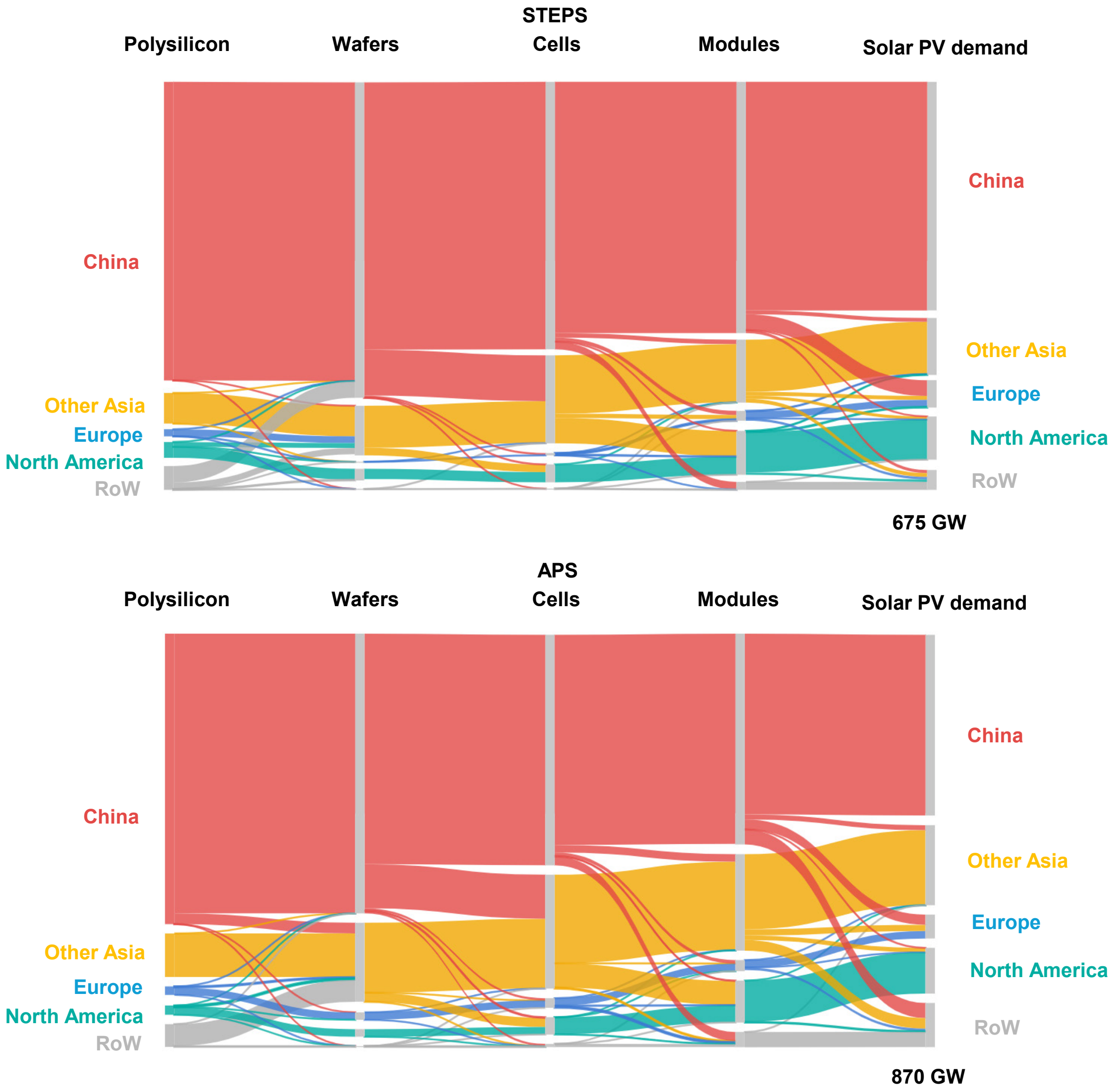


IEA. CC BY 4.0.

Notes: RoW = Rest of World. Flows are normalised for each sequential component and include quantities going to inventories for the demand step in 2023. Numbers below the charts refer to the total demand, not only the traded volume. The demand number excludes the quantities going to inventories.

Sources: IEA analysis based on InfoLink (2024); BNEF (2024a); SPV Market Research (2024); and UN Comtrade (2024) for the 2023 trade flows.

Figure A.8 Global manufacturing and trade flows of solar PV modules and components, Stated Policies Scenario and Announced Pledges Scenario, 2035

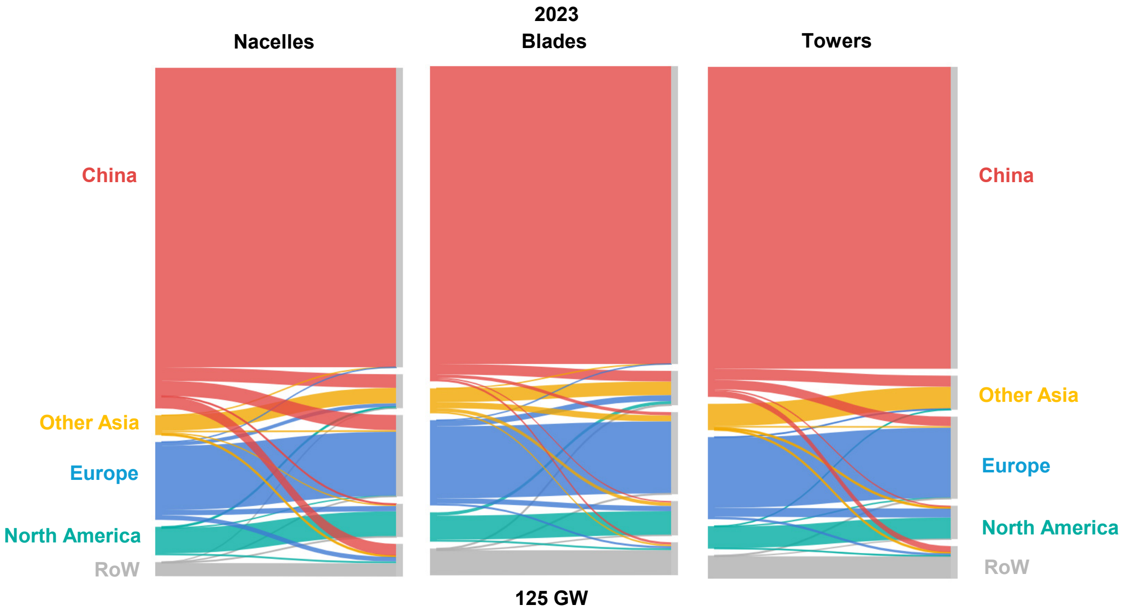


Notes: RoW = Rest of World, STEPS = Stated Policies Scenario, APS = Announced Pledges Scenario. Flows are normalised for each sequential component. Numbers below the charts refer to the total demand, not only the traded volume.

Sources: IEA analysis based on InfoLink (2024); BNEF (2024a); SPV Market Research (2024); and UN Comtrade (2024) for the 2023 trade flows.

Wind

Figure A.9 Global manufacturing and trade flows of nacelles, blades and towers, 2023

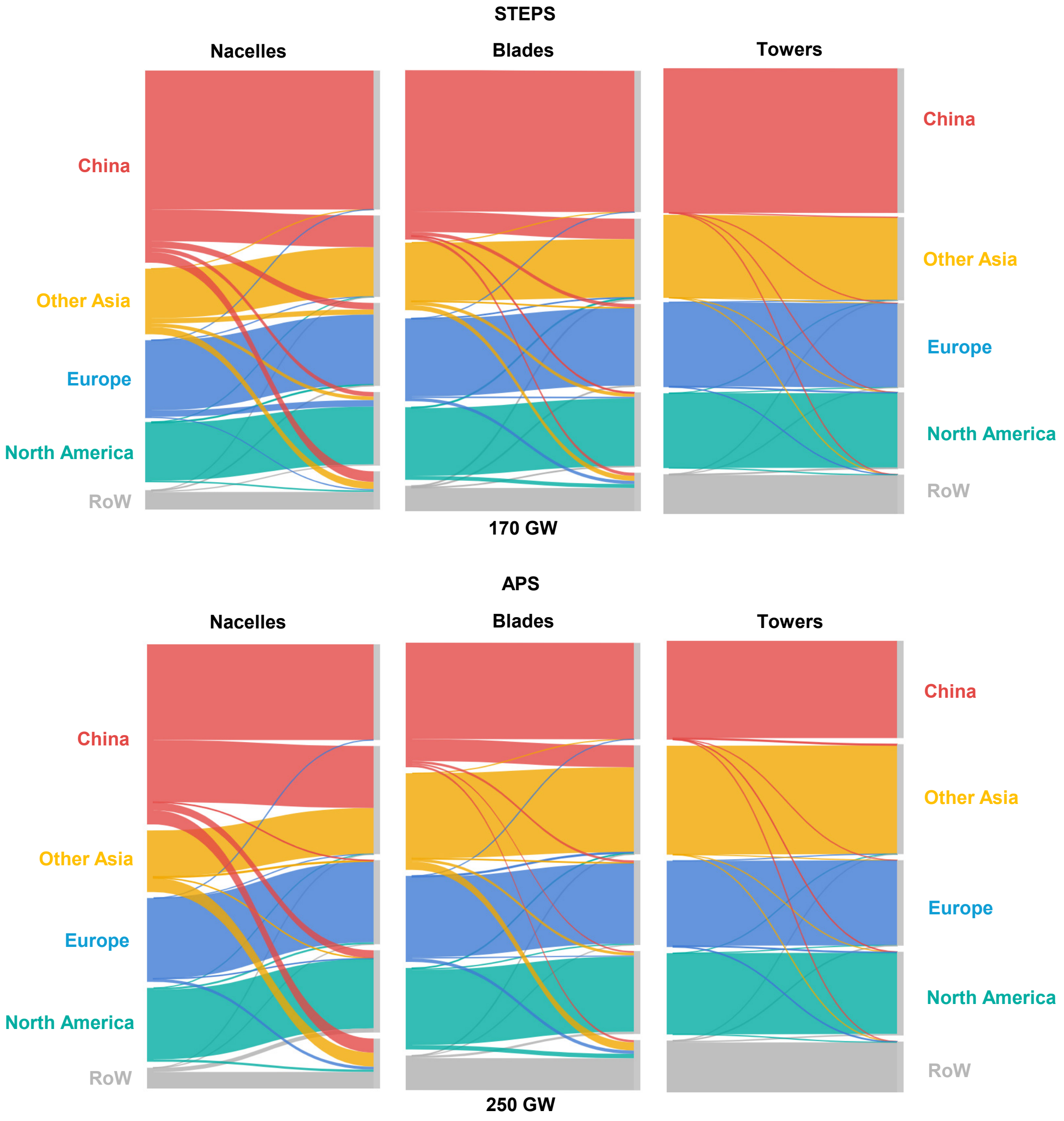


IEA. CC BY 4.0.

Notes: RoW = Rest of World. Flows are normalised for each component. Numbers below the charts refer to the total demand, not only the traded volume.

Sources: IEA analysis based on GWEC (2023); BNEF (2024c); S&P Global (2024a); Rystad Energy (2023); and USITC (2024) for the 2023 trade flows.

Figure A.10 Global manufacturing and trade flows of nacelles, blades and towers in the Stated Policies Scenario and Announced Pledges Scenario, 2035

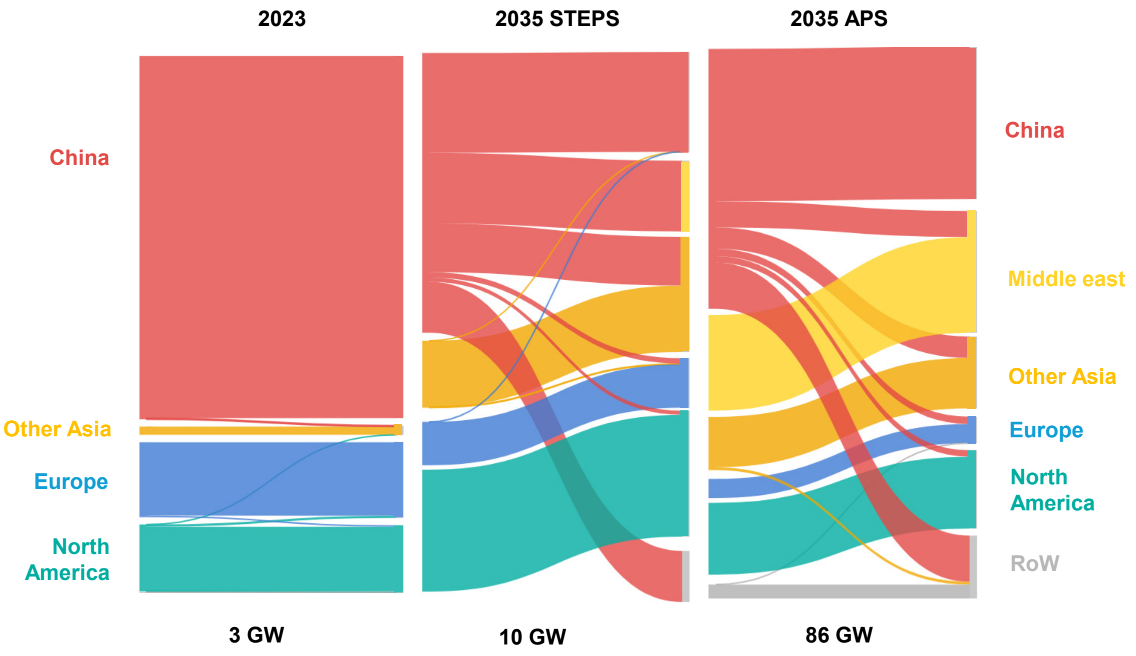


Notes: RoW = Rest of World; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Flows are normalised for each component. Numbers below the charts refer to the total demand, not only the traded volume.

Sources: IEA analysis based on GWEC (2023); BNEF (2024c); S&P Global (2024a); Rystad Energy (2023); and USITC (2024) for the 2023 trade flows.

Electrolysers

Figure A.11 Global manufacturing and trade flows of electrolysers, 2023, and in the Stated Policies Scenario and Announced Pledges Scenario, 2035

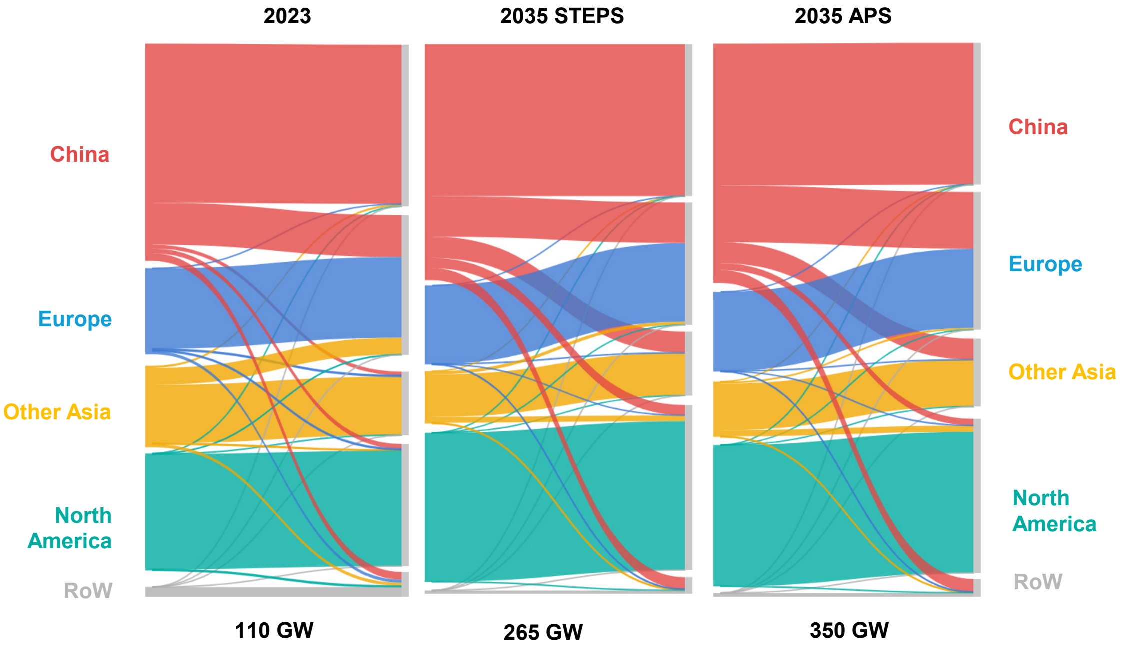


Notes: RoW = Rest of World; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Numbers below the charts refer to the total demand, not only the traded volume.

Sources: IEA analysis based on (IEA, 2024f), announcements by manufacturers and personal communications.

Heat pumps

Figure A.12 Global manufacturing and trade flows of heat pumps, 2023, and in the Stated Policies Scenario and Announced Pledges Scenario, 2035



Notes: RoW = Rest of World; STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario. Numbers below the charts refer to the total demand, not only the traded volume.

Sources: IEA analysis based on Oxford Economics for the 2023 trade flows.

Annex B – Manufacturing analysis

Industrial survey methodology

To support the analysis in *ETP-2024*, a survey was conducted with manufacturers and project developers to better understand the drivers for investments in clean energy manufacturing projects. The survey involved stakeholders from clean energy technology and near-zero emissions materials supply chains. 51 respondents who are actively involved in investment decisions for manufacturing facilities around the world (engineers, managers, and business or strategy professionals) participated. Responses were obtained anonymously from each of the following manufacturing supply chains: electric cars and batteries, solar PV, wind turbines, heat pumps and electrolysers, iron and steel, aluminium and ammonia.

Table A.3 Industrial survey questions

Please select from the following list the supply chain segment(s) in which your **main business activities** are situated:	
Where is your business **headquartered**?	
Where does your business conduct its **main activities** identified in Question 1?	
How important are the following **upfront cost** considerations when evaluating an investment decision? Would these same considerations be of **greater or lesser importance** if the investment was **in a developing country**?	• Government policy incentives and charges (e.g. investment tax credits) • Costs associated with trade and trade policy (e.g. capital controls) • Initial hiring and relocation costs • Cost of debt capital • Cost of equity capital • Infrastructure costs • Construction costs • Equipment costs • Hedging currency risk • Insurance costs
How important are the following **operational cost** considerations when evaluating an investment decision? Would these same considerations be of **greater or lesser importance** if the investment was **in a developing country**?	• Government policy incentives and charges (e.g. production tax credits) • Costs associated with trade and trade policy (e.g. tariffs on inputs or outputs) • Wage costs • Energy costs • Other input costs • Other fixed costs • Transport costs • Hedging currency risk • Insurance costs • Security costs
How important are the following **employment** considerations when evaluating an investment decision?	• Attractiveness of location for relocation of existing workers • Income taxes and employer contributions

Would these same considerations be of **greater or lesser importance** if the investment was **in a developing country?**	• Availability of high-skilled workers, such as engineers and managers (e.g. ISCO-08 Skill levels 3 and 4) • Availability of medium-skilled workers, such as clerical workers and plant operators (e.g. ISCO-08 Skill level 2) • Availability of low-skilled workers, such as labourers and delivery drivers (e.g. ISCO-08 Skill level 1) • Stringency of professional certification schemes and training regulations • Occupational health and safety standards and limits on working hours • High labour standards around non-discrimination and equal opportunity • High labour standards around termination, severance and dismissal, freedom of association and collective bargaining rights • Stringent enforcement of standards to prevent child labour, forced labour and human trafficking
How important are the following **infrastructure and supply chain** considerations when evaluating an investment decision? Would these same considerations be of **greater or lesser importance** if the investment was **in a developing country**?	• Local port infrastructure available and in good condition • Local road and rail infrastructure available and in good condition • Easy access to airports with frequent commercial flights • Efficient permitting procedures for new construction and infrastructure projects • High reliability of the energy supply • Access to low-cost renewable electricity and/or low-emissions fuels (i.e. biofuels, hydrogen and hydrogen-based fuels) • Good access to specific suppliers of key inputs locally • Good access to specific customers for key outputs locally • Few/no other competitors in the same industry • Large, or potentially large, domestic market
How would you rank the attractiveness of the following **government policies** when considering an investment decision?	• Investment incentives (e.g. investment tax credits) • Production incentives (e.g. production tax credits) • Project grants (e.g. non-reimbursable government funding matched by private investment) • Debt financing (e.g. government loans with preferential interest rates) • Green procurement policy (e.g. premium in government contracts for sourcing items produced with lower CO_2 emissions) • Off-take contract guaranteed by the government for a fixed period • High regulatory charges (e.g. CO_2 pricing) • Debt guarantees (e.g. government guarantees on project borrowing) • Project equity financing (e.g. government financing in return for project equity stake)
How would you rank the importance of the following considerations relating to **trade and trade policy** when considering an investment decision in an export-oriented location?	• Low/no border tariffs and quotas • Formalised bilateral partnership arrangements for a specific commodity or sector (e.g. a free trade agreement) • Low/no local content requirements • Short physical distance between partners, facility to facility • Short physical distance between partners, port to port • Depth and breadth of economic integration between jurisdictions

	• Low/no technical border charges (e.g. carbon border adjustments) • Low non-energy transport costs between jurisdictions (e.g. port and canal fees, insurance) • Availability of low-emissions shipping between jurisdictions • Presence of 'chokepoints' (e.g. Suez Canal) to traverse between jurisdictions
Please feel free to share any other perspectives, in particular with regards to any recent changes in the considerations covered in this survey that you think will delay or accelerate investments.	

Enabling indicators for manufacturing investments

A range of enabling factors – categorised here as the business environment, access to energy and transport infrastructure, and access to resources and domestic markets – will contribute to determining which location the investor chooses for manufacturing projects (see Chapter 4). Some factors that affect cost – the primary driver of the economic and financial viability of a clean energy investment – are determined by geographical location, notably mineral and renewable energy resources, and proximity to overseas markets and suppliers. The others are strongly influenced by policy.

The table below lists all the indicators which have been gathered for assessing the suitability of emerging markets and developing economies for developing manufacturing capacities. There are some sector-specific enabling conditions which cover key clean energy technologies – electric cars, batteries, solar PV and wind turbines – and their components, as well as key materials and chemicals – steel and ammonia (both for industrial and fuel-related applications) – and their precursors (iron).

The data collected for each indicator were normalised across countries to a value range of [0-1]. Advanced economies, including the United States, Japan and Germany, were used to provide the benchmark indicator values. The normalised values of all indicators for an overarching enabling factor were averaged to obtain one value [0-1] per enabling factor and country. Specific weights were applied for each supply chain, omitting indicators not relevant to a particular supply chain. Each enabling factor was then given an importance grade that is also unique for each supply chain, with values ranging from 1 (least important) to 5 (most important). The gradings were based on information gathered in industry surveys and on expert judgement. For all enabling factors within a supply chain, the averaged normalised enabling factor value was multiplied by the corresponding importance grade. Finally, the total opportunity value for each country was calculated for each technology or material by summing the weighted values of all enabling factors together.

Table A.4 List of the enabling indicators used in Chapter 4 for assessing the manufacturing potential of Emerging Markets and Developing Economies

Category	Enabling factor	Indicator	Description	Source
Business environment	Ease of doing business	Ease of doing business	The simple average of the scores for each of the Doing Business topics: starting a business, dealing with construction permits, getting electricity, registering property, getting credit, protecting minority investors, paying taxes, trading across borders, enforcing contracts and resolving insolvency	(World Bank, 2021)
		Political stability	Measures perception of the likelihood of political instability and/or politically motivated violence, including terrorism	(World Bank, 2023b)
		Corruption perception indicator	Measures perception of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests	(World Bank, 2024b)
	Industrial competitiveness	Competitive Industrial Performance index (CIP)	Benchmark of the ability of countries to produce and export manufactured goods competitively	(UNIDO, 2024)
		Economic Complexity Index (ECI)	Ranking of countries based on the diversity and complexity of their export basket	(Center for International Development at Harvard University, 2023)
		Total trade volume	Total trade flow considering imports and exports [kt]	(CEPII, 2024)
		Labour cost	Average hourly wage across all sectors	(ILO, 2024)
	Financing cost	Weighted average cost of capital (WACC)	Weighted Average Cost of Capital for more mature technologies [%]	(IEA, 2024a)
Energy and Infrastructure	Energy infrastructure	Electricity access	Share of population with access to electricity	IEA analysis
		Electricity demand per capita	-	(IEA, 2024h)
		Natural gas demand per capita	-	(IEA, 2024h)
	Reliability of electricity supply	System Average Interruption	Average total duration of outages (in hours) experienced by a customer in a year	(World Bank, 2024a)

Category	Enabling factor	Indicator	Description	Source
		Duration Index (SAIDI)		
		System Average Interruption Frequency Index (SAIFI)	Average number (count) of service interruptions experienced by a customer in a year	(World Bank, 2024a)
	Access to low-emissions energy	Renewable energy potential	Sum of solar and wind energy potential	(IEA, 2024a)
		Low-emissions energy supply	Share of low-emissions energy (excluding primary solid bioenergy)[6] in total primary energy supply	IEA analysis
		Regulatory Indicator for Sustainable Energy (RISE)	Regulatory Indicator for Sustainable Energy: assesses countries' policy and regulatory support for renewable energy	(World Bank, 2024a)
	Energy prices	Electricity prices	Price [USD/kWh] for consumers with demand > 1000 kWh/month	(IEA, 2024c) (Global Petrol Prices, 2023)
		Natural gas prices	Index considering end-use natural gas prices in 2021 for the industry (residential where data is missing) sector by country (or region where data is missing)	(IEA, 2024g)
	Transport infrastructure	Spare port container capacity	Port container spare capacity [TEU]	(MDS Transmodal Ltd., 2024)
		Port capacity - dry bulk	Capacity of a country's dry bulk ports [kt]	(Verschuur at al., 2022)
		Port capacity - ammonia	Capacity of a country's operational ammonia infrastructure [kt]	(IEA, 2024f)
		Logistics performance index	Reflects perceptions of a country's logistics based on the efficiency of customs clearance process, quality of trade- and transport-related infrastructure, ease of arranging competitively priced shipments, and quality of logistics services.	(World Bank, 2023a)
Resources and domestic markets	Raw and other material inputs	Iron ore production	-	(World Bureau of Metal Statistics, 2022)
		Lithium production	-	(IEA, 2024e)

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[6] Includes biofuels, biogases, renewable municipal waste, nuclear, hydro, wind, solar PV, solar thermal, geothermal, tide, wave and ocean.

Category	Enabling factor	Indicator	Description	Source
		Nickel production	-	(World Bureau of Metal Statistics, 2022)
		Phosphate production	-	(USGS, 2024b)
		Aluminium production	-	(IEA, 2024a)
		Copper production	-	(World Bureau of Metal Statistics, 2022)
		Crude steel production	-	(World Steel Association, 2024)
		Scrap steel availability	-	(IEA, 2024a)
		Iron ore reserves	-	(USGS, 2023a) (USGS, 2023b) (USGS, 2023c) (S&P Global, 2024b)
		Lithium reserves	-	(USGS, 2024a) (S&P Global, 2024b)
		Nickel reserves	-	(S&P Global, 2024b)
		Phosphate reserves	-	(USGS, 2024b)
		Solar resource potential	Energy potential from solar resources. Calculated electricity output for a 100 m^2 area with 1 MW installed considering country-specific resource availability [MWh/year]	(Global Solar Atlas, 2024)
		Wind resource potential	Energy potential from wind resources	(Shell, 2017)
		Water stress	Base level water stress	(WRI, 2024)
	Domestic demand	Solar PV deployment	Installed capacity	(IEA, 2024i)
		Wind deployment	Installed capacity	(IEA, 2024a)
		Crude steel consumption	Apparent consumption (production + imports - exports)	(World Steel Association, 2024)

Category	Enabling factor	Indicator	Description	Source
		N-fertilisers consumption	-	(IFA, 2024b)
		Electric car sales	Annual sales of new BEV and PHEV	(EV Volumes, 2024)
		EV production	Cumulated production of BEV and PHEV over 2010-2024	(EV Volumes, 2024)
	Market size of related industries	EV battery manufacturing capacity	Annual battery manufacturing capacity [GWh]	(BMI, 2024)
		Cathode and anode manufacturing capacity	Cathode and anode manufacturing capacity (GWh)	(BNEF, 2023)
		Ammonia production	-	(IFA, 2024a)
		Iron and steel market	Share of iron & steel value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
		ICE manufacturing capacity	Share of ICE manufacturing value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
		Basic chemicals market	Share of basic chemical value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
		Manufacturing industry	Share of manufacturing value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
		Electric fittings and batteries market	Share of electric fittings & batteries value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
		Aviation industry	Share of turbines, engines, fluidics, pumps & gears and aerospace sectors value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
		Mineral extraction market	Share of mineral extraction value added in relation to a country's gross value added [%]	(Oxford Economics, 2024a)
Resources and domestic markets	Workforce skills	Innovation	Intellectual property - resident applications of patents, trademarks, and industrial designs per million inhabitants	(WIPO, 2024)
		Employment in chemicals industry	Share of total working population employed in manufacture of chemicals and chemical products [%]	(ILO, 2024)
		Employment in electrical equipment industry	Share of total working population employed in manufacture of electrical equipment [%]	(ILO, 2024)
		Employment in manufacturing	Share of total working population employed in manufacture of	(ILO, 2024)

Category	Enabling factor	Indicator	Description	Source
		fabricated metal products	fabricated metal products, except machinery and equipment [%]	
		Employment in vehicle manufacturing	Share of total working population employed in manufacture of motor vehicles, trailers, and semi-trailers [%]	(ILO, 2024)
		Employment in mining metal ores	Share of total working population employed in mining of metal ores [%]	(ILO, 2024)
		STEM education	Number of STEM students per 1000 inhabitants (2018-2023 average)	IEA analysis based on (UNESCO, 2024)
		Vocational education	Proportion of 15-24 year-olds enrolled in vocational education	(UNESCO, 2024)
		Public spending on education	Public spending on education per capita [USD/cap]	(UNESCO, 2024)
		Public spending on R&D	Share of GDP spent on R&D [%]	(UNESCO, 2024)

Notes: EV = electric vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle; ICE = internal combustion engine; STEM = science, technology, engineering and mathematics.

Annex C – Shipping decarbonisation

Technologies for shipping decarbonisation

Table A.5 Deployment status of selected technologies to decarbonise shipping

Technology	Description	TRL 2020	TRL 2024	Importance for net zero	Deployment status
Operational energy efficiency					
Slow steaming	Slow steaming consists of voluntarily reducing the sailing speed of ships to save fuel. In order to keep the carrying capacity constant, the number of ships in the fleet would need to be increased in proportion, but because the energy consumption is a function of speed with an exponent higher than one, the net effect is to reduce fleet consumption.	9	9-10	High	Slow steaming started around 2008, the period when the market started to experience an oversupply of shipping capacity, declining freight rates, and increasing bunker prices. Nowadays, ships routinely sail at a much lower speed than their maximum (e.g. 16 vs 24 knots for containerships (IMO, 2020)), but there is potential for further reduction.
Dynamic route optimisation	Waves, wind, and currents have an influence on the ship's energy consumption, which can be reduced through algorithms that use artificial intelligence, relying on weather forecasts and data from satellites or buoy networks.	9	9	Moderate	The first systems were commercialised in 2014, and with the latest developments, overall energy savings of up to 3-5% can be expected. Major bulk carrier operators announced in 2023 that this solution will be rolled-out to their fleets (Dry bulk, 2023).
Trim and draught optimisation	Draught measures how deep the ship is submerged into the water and trim the difference between bow and stern draught. Depending on the trim, the wetted surface area of the hull will be different, which affects energy consumption.	9	9	Moderate	Actively planning cargo loading, and thereby optimising the trim and draught, can save fuel: typically 0.5-3% and up to 5% for container and Ro-Ro ships that tend to navigate in partial load conditions. Such systems have been on the market for 10 years and equip

Technology	Description	TRL 2020	TRL 2024	Importance for net zero	Deployment status
					1 000 ships today (DNV, n.d.).
Technological energy efficiency					
Kite sails	Large towing kites are attached to the ship with long cables to access strong winds 100 metres above the ship. Kite sails have the advantage of being fully retractable and take up limited deck space.	8	8-9	Moderate	A first full-scale prototype was installed in 2021. In 2024 a major shipping company announced plans to start commercial operation, ultimately with potential for deployment on 50 bulk carriers (The Maritime Executive, 2024). Energy savings are expected to be in the order of 3%.
Rotor sails	Rotor sails are vertically oriented spinning cylinders that attach to the vessel's deck to make a virtual sail.	8-9	8-9	High	Rotor sails can typically generate energy savings of around 10% and are suited to large ocean-going vessels, especially bulk carriers They are available commercially for new builds, as well as for retrofitting: currently over 15 ships are operating, with potential to equip 50 ships by 2025 (Norsepower, n.d.) (Anemoi, n.d.) (Lloyd's Register, 2023a)
Waste heat recovery	Waste heat recovery systems recover the thermal energy from the exhaust gas and convert it into electrical energy, while the residual heat can further be used for ship services (such as hot water and steam).	9	9-10	Moderate	Power/Steam Turbine Generator is a commercially available and mature technology that can generate energy savings of typically 5%. Organic Rankine Cycle has a higher saving potential but is less mature
Anti-fouling hull coating	Hull coatings are spread on the immersed body of the ship to reduce the hydrodynamic drag caused by corrosion, algae and shells.	10	10	Moderate	Anti-fouling coatings are available from several paint companies and common across vessel types and trades, but there is still room for significantly increased penetration (penetration rate estimated at 12.5% of ships in 2018 (IMO, 2020)). Typical energy savings can be in the order of 4-5%.
Hull form optimisation	Hull form optimisation is a highly effective tool for	8-9	9	Moderate	Hull form optimisation (through computational

Technology	Description	TRL 2020	TRL 2024	Importance for net zero	Deployment status
	reducing hull total resistance for a given speed on new vessels, if implemented early in the design process.				fluid dynamics) is available as a service from multiple international companies. Expected energy efficiency improvements is 3-8%, with ships operating at above 10 knots being the preferred target.
Air lubrication	Air lubrication uses compressed air released over the bottom of a vessel hull to reduce the friction incurred by the passing water.	8-9	9	Moderate	Up to 2018, 23 vessels were identified to have air lubrication system installed on board (ABS, 2019). Currently, this technology is readily available commercially and applicable to ships with large flat-bottom hulls, typically LNG carriers and some containerships. As of August 2024, it is deployed to more than 200 ships in service. The typical energy savings are 3 – 9%
Fuel switching					
Ammonia combustion engine powered ships	Ammonia is one of the most promising synthetic fuels, as it is carbon-free and easier to store than hydrogen. However, it is very toxic and thus necessitates specific design and operation measures, as well as refrigerated storage tanks more than 3 times larger than for diesel for the same energy capacity. Exhaust after-treatment is necessary to eliminate emissions of N_2O, which is a potent GHG, NOx and NH_3. Ammonia is hard to ignite, and the current engine designs make use of fossil or biodiesel as pilot fuel.	8-9	9	Very High	Wärtsilä's 4-stroke ammonia engine, suitable for smaller merchant vessels, has been commercially available since Dec. 2023 (Ammonia Energy Association, 2023). The main engine makers are announcing the commercialisation in the next 2 years of large 2-stroke ammonia engines suitable for ocean-going vessels (Reuters, 2024) (NYK, 2024) (WinGD, 2023). As of Aug. 2024, more than 20 ammonia ships are on order books, including 10 very large bulk carriers, 9 liquefied gas tankers, 2 Aframax oil tankers and 1 containership, with deliveries starting in 2026.
Methanol combustion engine powered ship	Methanol is easier to handle than ammonia, but still highly flammable and toxic. It necessitates double walled piping and storage	4-5	4-5	High	Methanol has been used as fuel by chemical tankers since the mid-2010s. In 2024, methanol ships represented close to 10%

Technology	Description	TRL 2020	TRL 2024	Importance for net zero	Deployment status
	tanks 2.5 larger than for diesel with the same energy capacity. Methanol is easier to ignite than ammonia, but current designs still typically use fossil or biodiesel as pilot fuel.				of ships on order in terms of gross tonnage (DNV, Maritime forecast to 2050, 2024a). As of Aug 2024, around 300 methanol ships are operating or on order, including around 170 containerships, 50 chemical tankers, more than 10 bulk carriers, and almost 10 oil tankers.
Hydrogen combustion engine powered ship	One of the difficulties in using hydrogen as a fuel on a ship is the need for cryogenic storage tanks 7.2 times larger than for diesel with the same energy capacity. Liquid hydrogen needs to be expanded to gas before combustion.	7	8	Moderate	Small scale demonstration vessels (tug and crew transfer vessel) have been operation since 2022 (Baird Maritime, 2022). As far as larger ocean-going vessels are concerned, in 2023 a Japanese engine maker, shipyard and ship operator announced their intention to start testing a 17 500 DWT ship powered by a hydrogen 2 stroke engine from 2027 (J-Eng, 2023).
Hydrogen fuel cell powered ship	Hydrogen fuel cells can have a higher energy efficiency than for a hydrogen combustion engine but a higher cost (in particular OPEX, as the fuel cell internals have a much lower lifetime than a combustion engine) and a lower energy storage density.	8-9	9	Moderate	The technological maturity depends on the type of membrane for the fuel cells: TRL8 for proton exchange membrane, TRL7 for solid oxide or molten carbonate. Almost 20 hydrogen fuel cell ships are currently operating or on order books, mostly smaller passenger and service vessels, as well as two 730 TEU containerships planned for delivery in 2025 and 2026.
Battery electric ship	In battery electric ships, the power for propulsion and auxiliaries comes from batteries, which are charged while at berth from the onshore electricity grid.	3-4	3-4	Moderate	Currently there are almost a thousand electric ships in operation and almost 500 on order. About two thirds of those are hybrids, the remaining one third being split between plug-in hybrids and pure electric (DNV, 2024c). Given the limitations of the energy density of batteries, most applications are on short-

Technology	Description	TRL 2020	TRL 2024	Importance for net zero	Deployment status
					distance routes (typically less than 50 nm) where they can charge frequently: ferries, offshore service ships, short range merchant ships. The recent development of a 700 TEU electric containership for fluvial navigation in China gives a perspective for a much longer range (Elective, 2024).
Nuclear propulsion	Pressurised water reactors (PWRs) have been used on military ships and civilian icebreakers for decades. The long refuelling cycle (several years) and high power density are appealing, but the high initial investment cost, high operation costs, safety and non-proliferation concerns have hindered the development of nuclear ships.	9	9	Low	Russia has currently 7 nuclear icebreakers in operation. In the future, marine applications could take advantage of modern SMRs. An initiative funded by the US DOE that started in 2021 considers that onshore demonstration could happen in 2025 and aiming at a demonstration in the maritime environment in 2028-2030 (DOE, 2021). In 2023, China announced that its design for a thorium reactor 24 000 TEU containership obtained AiP (The Maritime Executive, 2023).
Cold ironing	So-called “cold ironing” or Alternate Maritime Power (AMP) consists of plugging in the vessel to the grid instead of running the auxiliary engine(s) of the ship when at berth to operate ventilation, heating and cooling systems.	9	9	High	Relevant regulations are being introduced, especially in the European Union through AFIR (EU, 2023), to require that ships use shore electric power when at berth. Currently more than 30 ports in the world have at least 1 berth with onshore power for cruise ships, mainly in Northern Europe, China and North America (CLIA, 2024).
Carbon capture and storage					
Onboard Carbon Capture (OCC)	CO_2 captured after combustion is liquefied and stored onboard before being later off-loaded on shore and then ultimately stored permanently. OCC has a			Low	The different components of the onboard system (CO_2 capture, liquefaction, on board storage, discharging) are currently at TRL 7 to 8. Partial

Technology	Description	TRL 2020	TRL 2024	Importance for net zero	Deployment status
	significant impact on the ship's energy consumption (up to +40%), which has the side effect of increasing the consumption of fossil energy. This technology is often presented as a solution to alleviate the pressure on alternative fuel production ramp-up.				testing at scale has taken place in the past 2 years (MOL, 2024) (Offshore Energy, 2024a). A full system test at an unknown scale on a 14 000 TEU containership was also reported in 2024 (Offshore Energy, 2024b). A remaining challenge is to develop in parallel a network of CO_2 collection points at port, as well as for transportation to final storage locations.

Notes: TRL = technology readiness level. The TRL provides a snapshot in time of the level of maturity of a given technology. It provides a common framework that can be applied consistently to any technology to assess and compare the maturity of technologies across sectors. The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology then enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), through to testing in the conditions it which it will be deployed (TRL 5-6). The technology next moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9). Beyond this stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale: TRL10 denotes that the solution is commercial and competitive, but needs further integration efforts, and TRL11 denotes that it has reached predicable growth. SMR = Small Modular Reactor, AiP = Approval in Principle by a classification agency. This table does not aim to be exhaustive. For a more comprehensive list and description please refer to the IEA's Clean Technology Guide.

Sources: IEA Clean Energy Technology Guide (2024); US Department of Transportation (2022); GloMEEP (2019).ship order books from UN Global Platform (2024).

Ports for alternative fuels exports

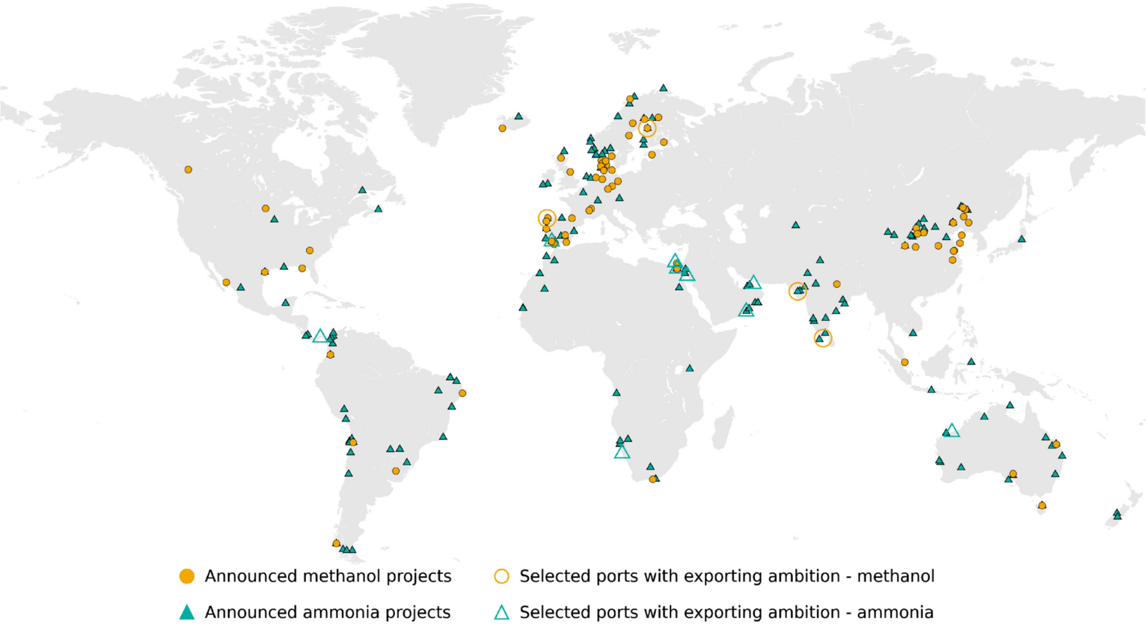
When considering options for ports that might have a role in bunkering low-emissions ammonia and methanol, a set of ports was selected (Table A.5) to limit the scope of the analyses. The selected ports have made explicit their intention to produce these fuels or are in the proximity of announced projects to produce these fuels (Figure A.13) (IEA, 2024f), but not all of them have made specific plans to develop the necessary refuelling infrastructure. The ports listed are those mentioned in Figures 5.37 and 5.38 of the report.

Table A.6 Selected ports for the analysis of alternative refuelling infrastructure

Fuel	Country	Port
Ammonia	Oman	Port of Salalah
Ammonia	Saudi Arabia	Port of NEOM
Ammonia	Australia	Port Hedland
Ammonia	Spain	Port of Huelva
Ammonia	Egypt	Port of Ain Sokhna

Fuel	Country	Port
Ammonia	Namibia	Port of Lüderitz
Ammonia	United Arab Emirates	Port of Fujairah
Ammonia	Panama	Port of Balboa
Ammonia	Egypt	Port of Damietta
Methanol	India	V.O. Chidambaranar Port at Thoothukudi (formerly Tuticorin)
Methanol	India	Port of Kandla
Methanol	Spain	Port of A Coruña
Methanol	Finland	Port of Kokkola

Figure A.13 Selected ports for the analysis of alternative refuelling infrastructure and methanol or ammonia announced projects



IEA. CC BY 4.0.

Source: IEA (2024f).

Annex D – Definitions

Glossary

Ad valorem tariff: A tariff rate levied as a fixed percentage of the value of the imported product at customs. This value includes the product's price, in this report modelled as the levelised cost of production plus a profit margin, along with freight and insurance costs.

Announced capacities: Refers to the aggregate stated capacity – or estimated nominal maximum output – of potential manufacturing facilities (projects) that have been announced. This includes projects for building new facilities or expanding existing ones that are at different stages of development. "Committed" projects include those that have already reached a final investment decision (FID), or are under construction, whereas "preliminary" projects include those that have not yet reached an FID, meaning feasibility studies or earlier steps are underway. Wherever data is available, we distinguish committed projects from preliminary announcements across the key technologies in focus, which allows for more robust projections of future manufacturing capacity.

Announced Pledges Scenario (APS): This scenario assumes that governments will meet, in full and on time, all of the climate-related commitments that they have announced, including longer-term net zero emission targets and pledges in Nationally Determined Contributions, as well as commitments in related areas such as energy access. It does so irrespective of whether or not those commitments are underpinned by specific policies to secure their implementation. Pledges made in international fora and initiatives on the part of businesses and other non-governmental organisations are also taken into account wherever they add to the ambition of governments. In addition, the scenario takes on board all the manufacturing projects that have been announced, including preliminary plans.

Battery: Batteries considered in the *ETP-2024* report include advanced electrochemical energy storage technologies based on lithium-ion (Li-ion) or post Li-ion batteries used in road transport or stationary storage applications. If not stated otherwise, battery always refers to battery cells.

Breakbulk shipping: refers to the transportation of goods that are too large or cumbersome to be placed in containers, or that are transported individually rather than in bulk. Breakbulk cargo typically includes items like machinery, vehicles, steel and construction materials. These items are loaded, stacked and transported piece by piece using cranes and other handling equipment, often requiring specialised handling and stowage.

Bunkering: The process of supplying fuels to a ship.

CAPEX: Capital expenses (or expenditures).

Chartering: The process of hiring or leasing a ship to transport goods from one port to another. This is a common practice in the maritime industry, in which shipowners lease out their vessels to companies (known as charterers) that need to transport cargo.

Clean energy technology: Those energy technologies that result in minimal or zero emissions of CO_2 and pollutants. For the purposes of this report, clean energy technologies refer to the following: Batteries, Electric cars, Solar PV, Wind, Electrolysers and Heat pumps.

Container shipping: Container shipping is the transport of goods using large, standardised containers that can be easily transferred between different modes of transportation (ships, trains, trucks) without unloading the cargo itself. These containers come in standard sizes (e.g. 20-foot and 40-foot containers) and are used to ship a wide variety of goods, from consumer products to machinery. Container ships are used to transport containers.

Critical materials: A wide range of minerals and metals that are essential in clean energy technologies and other modern technologies and have supply chains that are vulnerable to disruption. Although the exact definition and criteria differ among countries, critical minerals for clean energy technologies typically include chromium, cobalt, copper, graphite, lithium, manganese, molybdenum, nickel, platinum group metals, zinc, rare earth elements and other commodities, as listed in the Annex of the IEA special report on the Role of Critical Minerals in Clean Energy Transitions (2021).

Deadweight tonnage (DWT): A measure used in shipping to indicate the maximum weight a ship can safely carry, including cargo, fuel, fresh water, ballast water, provisions, crew and passengers. It represents the carrying capacity of the vessel, excluding the ship's own weight (the hull, engines, etc.).

Delayed Deployment Case: This case is a variation of the NZE Scenario that assumes a 5-year delay in the deployment of key clean energy technologies (solar PV, wind, EV batteries, electrolysers, heat pumps) across the global energy system starting in 2024. It illustrates the additional emissions that would result if it were not possible to scale up manufacturing of these technologies in line with NZE Scenario demand.

Dry bulk shipping: refers to the transportation of unpackaged, loose commodities in large quantities that are solid and dry. These goods are typically stored directly in the hold of a ship without the use of containers or packaging. Common examples of dry bulk cargo include coal, grain, iron ore, cement and salt. The ships used for this purpose are called bulk carriers or dry bulk carriers.

Electric cars: Refer to EVs that belong to the passenger light-duty vehicles category such as cars and pick-up trucks.

Electric vehicles (EVs): Vehicles that use electricity as a source of propulsion. Electric vehicles comprise battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

Electrolysers: A device that uses direct electrical current to drive an otherwise non-spontaneous chemical reaction. Commonly used in the production of chemicals such as chlorine. Water electrolysers split water into hydrogen and oxygen, for the production of hydrogen, and are increasingly being applied to energy challenges such as the conversion of CO_2 to useful products and the reduction of iron ore. In the context of the *ETP-2024* report, if not otherwise specified, electrolysers refer to water electrolysers for the production of hydrogen, including all major technologies such as alkaline, proton exchange membrane, solid oxide electrolysis and others. Manufacturing capacity refers to the assembly capacity, and upstream components capacity is not considered.

Export tax: A tax imposed on commodities being exported out of the country.

Freight rate: The price charged by a carrier (shipowner or charterer) or freight forwarder to transport goods from one place to another. This price is determined by the cost of transporting goods, as well as market conditions.

Heat pumps: A device that consumes energy, usually electricity, to transfer heat from a source to a sink using a refrigeration cycle (compression, condensation, expansion and evaporation of a refrigerant working fluid). The devices can extract heat from the outside air (air-source heat pump), shallow subsurface (ground-source heat pump) or other nearby sources as water. These may be designed to operate reversibly to provide air conditioning as well as heating, or only to provide heating. The performance of a heat pump, expressed as the coefficient of performance (COP) or seasonal coefficient of performance (SCOP), is usually such that the heat delivered is several multiples of the energy contained in the input electricity. Heat pumps in this report refer to those that deliver heat directly to households and residential or commercial buildings for space heating and/or domestic hot water provision. They include natural source heat pumps, including reversible air conditioners used as primary heating equipment. They exclude reversible air conditioners used only for cooling, or used as a complement to other heating equipment, such as a boiler.

High Potential Case: This case identifies opportunities for emerging markets to build out their clean energy manufacturing sectors where global demand for clean energy technologies and near-zero emissions materials is compatible with the energy sector reaching net zero emissions by 2050. This case assumes that emerging markets succeed in overcoming barriers to exploiting all their competitive advantages in manufacturing a targeted scope of clean technologies and near-zero emissions materials, tailored to their respective high potential areas and enabled by international support mechanisms.

HS codes: Harmonised System (HS) Codes are a standardised numerical system to classify internationally traded goods, developed by the World Customs Organization (WCO). HS codes are used by authorities to identify products, to determine tariffs applicable to a product and collect trade statistics. Internationally standardised HS codes consist of a two-digit number ("Chapter"), four-digit number ("Heading") and six-digit number ("Sub-Heading").

Import quotas: A limit on the quantity of a product that can be imported into a country in a given period. There are two types: absolute and tariff rate. Absolute quotas strictly limit the physical quantify of a product that can enter in a country, while tariff-rate quotas allow a certain quantity to enter at a reduced tariff rate, and once this is reached, the product can still enter but at a higher tariff.

Import tariff: An import tariff is a customs duty levied on an imported product. There are different types of tariffs: ad valorem tariffs (see Annex: ad valorem tariff), specific tariffs (see Annex: specific tariff), tariff-rate quotas (see Annex: import quotas) and compound tariffs, which combine an "ad valorem" duty and a "specific" duty, added together or subtracted from each other.

International marine bunkers: Includes marine fuels delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship.

Inter-regional trade: This covers all trade flows that move between distinct modelling regions, but does not capture any flows of international trade that might be taking place between countries belonging to the same modelling region.

Investment overnight: These are the capital costs (USD) that are considered to be incurred in a single time period ("overnight"), i.e. at the time of installation of a facility or deployment of a technology. They are calculated by multiplying the unit capital expenditure, without accounting for discount rates with the capacity additions (GW or GWh of annual capacity).

Investment spending: Investment spending (USD) is derived from overnight investments using the assumption of an even distribution of expenditure over the period between FID and the start of operations. This period is assumed to be 2 years for all materials, technologies and components considered in the analysis, apart from solar PV modules and cell facilities, for which we assume a period of 1 year. An even spending profile during this period is assumed, meaning that an investment with a 2-year FID-to-operation period will see 50% of the spending take place in the year the facility becomes operational and 50% the year before.

Investments: Investments always refer to manufacturing capacity investment if not stated otherwise. Investments for manufacturing of clean technologies and materials refer to greenfield capacity additions only. They do not include upgrades to existing facilities for clean technologies, while for materials the conversion of existing capacity to near-zero ones is accounted for (assuming the same cost as greenfield investment).

Levelised cost of production (LCOP): A measure of the average cost of producing a unit of output from a manufacturing facility over its lifetime.

Local content requirements: Policies that specify a minimum share of domestically manufactured goods, domestically supplied services or domestic labour that must contribute to a product or service, often expressed as a percentage of the final value. Certain incentives may be available only for products that meet these local content thresholds.

Low-emissions fuels: Includes bioenergy, low-emissions hydrogen and low-emissions hydrogen-based fuels.

Low-emissions hydrogen: Includes hydrogen which is produced through water electrolysis with electricity generated from a low-emissions source (such as renewables, e.g. solar and wind turbines, and nuclear). Hydrogen produced from biomass or from fossil fuels with carbon capture, utilisation and storage (CCUS) technology is also counted as low-emissions hydrogen. Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture – at high rates – is applied to all CO_2 streams associated with the production route, and if all CO_2 is permanently stored to prevent its release into the atmosphere. The same principle applies to low-emissions feedstocks and hydrogen-based fuels made using low-emissions hydrogen and a sustainable carbon source (of biogenic origin or directly captured from the atmosphere).

Low-emissions hydrogen-based fuels: Fuels produced from low-emissions hydrogen. Includes ammonia, methanol and other synthetic hydrocarbons (gases and liquids) made from low-emissions hydrogen when any carbon inputs, e.g. from CO_2, are not from fossil fuels or fossil-derived process emissions.

Manufacturing capacity: The maximum amount of a material, component or technology a facility is nominally able to produce.

Maritime chokepoints: A strategic, narrow passage connecting two larger areas of the world's oceans and seas. They are often straits or canals through which a significant share of global vessels transit.

Market size: The market size (USD) for clean technologies and materials is calculated based on the demand for this technology or material multiplied by its global unit price. In the calculation of total market size for clean technologies as a whole, only the final components are taken into account if these are in a serial supply chain, e.g. the market size for PV is equal to the market size for modules. For the case of the EV and batteries supply chain, the market size includes the total value of all electric cars (with their battery therein), as well as the value of batteries used in electric two- and three-wheelers, light commercial vehicles, buses, trucks, and stationary storage (altogether referred to as “other batteries”).

Modern bioenergy: Bioenergy including liquid biofuels (biogasoline, biodiesel, biojet kerosene, other liquid biofuels), biogases (biogas, biomethane) and all solid bioenergy products, except the traditional use of biomass.

NACE codes: NACE (Nomenclature statistique des Activités économiques dans la Communauté Européenne [Statistical Classification of Economic Activities in the European Community]) Codes are a standardised numerical system to classify industrial sectors within the European Union. NACE codes are used by authorities for statistical purposes and can correspond with the United Nations ISIC classification system.

Near-zero emissions materials: in this report, technologies that can produce steel from iron ore, aluminium from bauxite, and ammonia with emissions intensities that are compatible with the IEA Net Zero Emissions by 2050 Scenario are referred to as “near-zero emissions technologies”, and their outputs as “near-zero emissions materials’’. See Box 1.1 for more details.

Net Zero Emissions by 2050 Scenario (NZE Scenario): This scenario is a normative scenario that sets out a pathway to stabilise global average temperature at 1.5°C above pre-industrial levels. The NZE Scenario achieves global net zero energy sector CO_2 emissions by 2050 without relying on emissions reductions from outside the energy sector. In doing so, the advanced economies reach net zero emissions before EMDEs. The NZE Scenario also meets the key energy-related UN Sustainable Development Goals, achieving universal access to energy by 2030 and securing major improvements in air quality.

Non-tariff measures (NTM): Policy measures, other than ordinary customs tariffs, that can potentially have an impact on the value, quantity or quality of traded goods. These typically include regulations and technical specifications, such as requirements for efficiency, durability, environmental impact or safety, which can have a significant impact on trade costs, especially if they differ significantly between countries.

OPEX: Operating expenses (or operational expenditure), including both fixed and variable operating expenses.

Ro-Ro (roll-on/roll-off) shipping: Ro-Ro shipping involves the transportation of vehicles and wheeled cargo, such as cars, trucks, trailers and heavy machinery, that can be driven directly on and off the ship.

Shipping activity: In this report, shipping activity is defined as the mass of cargo multiplied by the distance over which the cargo is moved.

Specific tariff: A fixed charge levied at the point of import based on a defined physical quantity, such as per tonne or per unit, regardless of the value of the imported product.

Stated Policies Scenario (STEPS): This scenario is designed to provide a sense of the direction the energy system is heading in, based on a detailed review of the current policy landscape. The STEPS looks in detail at what governments are actually doing to reach their current targets and objectives across the energy economy. Outcomes in the STEPS reflect a detailed sector-by-sector review of the policies and measures that are actually in place or that have been announced; the aims of these policies are not automatically assumed to be met; they are incorporated in the scenario only to the extent they are underpinned by adequate provisions for their implementation. Aspirational energy or climate targets are not taken into consideration. This scenario also takes account of projects that have been announced to build manufacturing capacity for clean energy technologies and associated materials for which funds have been committed, i.e. they have reached the stage of a final investment decision (FID). In the case of local content requirements, a corresponding level of domestic production is assumed for certain components, depending on the technology and type of requirement.

Traditional use of biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire or basic improved cook stoves (ISO tier < 3), often with no or poorly operating chimneys. Forms of biomass used include wood, wood waste, charcoal, agricultural residues and other bio-sourced fuels such as animal dung.

Total cost of ownership (TCO): The total costs associated with acquiring, operating, and maintaining an asset over its lifecycle.

Twenty-foot equivalent unit (TEU): A standard unit of measurement used in the shipping industry to describe the capacity of container ships, and the volume of cargo handled at ports. It represents the size of a standard shipping container of size 20x8x8.5 ft.

Utilisation rate: The proportion of the maximum capacity of a facility which is used on average over a set period of time. For the purposes of *ETP-2024* and its respective modelling, this period is a calendar year.

Value added: A measure which reflects the value generated by producing goods and services. Value added is measured as the value of output minus the value of intermediate consumption.

Wet bulk shipping: Wet bulk shipping involves the transportation of liquid commodities in large volumes, such as crude oil, petroleum products, liquefied natural gas (LNG), chemicals, and other liquid cargo. These materials are typically carried in tankers, which are specially designed to transport fluids safely. The ships used are referred to as tankers, with specialised variants like oil tankers and chemical tankers.

Abbreviations and acronyms

ACC	Advanced Chemistry Cell
AFIR	Alternative Fuels Infrastructure Regulation
AiP	Approval in principle
AIS	Automatic Identification System
ALMM	Approved List of Models and Manufacturers
AMP	Alternate Maritime Power
APEC	Asia-Pacific Economic Co-operation
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
AVE	Ad valorem equivalent
BC	Back contact (cells)
BEV	Battery electric vehicles
BF-BOF	Blast furnace basic oxygen furnace
BIL	Bipartisan Infrastructure Law
BNDES	The National Bank for Economic and Social Development (Brazil)
BOF	Basic oxygen furnace
BP	Bayer process
BRI	Belt and Road Initiative
BTL	Biomass to liquid
CAPEX	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CII	Carbon Intensity Index

CO_2	Carbon dioxide
COP	Coefficient of performance
DAC	Direct air capture
DC	Direct Current
DRI	Direct reduced iron
EAF	Electric arc furnace
EC	European Commission
EEDI	Energy efficiency design index
EGA	Environmental Goods Agreement
EHPA	European Heat Pump Association
EIB	European Investment Bank
EITI	Extractive Industries Transparency Initiative
EMDE	Emerging markets and developing economies
ESG	Environmental, social and governance
ETP	Energy Technology Perspectives
ETS	Emissions Trading Scheme
EV	Electric vehicles
FAME	Faster Adoption and Manufacturing of Electric Vehicles
FAME	Fatty acid methyl ester
FAO	Food and Agriculture Organization
FID	Final investment decision
FTA	Free trade agreement
GDP	Gross domestic product
GEC	Global Energy and Climate
GHG	Greenhouse gas
GTFS	Green Technology Financing Scheme
GWP	Global warming potential
GX	Green Transformation
G7	Group of Seven
HFC	Hydrofluorocarbons
HFO	Heavy Fuel Oil
HH	Hall-Heroult
HHI	Herfindahl-Hirschman Index
HJT	Heterojunction (cells)
HPC	High Potential Case
HS	Harmonized Commodity Description and Coding System
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IDDI	Industrial Deep Decarbonisation Initiative
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development

ILO	International Labour Organization
IMF	International Monetary Fund
IMO	International Maritime Organization
IOE	Iron ore electrolysis
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
ISIC	International Standard Industrial Classification of All Economic Activities
ITC	International Trade Commission
ITU	International Telecommunications Union
JPN	Japanese yen
LCOP	Levelised cost of production
LFP	Lithium iron phosphate
LNG	Liquefied natural gas
LOI	Letter of intent
LPG	Liquefied petroleum gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MaT	Manufacturing and trade
MDB	Multilateral development banks
MEPS	Minimum Energy Performance Standards
MFN	Most-Favoured Nation
MIIT	Chinese Ministry of Industry and Information Technology
MOU	Memorandum of Understanding
MOVER	Green Mobility and Innovation Program (Brazil)
MSW	Municipal solid waste
NMC	Lithium nickel manganese cobalt oxide
NTM	Non-tariff measure
NZE	Net Zero Emissions by 2050 Scenario
NZIA	Net-Zero Industry Act
N_2O	Nitrous oxide
NO_X	Nitrogen oxides
NH_3	Ammonia
OCC	Onboard Carbon Capture
OCED	Office of Clean Energy Demonstrations (United States)
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OPEX	Operating expenditure
PEM	Proton exchange membrane
PERC	Passivated emitter rear cells
PHEV	Plug-in hybrid vehicles
PLDV	Passenger light-duty vehicles
PLI	Production Linked Incentive
PTA	Preferential trade agreements
PTC	Production tax credits
PV	Photovoltaic
PWR	Pressurized water reactors

R&D	Research and development
RCA	Revealed comparative advantage
RCEP	Regional Comprehensive Economic Partnership
RD&D	Research, Development and Demonstration
RISE	Regulatory Indicators for Sustainable Energy
Ro-Ro	Roll-on/Roll-off
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCOP	Seasonal coefficient of performance
SIGHT	Strategic Interventions for Green Hydrogen Transition
SMR	Small Modular Reactors
SMR	Steam methane reforming
SOE	Solid oxide electrolyser
STEPS	Stated Policies Scenario
SUV	Sport utility vehicle
TBT	Technical Barriers to Trade
TESSD	Trade and Environmental Sustainability Structured Discussions
TOPCon	Tunnel Oxide Passivated Contact
TRL	Technology readiness level
UNCTAD	United Nations Trade and Development
UNIDO	United Nations Industrial Development Organization
USD	United States dollars
USMCA	United States-Mexico-Canada Agreement
VLBC	Very large bulk carriers
VLOC	Very Large Ore Carriers
WACC	Weighted average cost of capital
WCO	World Customs Organization
WIPO	World Intellectual Property Organization
WPID	Working Party on Industrial Decarbonisation
WTO	World Trade Organization
ZEV	Zero-emission vehicle

Units of measure

DWT	Deadweight tonnage
EJ	exajoule
FEU	Forty-foot Equivalent Unit
g CO_2	grammes of carbon dioxide
g CO_2/kWh	grammes of carbon dioxide per kilowatt hour
GJ	gigajoule
Gt	gigatonnes
Gtce	gigatonnes of coal equivalent
Gt CO_2	gigatonne of carbon dioxide
Gt/yr	gigatonnes per year

GW	gigawatt
GWh	gigawatt hour
kg	kilogramme
km	kilometre
kt	kilotonne
kW	kilowatt
kWh	kilowatt hour
mb/d	million barrels per day
MJ	megajoule
Mt	million tonne
MTEU	million twenty-foot equivalent units
Mtpa	million tonnes per annum
MW	megawatt
MWh	megawatt hour
PJ	petajoule
t	tonne
tcm	trillion cubic meters
TEU	Twenty-foot equivalent units
tkm	tonne-kilometre
toe	tonne of oil equivalent
TW	terawatt
TWh	terawatt hour
W	watt

Currency conversions

Exchange rates (2023 annual average)	1 US dollar (USD) equals:
British Pound	0.80
Chinese Yuan Renminbi	7.08
Euro	0.92
Indian Rupee	82.60
Japanese Yen	140.49
Korean Won	1 305.66

Note: all values are expressed in the 2023 USD.

Regional groupings

Advanced economies: Australia, Austria, Belgium, Bulgaria, Canada, Chile, Colombia, Costa Rica, Croatia, Cyprus,[7,8] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel,[9] Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, United Kingdom and United States.

Africa: Algeria, Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Kingdom of Eswatini, Libya, Madagascar, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo (Congo), Rwanda, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Tunisia, Uganda, Zambia, Zimbabwe and other African countries and territories.[10]

Asia Pacific excluding China: Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[11]

Central Africa: Burundi, Chad, Cameroon, Central African Republic, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Republic of the Congo (Congo), Sao Tome and Principe.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Bolivarian Republic of Venezuela (Venezuela), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru,

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[7] Note by Republic of Türkiye: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the "Cyprus issue".

[8] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

[9] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[10] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Malawi, Mali, Mauritania, Sao Tome and Principe, Seychelles, Sierra Leone and Somalia.

[11] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga and Vanuatu.

Suriname, Trinidad and Tobago, Uruguay and other Central and South American countries and territories.[12]

China: Includes (The People's Republic of) China and Hong Kong, China.

East Africa: Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Seychelles, Somalia, South Sudan, Sudan, United Republic of Tanzania (Tanzania) and Uganda.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping. For the purposes of Chapter 4, the term “emerging markets” refers to all the countries in Latin America, Africa and Southeast Asia.

Eurasia: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, the Russian Federation (Russia), Tajikistan, Turkmenistan and Uzbekistan.

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, Gibraltar, Iceland, Israel,[13] Kosovo, Montenegro, North Macedonia, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus,[14,15] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

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[12] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), Grenada, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten (Dutch part), Turks and Caicos Islands.

[13] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[14] Note by Republic of Türkiye: The information in this document with reference to “Cyprus” relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the “Cyprus issue”.

[15] Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

North America: Canada, Mexico and United States.

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Southern Africa: Angola, Botswana, Kingdom of Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Zambia and Zimbabwe.

West Africa: Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo.

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Cover design: IEA
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