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Abstract

The 2026 edition of *Energy Technology Perspectives* is published against the backdrop of a fast-changing policy and technology landscape. Governments are working to establish secure and resilient supply chains for clean energy technologies while advancing key energy policy goals such as energy security, affordability and economic competitiveness, as well as climate and other environmental goals. In a landscape that is constantly evolving, this report aims to deliver timely insights into the status and outlook of technology deployment, manufacturing, project pipelines, investments, and trade of different energy technologies and materials. The aim is to provide useful analysis that can inform the considerations of policy makers around the world.

Energy Technology Perspectives 2026 examines demand-side dynamics for energy technologies — such as deployment trends and policy developments — as well as supply-side factors, including manufacturing capacity and trade flows, underpinned by robust modelling and quantitative analysis. This year's edition puts a special focus on vulnerabilities in energy technology supply chains and industrial competitiveness, analysing manufacturing cost structures and industrial policy impacts.

The IEA's *Energy Technology Perspectives* (*ETP*) series serves as the world's guidebook for clean energy technologies. As the IEA's flagship technology publication, *ETP* has been a key source of insights on all matters relating to energy technology since 2006. Over the past 20 years, *ETP* has expanded to encompass more data and analysis on different aspects of energy technologies, including infrastructure, supply chains and beyond. The 2026 edition aims to provide a comprehensive update on today's most pressing energy technology issues.

Foreword

As governments seek for new ways to drive economic growth and support national prosperity, many are looking at the potential opportunities from the emerging Age of Electricity that the International Energy Agency (IEA) has repeatedly highlighted in our recent analysis.

The data shows why. Today, a group of key technologies contributing to the Age of Electricity – including solar panels, wind turbines, batteries, electric cars, electrolysers and more – already represents a USD 1 trillion market. And in all of the IEA's scenarios about the future of energy, this valuation is set to rise sharply over the next decade, driven in part by booming demand for electricity.

Most of this value comes from more established technologies such as electric cars and renewables. They have all benefited from mass manufacturing and cost reductions and are an important reason why the Age of Electricity has emerged so rapidly.

At the same time, many emerging technologies are moving faster than you might think. Take electrolysers for low-emissions hydrogen production: despite a recent wave of project delays and cancellations, the anticipated surge in deployment by the end of this decade mirrors the pace of expansion seen when growth in solar PV first started to climb. Meanwhile, technologies still in early stages of development – such as nuclear fusion – are capturing widespread attention, although their real-world viability and impact still need to be proven.

Given the scale of the opportunity, countries and companies have been racing to secure their place in this fast-growing segment of the energy economy. Yet in the 17 months since we published our last *Energy Technology Perspectives* report, the backdrop has undoubtedly become more complex. Shifting policies, economic conditions and technological progress are creating uncertainty about the prospects and economic potential of these technologies.

This edition of *Energy Technology Perspectives*, the latest instalment of the IEA's flagship technology publication, provides fresh data and analysis to help make sense of this landscape, enabling decision makers to separate signal from noise. Its analysis of the factors that shape competitiveness in energy technology manufacturing – which highlights potential supply chain vulnerabilities and their implications for economic security – makes it a must-read for anyone developing industrial strategies and partnerships.

Several high-level takeaways stand out. First, the size of this opportunity will ultimately rely on the combination of energy, industrial and trade policies, all of which are closely intertwined. Countries will need to chart their own courses based on their resources and priorities. But even as many increasingly adopt defensive positions with the goal of protecting domestic industries, our analysis shows that the energy technologies examined in this publication will remain an important feature of global trade. While tariff increases are expected to put pressure on average costs for consumers, the impact will differ by technology – and the economics, in many cases, are still set to favour strong growth.

Second, international collaboration remains highly valuable, allowing countries to play to their strengths. Securing a competitive edge in technology supply chains will rely not only on support for domestic manufacturing, but also on establishing strategic partnerships with countries and companies around the world. This can reduce costs and increase diversification, which is crucial for energy security.

I would like to thank the dedicated members of the *ETP* team who produced this timely and insightful report under the leadership of the IEA's Chief Energy Technology Officer, Timur Gül. I hope decision makers around the world will find this data-driven analysis instructive as they look towards the future.

Dr Fatih Birol

Executive Director

International Energy Agency

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Executive summary

Deployment of many clean energy technologies, fuels and materials has been growing fast, but shifting policies, economic conditions and technological progress are creating uncertainty about their prospects and economic potential. Against this backdrop, the IEA's flagship technology publication *Energy Technology Perspectives (ETP)* aims to separate the signal from the noise, by providing timely data, scenarios and analysis across deployment, manufacturing, trade, competitiveness and security. At a time when misjudging the moment risks wasting capital or stalling momentum, this report has been designed to help decision makers navigate uncertainties.

Despite headwinds, the markets for clean energy technologies and fuels are expanding rapidly

Deployment of clean energy technologies rises in all IEA scenarios,[1] but the extent to which the market value grows will depend on policy direction. The combined global market value for clean energy technologies has grown 20% on average per year over the past decade, to reach nearly USD 1.2 trillion in 2025. In the Current Policies Scenario (CPS), their global market value grows most slowly, but it still doubles to around USD 2 trillion in 2035, about the size of the global crude oil market in 2025. At almost USD 3 trillion by 2035, their market value is higher in the Stated Policies Scenario (STEPS), with greater deployment offsetting the additional decline in costs. Electric cars are by far the largest clean energy technology market in 2035, accounting for around three-quarters of the total market value in all scenarios.

There are many growth opportunities for low-emissions fuels, especially those that can be directly used in existing infrastructure. In several segments – notably cars – low-emissions fuels are not only competing with fossil fuels, but increasingly with the rising use of electricity. However, the medium-term growth prospects remain bright: their market value grows significantly in both the CPS and the STEPS, from around USD 215 billion in 2025 to about USD 390 billion in 2035, equivalent to about 20% of the combined market for diesel and gasoline used in transport. Around 60% of this growth comes from the expansion of relatively mature biofuels such as biomethane, bioethanol and biodiesel.

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[1] ETP-2026 uses three main scenarios, consistent with those presented in the *World Energy Outlook 2025*. The CPS and the STEPS are exploratory and based on a set of starting conditions. The NZE Scenario is normative and describes a pathway to reduce global energy sector CO_2 emissions to net zero by 2050, while recognising that each country will follow its own route.

Increased use of fuels that are more costly and still at low levels of market penetration, such as sustainable aviation fuels and other hydrogen-based fuels, would require stronger policy support.

The market outlook for low- and near-zero emissions materials is very uncertain as production cost premiums remain high. Technologies like cement kilns fitted with carbon capture, and steel furnaces using electrolytic hydrogen, are expected to cost significantly more than their conventional counterparts over the next decade in most regions. The outlook for near-zero emissions materials is therefore highly dependent on policy support: the market value for near-zero emissions steel, cement, aluminium and ammonia reaches USD 5 billion in the CPS and USD 20 billion in the STEPS in 2035.

There is measurable progress across energy technologies that are at different stages of development today

The positive market outlook for clean energy technologies that underpin the age of electricity has been led by policy but is increasingly driven by cost-competitiveness. Cost reductions for many technologies like solar PV, batteries, electric cars or heat pumps have been enabled by their modularity and mass-manufacturing, while for others, like nuclear or geothermal, technology innovation has been a key driver. Around 80% of global solar PV and wind generation now occurs at lower levelised costs than for coal or gas, supporting a surge in global capacity additions. Battery prices have fallen by 75% over the past decade, boosting electric car sales and enabling a larger share of variable renewable energy in electricity supply. In some emerging markets, battery electric cars are becoming cheaper to buy than comparable internal combustion engine cars. The future pace of deployment of these technologies hinges on policy support to foster markets and overcome infrastructure bottlenecks.

There is evidence of progress – albeit less steady – for technologies at an early stage of deployment, and this is moving faster than many people think. Low-emissions hydrogen production; carbon capture, utilisation and storage (CCUS); and near-zero emissions material production typically involve large engineering projects that rely on policy support to scale up and reduce costs. Earlier high investor confidence and policy ambition has weakened recently, but growth opportunities exist. Global investment in low-emissions hydrogen production climbed to nearly USD 8 billion in 2025 – year-on-year growth of 80% – and expected growth in electrolyser deployment to 2030 is similar to the expansion seen as solar PV began to ramp up. For CCUS, average annual investment has grown more than 15-fold since 2020 to over USD 5 billion in 2025, with several landmark projects reaching final investment decisions (FIDs), though almost 90% of announced projects have not yet reached that milestone. Since 2020, new capacity for near-zero emissions steel production announced (105 Mt, around 5% of today's production) has been roughly double the conventional capacity added, but only 5% has reached FID.

Technologies at early stages of development, or with applications beyond energy, are capturing widespread attention, but their real-world viability and impact is yet to be proven. Start-ups developing technologies such as nuclear fusion, solid-state cooling, iron ore electrolysis, production of conventional cement without limestone or direct electrochemical ammonia production are now attracting increased investments. But they are still at early stages of technology readiness and face substantial technical and cost barriers. It is unlikely that they will reach significant market shares within a decade; if successful, however, they could trigger profound transformations, and these market shares could be worth trillions of dollars by mid-century. Several technical records for nuclear fusion were broken in 2025, and venture capital has flowed into the sector, but the timeline for commercialisation and technology costs remain deeply uncertain. Falling computation costs, more data and technical breakthroughs have driven AI capabilities to accelerate energy innovation, but the extent of its real-world impact remains to be seen.

Energy technology manufacturing and trade are showing signs of resilience to changes in industrial and trade policy

Many governments are adopting an increasingly defensive posture on clean energy technology trade, seeking to shield domestic industries from foreign competition and alleged unfair practices. Early evidence of the impact of tariff hikes in 2025 points to a flurry of short-term adjustments by manufacturers, including front-loaded shipments, deferred investments, precautionary stockpiles and a slowdown in some trade flows. However, of all global gross imports of clean energy technologies in 2025, only about 15% was accounted for by countries that now impose substantially higher tariffs. While tariff and duty increases are expected to put upwards pressure on average production and import costs, the impact in 2025 was, in many cases, partly balanced out by falling commodity prices, the substitution of imports with financially supported domestic production, and other alterations to trade patterns. Moreover, the impact of tariffs and duties on final consumer costs depends on the product: the same tariff levied on a final product like an electric vehicle has a greater impact than the same tariff applied to a system component, like solar PV modules, which typically account for around 10-15% of the consumer cost of a domestic rooftop solar installation in many advanced economies.

Trade continues to play a central role in the outlook for manufacturing key clean energy technologies, despite recent increases in tariffs. In the STEPS, the global value of net trade in these technologies more than doubles from USD 290 billion in 2025 to reach USD 620 billion by 2035. China remains the largest exporter by a wide margin, with the value of its net exports growing to USD 375 billion in 2035 – the latter figure is equivalent to around 10% of the country's total goods exports today. The projected rate of increase in the value of global trade is broadly in line with what was projected in *ETP-2024*, as trade policies are only one of many forces shaping clean energy technology supply chains; industrial and energy policies also play a role.

Continued industrial and trade policy responses to China's growing EV exports – worth an estimated USD 50 billion in 2025 – have increasingly re-routed them to new markets. While emerging economies accounted for less than 5% of China's EV exports in 2020, they now represent nearly 40%. In Central and South American countries, Chinese EVs are projected to make up around half of total EV sales on average in the STEPS by 2035. In the European Union, maintaining existing countervailing duties helps prevent the share of Chinese imports in the region's EV sales from increasing significantly above today's level of around 20% through to 2035. Nevertheless, given the size of the market, the region becomes the largest source of growth for China's EV exports in absolute terms. China remains the world's largest EV exporter in the STEPS to 2035, as exports grow almost sixfold. The North American market remains virtually closed to Chinese EV imports in this scenario.

Industrial and trade policies introduced in the United States and India are boosting downstream stages of solar PV manufacturing domestically, though China remains the largest producer across all supply chain steps. India experiences the largest increase in share of global production in the STEPS, rising from 3% in 2024 to more than 10% by 2035, and becomes a net exporter of modules by 2030. Existing policies and a decline in demand in the United States lead to near self-sufficiency by 2030 in the STEPS. In the European Union, the Net-Zero Industry Act has moved to the implementation phase, but the targets it sets are not accompanied by systematic financial support for domestic investment. This is reflected in the limited announcements for new solar PV manufacturing facilities and the targets not being met in the STEPS.

Concentration in clean energy technology supply chains remains a source of vulnerability

New analysis shows that production outside the largest exporter of clean energy technologies could, in principle, meet most demand in those countries on aggregate, but there are weak links within each supply chain. Each of the key supply chains analysed contains at least one step where less than one-quarter of demand outside of China could be met with supply outside of China, posing risks to the resilience of the entire supply chain. China's manufacturing strengths mean the country accounts for 60-85% of production capacity for key supply chains, and over 95% for some production steps. The economic impact of a disruption would differ for each supply chain and technology. For example, each month of a halt in battery supply chain exports from China would lead to an estimated loss in output of USD 17 billion from electric car factories elsewhere, with facilities in the European Union accounting for over half of the losses. Each month of disruption of Chinese exports of solar supply chain components would mean that solar PV module production plants outside China lose output worth around USD 1 billion, with more than 40% of the affected output located in Southeast Asia and India.

Supply chain concentration is especially acute for metal and mineral processing, and midstream production steps. Metals and mineral processing capacity outside China is adequate for materials like steel and copper, but far from sufficient for most critical minerals. Magnet rare earth elements – used in wind turbines and electric cars as well as multiple other technologies from drones to data centres – are particularly affected, as refining is dominated by China; the vulnerabilities associated with such dependencies were brought into sharp focus when China recently announced export restrictions on these elements. On the basis of committed manufacturing and mining projects, and projected market trends in the STEPS, no major change in the diversity of clean energy technology supply chains is likely to occur before 2030.

The impact of Chinese clean energy technology manufacturing companies extends beyond the country's borders. Chinese firms account for a large portion of production capacity located outside China in the solar PV industry. In contrast, Chinese ownership of battery manufacturing capacity outside China remains limited (5%) but is expected to rise to around one-quarter by 2030 based on projects in construction or at FID. Dependencies in the supply chain extend to IT systems; increased digitalisation brings exposure to new, evolving cybersecurity risks that can affect energy technologies' control systems, and with them entire distribution grids.

The present wave of clean energy technology manufacturing investment is waning – the future trajectory of investment will be shaped by efforts to diversify supply chains. Global manufacturing investment for key clean energy technologies fell back slightly to just under USD 200 billion in 2024 from a high of USD 220 billion in 2023, and it is expected to have continued to decline gently through to year-end 2025. Manufacturing investment for most technologies does not return to the levels reached over the past 2 years in the STEPS and CPS through to 2035. This is largely due to a surplus of existing manufacturing capacity relative to current demand for solar PV and batteries, and because increased investment to meet future demand for EVs is offset by reduced investment for other technologies. Continued manufacturing investment in the STEPS is, in large part, driven by efforts to diversify supply chains: for example, the combined share of the European Union and the United States in global clean technology manufacturing investment increases from less than 25% in 2024 to more than 35% on average during 2031-2035.

If not addressed, industrial competitiveness could become a stumbling block for energy and economic policy goals

In clean energy technology manufacturing, the factors shaping industrial competitiveness differ across supply chains. China's competitive edge and low costs reflect decades of accumulated advantages, including innovation, large-scale production, manufacturing efficiency, a skilled workforce, integrated supply chains and access to cheap resources and labour – all reinforced by consistent policy and financial support**.** Across all supply chains considered, there are opportunities to reduce the cost gap with China as experience ramps up in other countries, and through continued innovation. For batteries, higher manufacturing efficiency accounts for over 40% of the cost difference between China and Europe. Energy and labour cost differences account for a large share of the cost gap with Europe in energy and labour-intensive steps, such as upstream solar PV manufacturing (65% of the gap) and in wind blade production (75%). Electrolyser manufacturing is not yet established at scale anywhere, and there is a trade-off between low-cost production, efficiency and durability, meaning that production in advanced economies can still be competitive.

In upstream industries like steel, aluminium and chemicals, energy costs remain critical to competitiveness in near-zero emissions material production. Energy costs can account for over two-thirds of total production costs in upstream industries; for near-zero emissions technologies, energy spending could be several times higher. The impacts are profound: During the 2022 global energy crisis, for example, output from upstream industries in the European Union fell sharply. In contrast, since the early 2020s, access to cheap shale gas in the United States has significantly increased its share of global petrochemical feedstock and product exports. Low-cost renewables could make hydrogen-based steelmaking cost-competitive with conventional technologies in the future under specific conditions in some major steel-producing countries like the United States, China and India. In others, like Europe and Japan, higher prices mean production costs would remain 50-80% higher than elsewhere, surpassing regional differences for conventional steel production. Yet offshoring ironmaking to regions with competitive renewables could cut these cost differences to 30-40%, with limited effects on jobs.

To rise to the moment, countries will need to identify and play to their strengths and look to strategic partnerships to increase industrial competitiveness. While downstream industries typically generate more direct value added to the economy, strategic upstream industries are a source of indirect value creation, and are crucial to multiple sectors beyond energy, including defence. There is a balance to be struck between domestic production and imports of technologies and materials; the way this balance plays out depends on the relative strategic importance of these industries. Some emerging markets with particularly low energy costs – such as in the Middle East or North Africa – could achieve production costs even lower than China's for energy-intensive processes. Producing solar PV modules made in the European Union with imported wafers from North Africa could cost almost 20% less than producing a fully EU-made module. India, Southeast Asia and the Middle East could, in principle, produce polysilicon and wafers at comparable costs to China, and Southeast Asia already has production capacity in place for these commodities. For wind turbines, producing in Europe while importing components from India could cost only 15% more than producing turbines in China, cutting 75% of the production cost gap between Europe and China. Strategic co-operation between countries for specific supply chain steps can reduce costs and increase diversification.

Introduction

Report scope and structure

The International Energy Agency's (IEA) *Energy Technology Perspectives (ETP*) flagship series of reports has been providing critical insights into the technological dimensions of the energy sector since 2006. Revamped in 2020, it now serves as a guidebook for clean energy technologies globally, focusing on themes that are particularly pertinent for policy makers. This reflects the pivotal role of those technologies and innovation in meeting the policy goals of energy security, economic development and environmental sustainability. This new edition of *ETP* aims to provide a comprehensive update on developments related to energy technologies, with a special focus on security of supplies and industrial competitiveness.

In the context of a fast-changing geopolitical landscape, this new *ETP* edition provides insights into the status of and outlook for the deployment and manufacturing of clean energy technologies and related materials, including production costs, affordability, project pipelines, investments and international trade. It also examines the drivers of market dynamics, including both demand and supply-side factors, with a particular focus on policy developments. The quantitative analysis draws on the IEA's *Global and Energy Climate model* (IEA, 2025a) and *Manufacturing and Trade model* (IEA, 2026).

The analytical scope of the report differs for technology deployment and manufacturing. The analysis of technology deployment covers a very wide range of technologies and materials; some, such as carbon capture utilisation and storage, sustainable aviation fuels, alternative propulsion systems for ships and near-zero emissions cement, are at an early stage of deployment today. The analytical scope for manufacturing is narrower and limited to technologies and components that have complex supply chains and that are mass-manufactured and traded today, such as batteries, solar PV or wind.

Chapter 1 of this year's *Energy Technology Perspectives* is overarching and addresses ten key questions related to energy technologies and their supply chains, each of which is inherently complex and for which the IEA has observed over the past year a need for analytical insights among high-level decision makers in government and the private sector. The remainder of the report is presented in three parts: Part A explores the outlook for the deployment of energy technologies, materials and fuels on the basis of IEA scenarios. It features visual dashboards with key metrics for each major technology, including market size, cost competitiveness, technical performance, infrastructure needs and innovation. Part B examines the current state and the outlook for manufacturing and trade. Part C assesses the risks posed by high levels of concentration in the supply chains of selected clean energy technologies, examines the drivers and trends in industrial competitiveness across regions, and explores strategies for narrowing competitiveness gaps in selected clean energy technologies as a means of promoting diversification and reducing the concentration of supply. It ends with an overview of strategic considerations for navigating tensions and trade-offs between different policy goals in view of security risks and competitiveness challenges.

Scenarios

As in previous editions of *ETP*, the projections for technology deployment, manufacturing and trade presented here are based on scenarios analysis. The scenarios differ primarily in their assumptions about government policies. Three scenarios are used in this report:

- The **Stated Policies Scenario (STEPS)** is designed to reflect the direction of travel of the global energy sector based on current energy-related policies, including those that have already been adopted, announced, or are in the advanced planning stage – even if they are not yet enshrined in law or regulations. Examples of the latter include power sector development plans aimed at achieving a certain mix of generation assets by a specific date, regulatory reforms in the transport sector and energy efficiency targets for appliances. Policy targets are not assumed to be automatically met: in each case, their prospects are assessed taking account of market, infrastructure readiness and financial constraints. The STEPS assumes that time-bound policies continue beyond the currently-stated durations and retain a similar pace of change. However, it does not assume that aspirational goals, such as those included in the Paris Agreement, are achieved.
- The **Current Policies Scenario (CPS)** sets out a pathway for the future of the energy system in which no change in energy-related policies is assumed beyond what is already in place. The CPS therefore builds on a narrow reading of today's policy settings, only considering those that are adopted in legislation and regulation, and assuming no changes will be made, even where governments have indicated their intention to do so. Where existing policies target a range of outcomes, it is assumed that the lower end of the range is achieved. In the CPS, policies that are time-bound or that target specific years are not strengthened after they expire. Alongside this view of the policy landscape, the CPS also offers a generally cautious perspective on the speed at which new energy technologies are deployed and integrated into the energy system. It tends to project slower adoption of new technologies in the energy system than seen in recent years, or than projected in the STEPS.

- The **Net Zero Emissions by 2050 (NZE) Scenario** is a normative scenario that maps out a global pathway for the energy sector to achieve net zero carbon dioxide (CO_2) emissions by 2050, consistent with the long-term goal of limiting the rise in global average temperatures to 1.5°C (with a 50% probability). In contrast with previous editions, the NZE Scenario is no longer a low-overshoot scenario: it assumes that warming exceeds 1.5°C degrees for several decades before returning below 1.5°C by 2100. This adjustment reflects persistently high emissions in recent years and the slow deployment of some key technologies. Achieving this pathway requires not only a very rapid transformation of the energy sector but also large-scale deployment of CO_2 removal technologies, which remain unproven at large scale.

All scenarios use 2024 as the base year and extend annually to 2050, although the analytical focus is on the next 10 years. In some instances, historical data on energy technology supply and demand, markets and technology costs are provisional or estimated. Population and economic growth rates are assumed to be similar in all scenarios.

As the IEA's guidebook on clean energy technologies, the primary focus of the *ETP* scenario analysis is on the STEPS to assess the implications of current government energy-policy intentions for the future deployment, manufacturing and trade of clean energy technologies and materials. The CPS and NZE Scenario are used mostly for the purpose of benchmarking to reflect on lower and higher outlooks for deployment.

It is important to note that none of the scenarios is a prediction or forecast. Rather, they serve as analytical tools to explore the implications of different policy and technology choices. They provide a quantitative framework to support decision-making in the energy sector and offer strategic guidance on technology choices for governments and other stakeholders. The scenarios are consistent with those presented in the *World Energy Outlook 2025* (IEA, 2025b).

References

IEA (2025a). *Global Energy and Climate Model documentation*. Retrieved from: https://www.iea.org/reports/global-energy-and-climate-model

IEA (2025b). *World Energy Outlook 2025*. Retrieved from: https://www.iea.org/reports/world-energy-outlook-2025

IEA (2026). *Manufacturing and Trade Model documentation*. Retrieved from: https://www.iea.org/reports/manufacturing-and-trade-model

Chapter 1. Ten key questions about energy technologies and their supply chains

Introduction

The global energy system is in flux, providing the backdrop to the analysis of energy technologies and their supply chains set out in this edition of the *ETP*. Decision-makers are confronted by a constant stream of energy-related headlines, often stripped of context. A development that might transform investment decisions in one region may barely register elsewhere or even have the opposite effect.

Over the past year, the uncertainties clouding the outlook for energy technologies have intensified. Governments and companies are pushing ahead with plans to expand manufacturing capacity for technologies such as solar photovoltaic (PV), batteries and lower-emissions steel plants, despite sizeable global surplus capacity. Long-standing assumptions about steady cost declines are being tested, in part by the imposition of import tariffs whose implications are not always clear. As the energy system electrifies, optimistic expectations about demand growth spurring investment sit uneasily alongside reports of shortages in critical grid components. In areas such as carbon capture, utilisation and storage (CCUS) and hydrogen, announcements of record investment coincide with what appear to be contradictory claims of sluggish deployment and rising costs.

This chapter draws together the latest IEA analysis of these issues and highlights insights from the chapters that follow, organised around ten questions on energy technologies and supply chains. The questions and answers are intended to engage senior decision-makers by providing a clear, factual and neutral guide to today’s most pressing developments – not an exhaustive account, but a concise guide to what matters now. Those questions are:

1. How are recent shifts in trade policy affecting clean energy technology supply chains?
2. How will today’s low profits in clean energy technology manufacturing affect innovation and investment?
3. How can policy help close the cost gap with the People’s Republic of China (hereafter, “China”) in energy technology supply chains?

4. Is the current electricity transformer shortage a cause for concern?
5. Is there a case for investing in a domestic battery sector when China holds such a large cost advantage?
6. Has the hydrogen bubble burst?
7. Is carbon capture, utilisation and storage finally taking off?
8. Large, modular and fusion reactors all have renewed momentum: how quickly can nuclear be brought online?
9. Can heavy industries in advanced economies restore their competitive edge?
10. Is there a technology on the horizon that can replicate the explosive growth of solar PV and batteries?

Some of these questions concern technologies such as transformers, CCUS, hydrogen and nuclear energy that fall outside the scope of *ETP-2026*, which focuses on clean energy technology supply chains. The answers to the others draw directly on data and assessments presented elsewhere in the report; these are summarised here, with references in the text to guide readers to the full analysis.

1. How are recent shifts in trade policy affecting clean energy technology supply chains?

Why it matters

Trade policy has rarely been so prominent in global headlines as in recent months. The total number of restrictive measures in place worldwide rose sixfold in less than a decade, from just over 600 in 2015 to nearly 3 300 in 2024 (Global Trade Alert, 2025). The first half of 2025 brought another wave of announcements, with tariffs being the predominant tool. Discriminatory trade measures can take several forms, but the result in most cases is to raise the relative price of imports. Tariffs are intended to shield domestic producers from foreign competition, but some of the increased costs of doing so will fall on consumers. Other measures such as quotas, export controls, border adjustments and standardisation rules, add further restrictions to cross-border trade.

The manufacturers of clean energy technologies are not immune to these developments. The rapid global rollout of many clean energy technologies in recent years has been underpinned by international trade, which has enabled economies of scale, specialisation and vigorous competition. Solar photovoltaic (PV) module prices have tumbled by around 85% over the past 8 years, driving a near-sevenfold increase in global deployment. Theoretically, mounting tariffs and other trade measures that push up prices risk stalling – or even reversing – these gains in the countries that impose them. Yet trade policy does not operate in isolation. Its effects on costs, prices and deployment depend on how it intersects with wider energy, climate and industrial policies, which can blunt or amplify its influence.

What is happening

Many governments are adopting a more defensive posture on trade, aiming to shield domestic industries from foreign competition and alleged unfair practices. Low-cost Chinese exports of clean energy technologies are accelerating deployment in several markets – especially in emerging economies – but growing unease over China's surplus industrial capacity and surging export volumes has prompted trade policy action from the United States, European Union and Canada. This is exemplified by these countries' deployment of duties to target imports of Chinese solar PV panels, wind turbines and electric vehicles (EVs) and "level the playing field" for domestic producers. More sweeping tariffs have also emerged: recently in the United States, and for a longer period in India, the government has imposed broad tariffs covering a wide range of goods.

Table 1.1 Announced trade-weighted average import tariff and duty rate on selected clean energy technologies, 2023 and 2025e

Product	United States			China			European Union			India		
	2023	2024	2025e	2023	2024	2025e	2023	2024	2025e	2023	2024	2025e
Solar PV modules	16%	246%	191%	0%	0%	0%	0%	0%	0%	38%	21%	21%
Wind nacelles	1%	1%	23%	8%	8%	18%	3%	3%	3%	10%	8%	8%
Battery cells	2%	19%	56%	9%	9%	9%	2%	2%	3%	20%	15%	16%
Electric vehicles	2%	2%	23%	15%	15%	16%	6%	16%	13%	125%	56%	56%
Average on all goods	2%	2%	18%	3%	3%	13%	3%	3%	3%	12%	12%	12%

Notes: e = estimated. The rates are calculated by combining all applicable duties, including base tariffs or preferential reductions, anti-dumping and countervailing duties and other surcharges, and weighting them by each partner country's share in total imports. Values for all goods are taken directly from The Budget Lab analysis and refer to the weighted average tariff rate across all imported goods.

Sources: IEA analysis based on World Trade Organization (2025); The White House (2025); US National Archives (2025); International Trade Administration (2025); Office of the United States Trade Representatives (2025); China, Ministry of Finance (2025); European Commission (2025); Diário Oficial da União [Official Diary of the Union] (2025); Sitharaman (2025); Brown (2025); Financial Times (2025); World Bank (2025); and The Budget Lab (2025).

For clean energy technologies, the steepest tariff increases have occurred in the United States, though they did not start from a blank slate. Several technologies or components, including solar PV modules, already faced substantial duties in 2024 (Table 1.1). China first responded with broad tariffs on a wide range of US goods and export controls on a set of materials and components that are critical to clean technology supply chains, from rare earth elements and magnets to high-energy-density battery materials and parts. Yet, as part of the October 2025 trade agreement, China agreed to suspend many of these retaliatory measures (see Chapters 4 and 5). Other US trading partners, notably the European Union, have launched public consultations, but have yet to take formal action. Elsewhere, tariff levels have remained broadly unchanged, though they remain high in India.

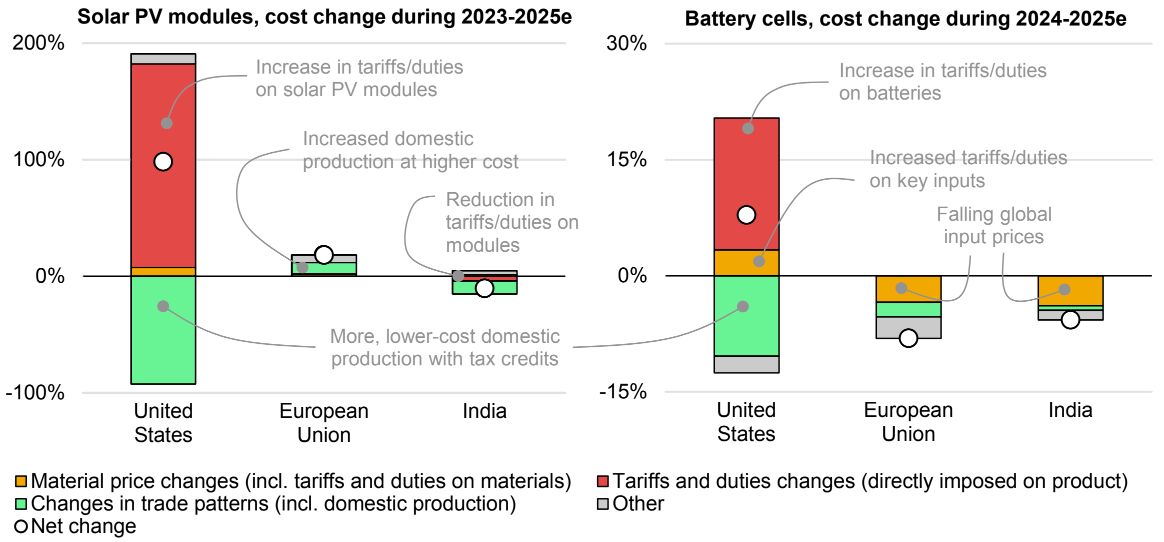
What it means

While tariffs are changing frequently at the moment, and the full impacts of the uncertainty this generates will take time to register, it is instructive to examine the potential impact on production costs. Early evidence of the impact of the recent tariff hikes in 2025 points to a flurry of short-term adjustments, including front-loaded shipments, deferred investments, precautionary stockpiles and a slowdown in trade flows. Disregarding these short-term impacts, our analysis shows that, where they are increased, tariffs put upwards pressure on average delivered costs (i.e. the average cost to customers considering both imported and domestically produced units).

In the United States, we estimate that average delivered costs increased by around 100% for solar PV modules during 2023-2025 and by around 8% for battery cells during 2024-2025 (periods of sharp tariff increases for each technology). However, the upwards pressure on average costs due to tariffs is substantially offset by changes in material and component prices, and changes to trade patterns, including changes in the share of domestic production. Other key importing countries and regions like India and the European Union saw overall decreases in average delivered costs over the same periods, with the exception of solar PV modules in the European Union (Figure 1.1).

Two main factors blunt the impact of recent tariff hikes globally: the United States – where the sharpest tariff increases have taken place – accounts for about 15% of global gross imports (including intra-EU trade); and higher domestic production and shifting trade flows dilute the effect of pricier imports within the US market. The rise in costs may therefore remain modest relative to the headline tariff increases, even though the measures clearly run against the long-standing trend of declining costs driven by innovation and economies of scale. For end users, the impact is weaker still. In markets such as the European Union and the United States, for example, PV modules typically represent only 10-15% of the cost of a residential rooftop solar installation.

Figure 1.1 Changes in average delivered costs for solar PV modules and battery cells in key importing regions, 2023-2025e



Notes: e = estimated. The average cost in 2025e reflects the impact of tariffs announced as of 1 November 2025 on new imports, without accounting for use of stockpiles of earlier imports. Delivered costs refer to the weighted average unit cost of supply, including both domestic production and imports, with the latter including tariff and transport costs. Costs presented are inclusive of explicit financial support mechanisms in industrial strategies, such as the production tax credits in the US Inflation Reduction Act. The increase in component costs due to tariffs is included in "Material price changes".

Sources: IEA analysis based on a range of data sources; see IEA (2026), for details.

The impact of tariff increases in 2025 on the average delivered cost of key technologies has often been outweighed by declining costs for key inputs and shifting trade patterns.

There are, however, early signs that firms are already adjusting their investment and trade strategies. Some Chinese EV manufacturers have shifted planned investments towards the European Union following the introduction of countervailing duties in 2024. In solar PV, steep anti-dumping and countervailing duties on cells and modules from Southeast Asia have contributed to the scaling-back of planned capacity in parts of Southeast Asia.

Over the medium-term, other forces will come into play. Despite the recent tariff increases, international trade remains central to the outlook for clean energy technology manufacturing. In the Stated Policies Scenario (STEPS), in which global tariffs are assumed to remain at their 1 November 2025 levels, the value of global trade in the leading technologies more than doubles over the next decade, broadly in line with the increase projected in *ETP-2024*. This is because tariffs are just one part of a wider policy landscape: industrial and energy policies continue to exert significant influence on the development of supply chains.

Industrial policies remain powerful drivers of domestic manufacturing, notably for solar PV. India's Production Linked Incentive scheme and US production tax credits under the Inflation Reduction Act continue to provide strong incentives. In the STEPS, India and the United States meet virtually all of their demand by 2030, though both remain dependant on imports of wafers and polysilicon, respectively (Figure 1.2). Tariffs are already visible in market prices: higher import costs contribute to a gap of about 150% between US domestic prices and those in other major markets. The gap is large enough to sustain domestic output with limited effect on deployment, given the small share of modules in the total cost of solar PV installations.

Energy policies that shape domestic demand also strongly impact the viability of domestic manufacturing. The outlook for US battery demand – both for EVs and stationary storage applications – has shifted markedly since *ETP-2024*. The repeal of the Clean Vehicle Tax Credit 2025 and ongoing revisions to California's Advanced Clean Cars II regulation and national fuel economy standards lead to a projected 60% reduction in US battery demand in 2030 in the STEPS compared to the earlier projection. This lowers import needs and results in significant surplus domestic manufacturing capacity based on today's project pipeline (see Chapter 5). By contrast, other major importing regions have seen little change in demand-side policies and have not raised tariffs to the same extent, leaving their outlooks broadly unchanged.

Continuing industrial and trade policy responses to China's growing EV exports – worth around USD 35 billion[1] in gross terms in 2024 – are already reshaping trade patterns. Emerging economies accounted for just over 5% of China's EV exports in 2020; they now take one-third. In major emerging markets without plans for large-scale manufacturing, particularly in Latin America, imports from China are projected to make up around half of total EV sales in the STEPS by 2030. The European Union remains the largest single market for Chinese EV exports in 2030, though China's current near 20% share of EU EV demand does not rise further. In Southeast Asia, where low-cost Chinese EVs and favourable trade policies are boosting sales today, industrial strategies continue to drive investment in domestic manufacturing capacity, which expands eightfold between 2024 and 2030 in the STEPS. By 2030, less than 5% of EVs sold in the region are projected to come from China, down from more than half.

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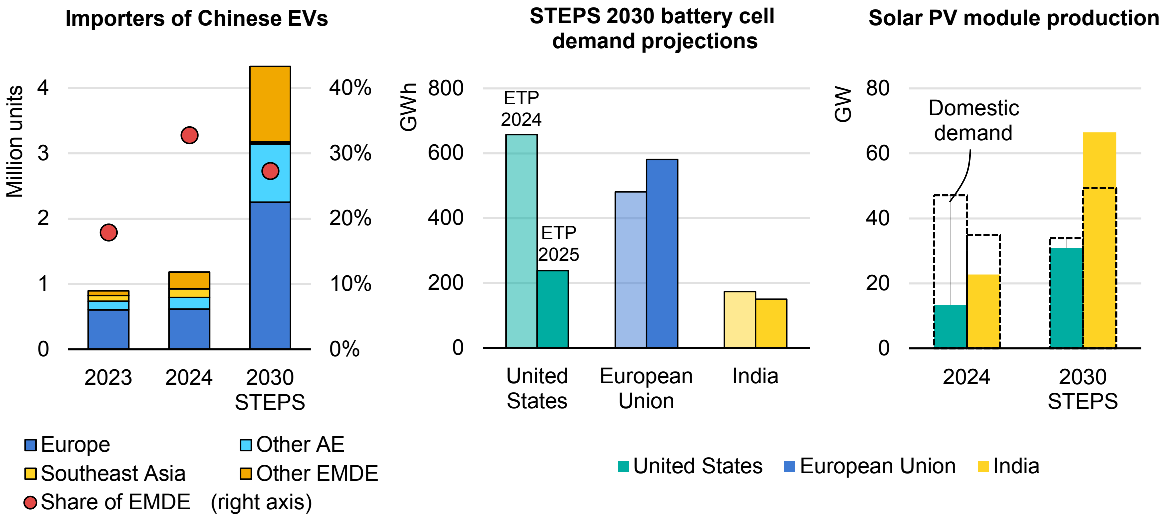
[1] Unless stated otherwise, USD figures are real 2024 dollars in market exchange rate terms throughout this report.

Figure 1.2 Key indicators for manufacturing and trade of selected clean energy technologies by selected countries and regions in the Stated Policies Scenario, 2023-2030



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Notes: STEPS = Stated Policies Scenario; EVs = electric vehicles; EMDE = emerging markets and developing economies; AE = advanced economies. Battery demand refers to EVs and battery energy storage system deployment.

Tariffs are just one part of a wider policy landscape, with industrial and energy policies continuing to exert significant influence on the development of supply chains.

2. How will today's low profits in clean energy technology manufacturing affect innovation and investment?

Why it matters

Governments around the world are doubling down on industrial strategies and policies to support clean energy technology manufacturing. Yet the context is evolving rapidly: razor-thin margins and oversupplied markets that started to emerge before 2025 have only intensified, while tighter public finances are making it harder to lure investment through targeted subsidies. Policy makers now face a delicate balance between the longer-term economic and environmental benefits of faster deployment and expanded production of equipment that will power future energy systems, and more immediate economic priorities. What the right balance will look like will vary by country and technology, depending on energy security concerns, comparative advantages, existing skills and how far the equipment has become commoditised. As global supply chains grow more complex, understanding how they generate skilled jobs in industrial hubs and how energy systems can be shielded from equipment shortages during trade disruptions is becoming ever more important.

The past year has seen a steady flow of headlines on plummeting margins across the clean technology manufacturing sector. Meanwhile, many firms, eyeing public support, are eager to launch demonstration and commercial projects to produce emerging technologies, with construction already underway in some cases. The weak finances of many producers raise difficult questions. What happens when new capacity is added to well-supplied markets? Are some of these technologies structurally destined to be low-margin businesses? And if so, what does that mean for public budgets and for the ability of firms to fund innovation? A common critique is that governments expect companies to both operate in a low-profit environment and simultaneously invest in more diversified supply chains and technology innovation. Does that place a bigger burden on governments to undertake R&D?

What is happening

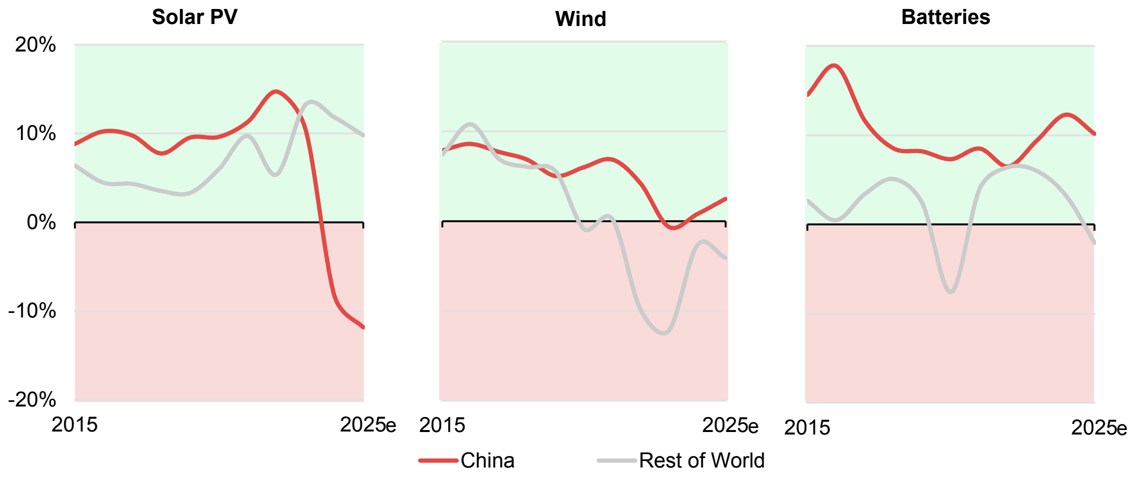
Profit margins for energy technology manufacturers have been generally low and volatile in recent years, though the degree of volatility varies by technology and region. Global excess capacity and fierce competition, particularly in China, have driven steep price cuts; solar PV modules have at times been sold below cost. The Chinese government has signalled a willingness to curb the intense local competition that has resulted partly from public support to manufacturers, but meaningful consolidation is likely to take time.

The prices of solar PV modules, wind turbines and batteries have fallen dramatically over the past decade. Gains in manufacturing efficiency, technological innovation and economies of scale have been major drivers. The globalisation of supply chains – and the ability to trade components – have also helped push down prices, as detailed in Chapter 4. Part of the decline reflects companies accepting margins far below those typical of “blue-chip” firms. This is most pronounced in China, where manufacturers have expanded capacity aggressively to win market share. Extensive vertical integration has helped those firms withstand intense price pressure, enabling them to absorb thinner margins and push prices down across international markets (Figure 1.3):

- The solar PV industry has become highly commoditised, dominated by large Chinese producers – seven of the world’s ten largest manufacturers are based in China – and characterised by fierce price competition that has eroded profitability. The average profit margin (based on earnings before interest and tax, or EBIT) of the world’s largest publicly listed firms hovered around 10% from 2015 to 2023, but turned negative in 2024 despite record global sales, driven by a sharp drop in margins among Chinese manufacturers. The top seven Chinese producers collectively posted losses of close to USD 4 billion. By contrast, average profit margins for the world’s top 500 manufacturing companies did not experience a similar decline, remaining close to 10% in 2024.

- Wind manufacturers face a different mix of pressures. Policy changes have made future demand less predictable, and the expected benefits of industry-wide standardisation have yet to materialise. Instead, supply chain disruptions, delivery delays, forward-pricing practices and rising input costs have battered profits, especially in the European Union. Adjustments to pricing strategies and contracts have lifted margins for most firms in advanced economies since profits bottomed out in 2022, but global average margins have continued to fall as the performance of a few large manufacturers has deteriorated. In China, the phase-out of central government subsidies for wind farms in 2022 pushed margins towards zero in 2024.
- Battery-makers have fared slightly better. The industry remains more concentrated than solar PV and wind, with scale and technology advantages still concentrated among a small group of leading firms, including one major Chinese producer – CATL – that significantly boosts the global average (see Chapter 4). This more consolidated industry structure has helped maintain relatively stable margins in China. In Europe, however, production costs remain roughly 50% higher than in China, denting profitability and eroding market share.

Figure 1.3 Profit margins for manufacturers of selected clean energy technologies by region, 2015-2025e



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Notes: Profits are calculated on earnings before interest and tax basis. Regions are weighted by revenue. Companies are categorised by their headquarters. Covers publicly listed companies only. Includes companies representing 65% of the global market for solar PV, 80% for wind and 65% for batteries. Data for 2025 is up to June 2025.

Source: IEA analysis based on S&P Global (2025).

Intense competition in China’s solar PV sector has depressed profits worldwide, but the more consolidated structure of the battery sector has maintained comparatively stable margins.

What it means

Industrial strategies to build new supply chains must strike a fine balance: keeping prices high enough for producers outside China to reinvest and remain competitive, without eroding affordability or access and without insulating firms from competitive discipline. Designing effective policies to achieve these goals is no small feat.

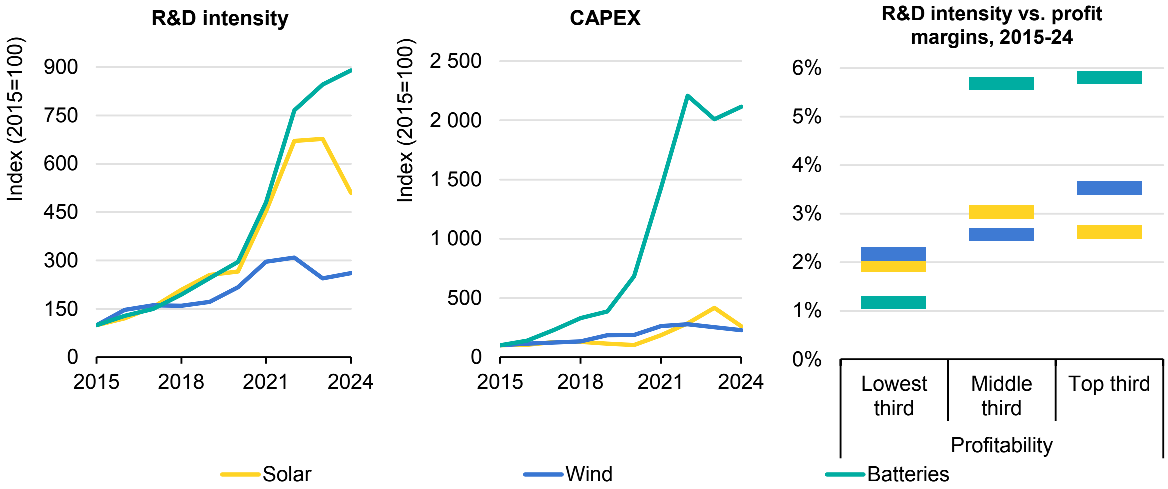
Profitability is not merely a cyclical concern or a matter for shareholders. Energy technologies are strategic assets, which justifies government intervention to ensure the long-term durability of both established and emerging industries. Persistently low margins weaken firms' ability to invest in new capacity and R&D, slowing innovation and eroding competitiveness.

Because companies often target a relatively stable ratio of R&D to revenue, falling revenues have immediate consequences. Between 2022 and 2024, R&D spending by solar PV manufacturers fell by around 25%, driven largely by Chinese firms (Figure 1.4), while R&D spending in the wind sector declined by around 15%. Capital investment followed a similar pattern, falling 10% in solar PV and 20% in wind. Battery producers are an exception: total R&D spending continued to rise in 2024, led by companies in China, Korea and Japan, despite lower revenues. Yet even here, the share of revenues devoted to R&D has slipped from 8% in 2015 to 5% in 2024 – closer to the levels seen in the more mature solar PV and wind sectors.

Within each industry, more profitable firms typically invest a larger share of revenue in R&D. Among battery manufacturers, the top two-thirds ranked by profitability spent a proportion of revenue on R&D that was five times higher than the bottom third over 2015-24. This pattern is particularly pronounced for batteries and, to a lesser extent, wind – sectors where ongoing innovation is essential to further cost reductions. The link is weaker for solar PV, where technological leadership matters less than economies of scale and the ability to operate efficiently.

The main aims of industrial policy – encouraging domestic production to guard against import disruption, ensure supply chain security, support economic growth and achieve technological leadership – are in jeopardy if margins stay low and depress investment in new capacity and innovation. In this case, policy makers need to devise strategies that target risks with specific tools. Import tariffs and other forms of government aid can, in some cases, be appropriate provisional tools to help domestic producers compete. For example, new tariffs have helped to shield US solar PV companies and EU EV manufacturers from excess capacity in China. However, they should be linked to global price benchmarks to maintain downward price pressure over time and prevent domestic firms from becoming "flabby" and inefficient.

Figure 1.4 R&D and overall capital expenditure, and average R&D intensity according to profitability for selected clean energy technologies, 2015-2024



Notes: CAPEX = capital expenditure. Profits are calculated based on earnings before interest and tax. R&D expenditure is calculated as a share of total revenues. Lines represent revenue-weighted average of R&D intensity (expenditure over revenues) by percentile of profit margins (0-33%, 33-66%, 66-100%). Covers publicly listed companies only. Includes companies representing 65% of the global market for solar PV and wind, and 60% for batteries.

Source: IEA analysis based on S&P Global (2025).

Battery manufacturers have sustained rising R&D and capital spending despite lower revenues, with the most profitable companies investing far more than their weaker rivals.

Other measures may be needed to keep innovation on track. Ensuring innovators have access to capital and credible growth prospects can accelerate progress in manufacturing efficiency, smarter material use or advances in chemistry and design. Governments have a range of tools at their disposal, including tax incentives, concessional finance for scale-up and dedicated R&D grants (IEA, 2025e). Additionally, regional manufacturing hubs might be encouraged to develop more integrated supply chains. In the solar PV sector, vertically integrated producers (IEA, 2022b) have generally achieved bigger and more stable profits than those confined to manufacturing individual components or assembly of finished modules. However, intervention in this area demands careful planning and a realistic assessment of the scale and scope required to capture these advantages.

3. How can policy help close the cost gap with China in energy technology supply chains?

Why it matters

China is the undisputed giant of clean energy technology manufacturing. It produced around 80% of solar PV modules and batteries globally, as well as over 70% of nacelles for wind turbines – more than any other country and at prices other regions struggle to match. While the vast majority of that production serves the domestic market, the country is also a major exporter. Governments in Europe, North America and elsewhere are understandably keen to build up their own industries, both to reduce dependence on imports and to capture the economic dividends of industrial growth.

One obstacle is cost. Two decades of large-scale investment, industrial integration and policy support to scale up domestic demand and manufacturing have left Chinese firms highly competitive. For now, substituting Chinese imports with local output means higher costs for producers and consumers alike, unless governments step in with subsidies.

However, this does not mean the production cost gap is unbridgeable. Careful policy design – grounded in a realistic understanding of where cost reductions are achievable – can narrow, and in some cases close, the gap. That entails targeted investments in manufacturing and automation, demand policies that support economies of scale and reforms to electricity markets aimed at lowering prices. Without such focus, there is a risk that these industries can survive only with constant injections of public financial support or measures to restrict trade.

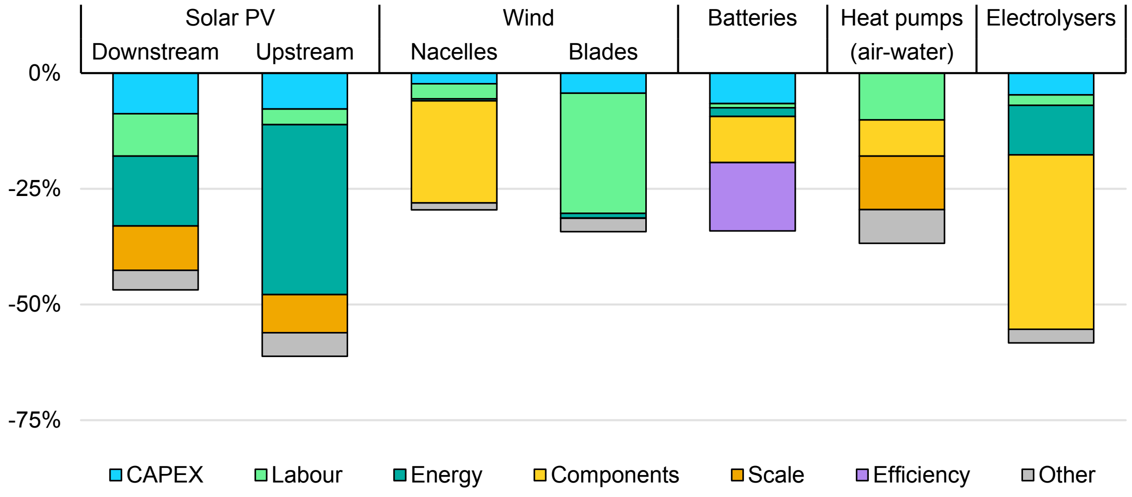
What is happening

Production costs in China can be less than half those in advanced economies, such as the European Union, specifically in some production steps. But the reasons differ markedly across technologies (Figure 1.5):

- Solar PV: One-third of the gap in cell and module manufacturing costs stems from higher energy prices; for example, European firms pay two to three times more, on average, for electricity than their Chinese rivals. Scale also matters: larger Chinese plants explain up to 20% of the cost differential. Lower labour costs contribute much less than energy in polysilicon and wafer production.
- Wind power: For turbine blades, labour accounts for around 75% of the gap, with cheaper energy playing a negligible role. For nacelles, the labour share is far smaller, at about 10%, with components accounting for almost the entire cost gap, though lower component costs can themselves be a function of lower labour costs and economies of scale.

- Batteries: China's edge is strongly supported by manufacturing efficiency, thanks to integrated supply chains, advanced manufacturing processes and production scale. Access to cheap components also contributes.
- Heat pumps: The gap relates primarily to cheaper labour, components and production scale rather to energy costs. Around half of the total cost difference stems from China's huge component manufacturing base, especially for compressors, and the scale of heat pump manufacturing. It supplies about 90% of global demand for rotary compressors and roughly one-third for scroll compressors. Vertically integrated supply chains and China's dominant position in global air-conditioner production also contribute to lower costs.
- Electrolysers: Cheaper components – in some cases linked to different technology choices such as alkaline rather than proton exchange membrane electrolysers – explain most of today's cost gap. Production scale could become a more important factor if manufacturing capacity expands much more rapidly than in Europe over the next few years. Several of China's major electrolyser manufacturers have also entered the sector from the solar PV and wind industries, drawing on their established manufacturing know-how and well-developed component supply chains.

Figure 1.5 Difference in manufacturing costs in China compared with the European Union for selected clean energy technologies by cost factor, 2024



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Notes: CAPEX = capital expenditure. The analysis is based on the levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Downstream solar PV refers to cell and module production; upstream solar PV refers to polysilicon and wafer production. Batteries refer to lithium-ion battery cells using lithium nickel cobalt manganese oxide as cathode active material and graphite as anode active material. Labour cost for battery production in the European Union is calculated as the production-weighted average of labour costs in 2024. Components refers to the cost of component and material inputs. Efficiency refers to production efficiency and is inversely proportional to scrap rates and manufacturing line downtime, and directly proportional to automation of production processes.

The reasons for China's lower manufacturing costs vary widely by technology, requiring different policy mechanisms to help close the gap.

The often-cited story of cheap Chinese labour is insufficient as an explanation for China's cost advantage; outside labour-intensive products like turbine blades, it explains little. As manufacturing becomes more automated, the importance of labour costs will diminish further. In some instances, China's faster adoption of automation means that labour intensity is already lower there than in high-income regions, even though Chinese labour remains cheaper.

Energy costs are also not the primary source of China's competitiveness, except in solar PV manufacturing – specifically for polysilicon and wafer production. China's real strengths lie in scale, tightly integrated supply chains and process efficiency. Some of these advantages have been shaped by financial and other forms of government support, especially during the early stages of industry development (see Chapter 4).

What it means

Closing the gap is possible. Policies will be most effective if they concentrate on areas where manufacturing efficiency gains, scale effects and innovation can make a difference – rather than, for example, trying to compete on the basis of low-cost energy or labour. Every country should take into consideration their domestic strengths and comparative advantages, as well as tolerance for geographically concentrated supply chains, when identifying priority areas for onshoring manufacturing. Lithium-ion batteries show the way: in the European Union, their production cost[2] could be cut by one-third – closing a staggering 80% of the gap with China – through measures that enhance manufacturing efficiency and secure access to cheaper components and materials. Continuous improvements in manufacturing processes, supported by learning-by-doing, innovation and automation, can deliver substantial efficiency gains. At the same time, partnerships with countries that supply key materials and components can secure access to competitively priced inputs.

Economies of scale are indispensable for all types of technology. However, no manufacturer will invest without confidence in future demand. Governments can play a role in providing it. Fuel economy and emissions standards for vehicles, for example, give clarity to investors and guarantee markets for EVs and batteries, which in turn can support the development of enabling infrastructure such as charging stations. Targets for clean energy deployment and long-term public procurement programmes can also help. Larger, more predictable markets encourage standardisation, learning-by-doing and lower unit costs – a key driver

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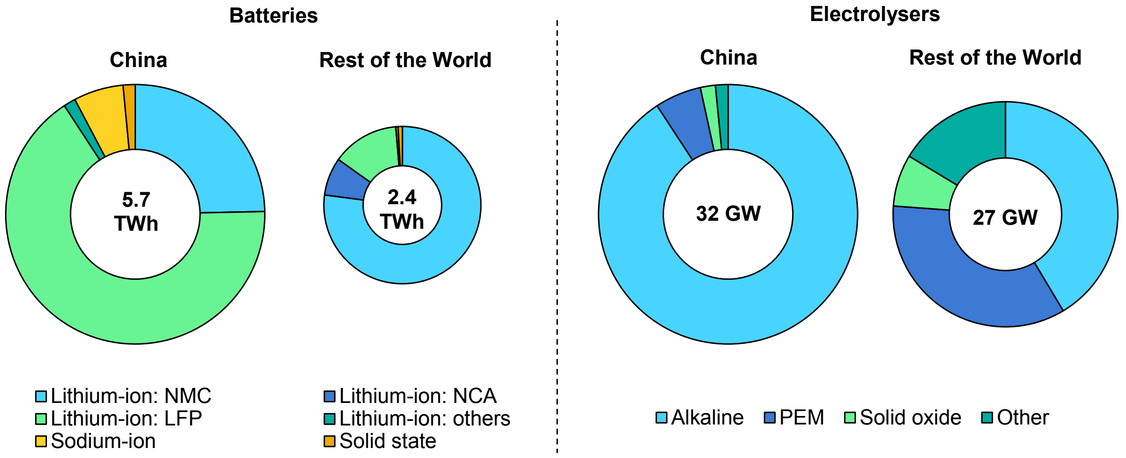
[2] Production costs refer to the estimated average direct manufacturing cost in the European Union if key battery components (cathode and anode active materials) were produced domestically.

behind wind turbine price reductions in recent years. Tax credits, concessional loans and investment guarantees can help attract capital to larger plants to reach competitive scale, but not to keep sub-scale facilities afloat.

Governments can also encourage domestic manufacturers to seek partnerships with leading equipment makers and support training programmes. New entrants in complex industries such as batteries and solar PV often struggle with low yields, due to lack of experience related to the complicated manufacturing processes for these products. Partnerships with established manufacturers can raise quality faster, transfer know-how and strengthen local supply chains. High-yield factories, with less waste and fewer defects, mean lower costs. Close relationships with nearby customers, a traditional strength in sectors like cars and chemicals, can also provide an edge. In addition, policy makers can support firms seeking to compete on quality as well as cost; for example, by focusing on higher-value products in key niches that are less common in Chinese portfolios. Some non-Chinese electrolyser producers are adopting such an approach, by focusing on the development of non-alkaline electrolysers, such as proton exchange membrane or solid oxide electrolysers.

Figure 1.6 Current and future committed battery cell and electrolyser manufacturing capacity by technology in China and the rest of the world, 2030



Notes: NMC = lithium nickel manganese cobalt oxide; NCA = lithium nickel cobalt aluminium oxide; LFP = lithium iron phosphate; PEM = proton exchange membrane. Committed manufacturing capacity in 2030 is based on current manufacturing capacity, committed expansions and additional committed capacity. Committed refers to projects that are either under construction or have reached a final investment decision. Solid state refers to semi-, quasi- and all-solid-state batteries. Due to limited data availability on the status of sodium-ion battery projects, the same committed-to-announced capacity ratio as for new lithium-ion battery plants is assumed for sodium-ion capacity.

Sources: IEA analysis based on data from BMI (2024); and BNEF (2025) as well as announcements by manufacturers and personal communications, gathered by the IEA.

Battery and electrolyser producers outside China are focusing on different technologies – other than LFP batteries and alkaline electrolysers – in order to compete.

Innovation – a necessary condition for success, though insufficient on its own – is another obvious area where governments can make a difference. This can take the form of direct involvement in R&D and demonstration projects, measures to help technologies cross the so-called "valley of death" between early-stage development and commercialisation, or incentives that mobilise private sector investment. Breakthroughs will certainly play a role, but only if they deliver significant cost or performance improvements over market-leading products, which are increasingly "good enough" for most applications (IEA, 2025a). Chinese manufacturers are also continually innovating and optimising, making this a moving target. Prioritising innovation funding in areas with the greatest potential upside will be key to effective strategies.

Energy costs are not a critical factor for all technologies, but high electricity prices can be a major handicap for the solar PV sector and a drag on certain other electrified manufacturing processes – especially in Europe. Policies to reform wholesale power markets in order to expand the role of low-cost and low-emissions electricity and provide competitive tariffs for electricity-intensive energy technology manufacturing can therefore help to close the cost gap.

Ultimately, governments are faced with tough strategic choices. Each country will define 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. Smart industrial strategy means focusing efforts where scale and efficiency can deliver results, by stimulating demand, cutting input costs and accelerating learning. Every tool to boost competitiveness – whether it takes the form of subsidies, standards or funding for innovation – comes with a price tag. The priority should be to identify technologies where cost parity is genuinely within reach, or that serve to meet a particular strategic interest, and avoid propping up those where it is not. Evidence-based choices will determine whether new supply chains are competitive, resilient and built to last.

4. Is the current electricity transformer shortage a cause for concern?

Why it matters

A transformer is a passive device that transfers electrical energy between circuits and alters voltage levels, stepping up voltage for efficient long-distance transmission and stepping down voltage for safe local distribution. It is a critical link in electricity grids, connecting generation, transmission, distribution and end users. In the United States alone there are between 60 and 80 million distribution transformers, while in the European Union there are roughly 4.4 million power transformers. Reports of shortages in this essential equipment have therefore caused concerns among grid operators and policy makers.

A lack of transformers, or a sharp rise in their cost, could stall electricity projects of all kinds. In an era of rapid electrification, such bottlenecks could derail policy goals, from leadership in artificial intelligence (AI) to the rollout of EVs. Uneven impacts across regions could undermine the competitiveness of key industries. In several large economies, ageing infrastructure poses a further risk: without timely replacement of transformers and other critical assets, grid failures could become more frequent.

What is happening

There is clear evidence of rising lead times and prices in the transformer market over the past few years. In the United States, lead times for deliveries of some transformer classes have tripled to around 150 weeks since 2021, while prices have risen nearly 70% since 2020. These trends are the result of demand growth outpacing investment in new manufacturing capacity. Unexpectedly rapid growth in global demand is being driven by four main factors:

- Replacement of ageing infrastructure in advanced economies.
- Deployment of distributed electricity generation, which requires transformers at each network connection.
- Construction of large new electricity-consuming facilities, such as data centres and EV charging networks.
- Rapid expansion of power grids in emerging markets and developing economies (EMDEs).

Global demand growth is being led by fast-growing economies such as China and India, which are expanding grids to connect more distributed power sources and supply new customers. In Europe, electrification and higher renewables penetration are also pushing up demand, resulting in similar lead times as in the United States. In America, grid upgrades (70% of transformers are over 25 years old), renewable energy projects, EV charging and the fast-expanding data centre sector are the main drivers. By 2030, US electricity demand from data processing is expected to exceed that of all domestic energy-intensive manufacturing combined. Because these applications require similar transformer types, and data centre developers often pay more, they are pulling ahead in procurement.

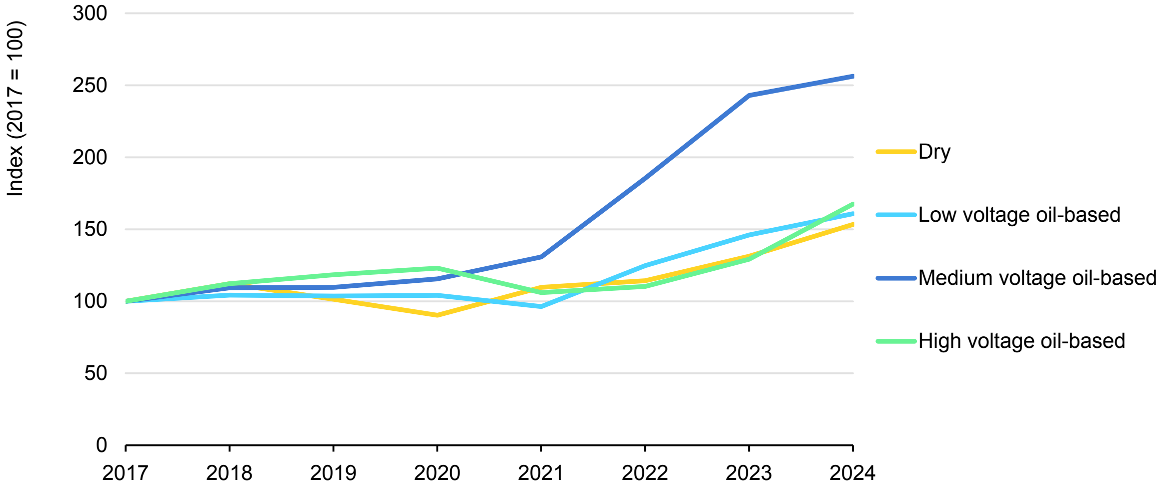
The transformer supply-demand gap varies by region. The tightest market is in the United States, where past boom–bust cycles have made manufacturers reluctant to expand capacity until demand is certain, and where data centres and liquefied natural gas projects have added strong, sustained demand. While China appears to be well supplied thanks to its large export volumes, the situation in Europe is more complex: the region can export significant quantities of oil-based high-voltage transformers yet still needs to import large volumes of transformers of all types, suggesting a tight market.

Market tightness is most severe for large power transformers. The largest ones step up or step down high voltages used for long-distance transmission, with capacities of up to 1 000 megavolt amperes (MVA) and weights of 400 tonnes – enough to handle the output of a nuclear plant. A 12-turbine wind farm typically needs 40-60 MVA, similar to the requirement for stepping down high-voltage supply to a large data centre. These units are custom-built to fit specific projects and space constraints, requiring high-tech equipment and a skilled workforce. This complexity limits new entrants and has led to a concentrated global market in which manufacturers avoid maintaining large surpluses. Added to their sheer weight, oil-filled transformers contain chemicals that are awkward and expensive to transport over long distances. This means spare manufacturing capacity in other parts of the world cannot easily fill any gap in local supply. Alternative oils such as esters are becoming more common, but do not eliminate logistical constraints.

Smaller distribution transformers, which step down voltages for use in homes and factories, are far more compact – an EV fast-charging station rated at 350 kW typically needs a 2-3 MVA unit – and more standardised, making them much easier to ship and trade internationally. In the United States, distribution transformers typically fall in the 2-5 MVA range, whereas, in Europe, capacities below 1 MWA are more common. Despite these regional differences, their relative uniformity and manageable size mean they are less affected by regional market imbalances.

Inflation has added further upward pressure to transformer prices. Raw materials – especially copper for windings and grain-oriented electrical steel for cores – can account for up to half of total costs; both have seen significant price increases since 2021 (Figure 1.7).

Figure 1.7 Global average prices of imported transformers, 2017-2024



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Notes: Based on total import values and mass reported in customs data. Values are inflation-adjusted. Dry refers to dry-type transformers; low voltage refers to power capacity rated below 650 kVA, medium voltage to 650-10 000 kVA and high voltage to above 10 000 kVA.

Source: IEA analysis based on Sinoimex (2025).

Transformer prices have risen steeply since 2021 as manufacturing has struggled to keep pace with rising demand, with oil-based transformer prices rising the most.

What it means

Manufacturing capacity for transformers is expanding, but any fundamental rebalancing of supply and demand will take years. At first glance, trade flows suggest that global markets are adapting. The combined value of transformer exports and imports more than doubled between 2020 and 2024, with China, Mexico, Europe[3] and Korea emerging as the main exporters, and the United States and the Middle East as the main importers (Figure 1.8). Yet the headline figures are misleading. Much of the increase reflects cost inflation rather than rising volumes: there is little evidence that more transformers are actually being shipped across borders.

Limited flexibility to address local market imbalances through trade has left suppliers in advanced economies relatively well-insulated. Despite rising input costs, manufacturers have generally preserved healthy margins, often reaching 20% of end-customer prices. While international trade continues to play an important role in alleviating cost pressures, resolving structural bottlenecks ultimately hinges on sustained investment.

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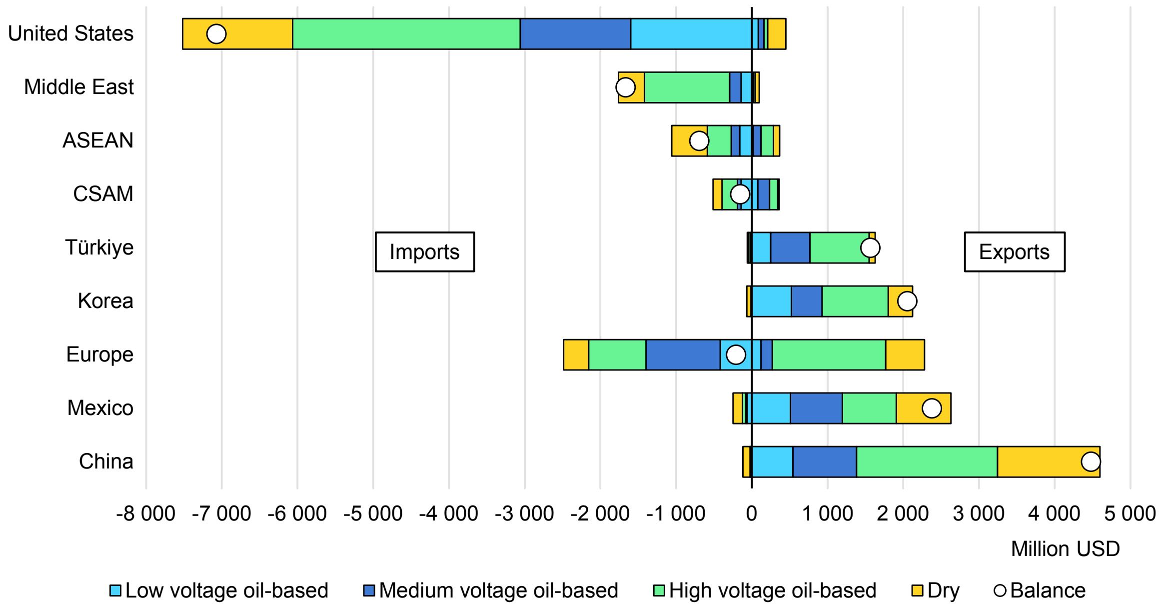
[3] Europe refers here to the European Economic Area, made up of 27 EU countries, Norway, Iceland, Liechtenstein and the United Kingdom.

Several manufacturers have already announced capacity expansions on the back of firm demand from grid and generation projects. For example, Hitachi Global has committed more than USD 100 million to upgrade and modernise its power transformer factories in Canada to meet the rapid growth in North American demand. The company is also investing USD 30 million to expand its manufacturing facility in Germany. These projects form part of a broader USD 1.5 billion investment programme aimed at gradually expanding the company's global transformer capacity through to 2027. Other suppliers are following suit. Hyundai Power Transformers is investing USD 33 million to expand production in Alabama by around 60%, while Siemens Energy has announced a USD 150 million investment to establish its first US power transformer factory in North Carolina, with manufacturing scheduled to begin in 2027.

The most effective action governments can take to rectify bottlenecks is to provide visibility, through clear long-term investment plans for the grid, stable policies for generator connections and stronger co-ordination with equipment suppliers on standards and certifications. These measures are essential to give manufacturers and project developers the confidence to commit. Clear rules could also help developers secure firm transformer contracts, reducing uncertainty around project timelines. Improving the efficiency of today's grid infrastructure is equally important. However, many regulatory frameworks still favour hardware investments over operational upgrades, including digitalisation, that could raise system efficiency and reliability. Aligning regulations to support both modernisation and smarter system operation would ease pressure on supply chains while improving overall grid performance.

Beyond shoring up today's supply, governments can also encourage innovation to reshape tomorrow's demand through support for technologies that reduce transformer size, material requirements and losses in operation. Improved lifecycle efficiency standards could both encourage innovation and enhance grid reliability, considering the specific challenges of rapid technological change in a highly regulated industry such as electricity networks. For instance, amorphous core transformers can substantially cut standby losses, but require modifications in manufacturing and present challenges for grid integration due to increased dimensions and weight. Promising areas include additive manufacturing, solid-state and smart transformers, as well as technologies to increase the capacity of current grids, such as dynamic line rating and high-temperature low-sag conductors. Targeted support – whether through direct R&D funding, incentives for adoption or regulatory "sandboxes" that allow new approaches to be tested in real systems – can speed the transition to a leaner, more resilient transformer market (IEA, 2025e).

Figure 1.8 Major exporters and importers by transformer type and value, 2024



Notes: ASEAN = Association of Southeast Asian Nations; CSAM = Central and South America; Europe = European Economic Area, made up of 27 EU countries, Norway, Iceland, Liechtenstein and the United Kingdom. Dry refers to dry-type transformers; low voltage refers to power capacity rated below 650 kVA, medium voltage to 650-10 000 kVA and high voltage to above 10 000 kVA.

Source: IEA analysis based on Sinoimex (2025).

China, Mexico, Europe and Korea are the biggest transformer exporters, with global trade more than doubling since 2020.

5. Is there a case for investing in a domestic battery sector when China holds such a large cost advantage?

Why it matters

This question is hotly debated, and with good reason. Batteries are no longer just a component industry: they are a strategic technology. They underpin the shift to EVs, bolster the resilience and flexibility of power grids, are vital to the functioning of several rapidly expanding applications, including data centres and humanoid robots, and are increasingly central to defence applications, with drones being a prominent example. Their deployment also strengthens energy security, reducing reliance on oil in road transport while enabling greater use of domestic intermittent renewables.

However, strategic importance comes with strategic risk. Today, between 60% and nearly 100% of each step of the battery manufacturing supply chain sits in just one country: China. This outsized role is the result of years of sustained investment, public support, technology innovation, integration along the supply chain and the development of world-class expertise.

Japan and Korea have also built strong battery industries with global reach, though they are less integrated than China’s when it comes to battery component manufacturing and mineral processing. By contrast, producers operating in Europe and North America face higher costs and often struggle to match the prices or quality of Chinese products.

The dilemma facing policy makers outside China is how far to push for home-grown capacity, if at all. New production locations may take years to achieve competitiveness, raising questions about the value of subsidising investment today. Yet for countries and regions with major automotive sectors, such as Europe, Japan, Korea and North America, the battery industry is more than a cost equation: it is a critical link between vehicle manufacturing and control over mineral supply chains. The automotive sector remains a pillar of industrial strength, but its future increasingly hinges on secure, affordable access to batteries.

This explains the divergence of views. Some argue for aggressive subsidies to scale domestic production quickly. Others see greater promise in funding innovation to leapfrog to next-generation technologies, where cost gaps may be smaller. A third camp stresses the importance of forging resilient supply relationships with established producers abroad or encouraging them to invest in manufacturing capacity close to domestic markets.

What is happening

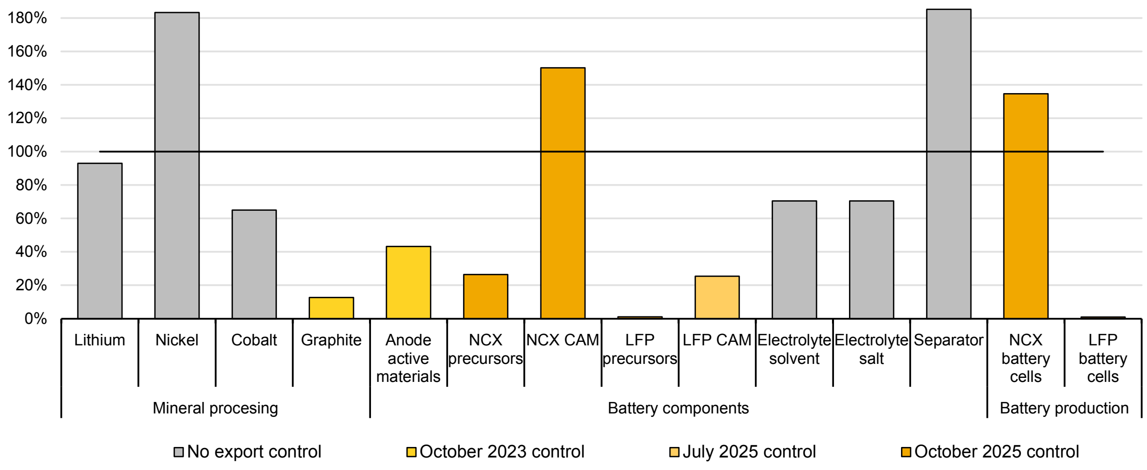
Chinese, Korean and Japanese companies dominate global lithium-ion battery cell production, accounting for 99% of output. In 2024, roughly 80% of all batteries were produced in China. The European Union and the United States together contributed around 15%, mostly from factories built by Korean and Japanese firms. Chinese producers are also extending their reach abroad through local manufacturing investments or technology licensing agreements.

Building a competitive domestic industry is neither quick nor cheap. When a new producer begins operations, the share of output that is unfit for sale is often much higher than that needed to achieve profitability. It can take more than 5 years from the start of production for a new facility to reach close to its nominal capacity (Fraunhofer, 2024). For regions without a strong industrial base in batteries, mastering the process demands patient capital and long-term commitment. Governments, for strategic reasons, may choose to share some of the investment risk with private players through direct financial support or by encouraging investments or joint ventures that bring in established producers with expertise and privileged access to supply chains.

Lack of investment in the midstream battery supply chain poses a growing risk to global supply security. Production capacity and technical expertise for essential components such as active materials and their precursors remain heavily concentrated in China. Korea and Japan are the only other countries with notable midstream industries, offering opportunities to diversify sourcing for some components while leaving many others reliant on Chinese supply (Figure 1.9).

This structural imbalance is unlikely to ease without a ramp-up in investment and stronger international co-operation. China continues to wield substantial influence: export controls on key battery components introduced since late 2023 target precisely the most vulnerable links in the battery supply chain. If the most recent restrictions – announced in October 2025 and later paused for one year following the latest trade agreement with the United States – were to be enforced, battery production outside of China could face serious disruption.

Figure 1.9 Share of battery demand outside China that could be met without supply from China, 2024



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Notes: NCX includes lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminium oxide (NCA); LFP = lithium iron phosphate; CAM = cathode active material. 100% refers to global demand excluding China. The export controls announced in October 2025 are temporarily suspended at the time of writing. Lithium, nickel, and cobalt refer to total production capacity and demand across all sectors. Bars refer to production outside of China if the utilisation rate were to be increased to 85% of nameplate capacity. Some export controls on lithium processing apply, but since they refer specifically to lithium processing technologies, they are not considered in the figure. Batteries with an energy density greater than 300 Wh/kg and lithium-rich manganese-based chemistry are also subject to export controls. The NCX cells affected by export control are those with an energy density greater than 300 Wh/kg. All facilities able to produce graphite anode suitable for battery applications are included within the scope of anode manufacturing capacity. LFP is deployed in over 90% of battery energy storage systems, while electric vehicles rely on a combination of NCX and LFP.

Sources: IEA analysis based on data from EV Volumes (2025); BMI (2024); and BNEF (2025).

Nearly all battery energy storage systems and over 70% of EV batteries used outside China could not be produced without Chinese-made batteries or components.

Efforts to diversify the battery supply chain will only succeed if they are grounded in sound economic fundamentals. Europe and the United States have attracted substantial investment in battery cell manufacturing, driven by robust automotive industries that offer large and expanding sources of demand. The same principle applies further upstream: scaling up midstream production capacity requires predictable, large-scale demand to justify investment. A competitive and stable manufacturing base can provide this anchor. However, production costs in Europe and the United States remain up to 50% higher than in China, if excluding tax credits or other support measures, complicating efforts to establish a self-sustaining midstream industry.

Partnerships with incumbent manufacturers can help bridge the gap, as they accelerate production cost reduction and can influence suppliers to relocate production. But building a midstream industry through purely market-driven dynamics takes time, which may not align with supply security concerns. Targeted strategic midstream investments in regions scaling up battery production may therefore be justified as a form of insurance against short-term supply shocks.

Innovation is sometimes seen as a shortcut – a way for latecomers to leapfrog incumbents by betting on new technologies, such as sodium-ion or solid-state batteries (IEA, 2025a). Sodium-ion batteries are already commercial in China, but their limited energy density makes them competitive only during periods of high lithium prices or for targeted applications, such as in cold climates. In addition, they are unlikely to offer a competitive opening for new entrants – China accounts for over 95% of the announced manufacturing capacity. Solid-state batteries remain at the prototype stage and are expected to begin entering markets between 2027 and 2030. However, high initial costs and nascent supply chains will likely restrict their initial use to premium segments and emerging applications such as humanoid robotics.

However, potential disruptive breakthroughs are a risky foundation for industrial strategy. The battery industry continues to optimise established technologies, breaking records on energy density, ultrafast charging, safety, and longevity. Without an efficient and competitive battery ecosystem already in place, even promising advances may struggle to reach commercial scale quickly enough to deliver real benefits and compete with increasingly optimised lithium-ion technologies.

What it means

Building and maintaining a domestic battery production base, even at a modest scale, is less about competing with China today than about securing strategic resilience for tomorrow. The benefits of doing so are reinforced by the need to supply applications that are less sensitive to cost, notably in defence. Yet battery manufacturing is a complex business: developing experience, building supply chains and achieving cost reductions will take time. Relying solely on market forces to nurture a midstream industry may not bring results fast enough to address pressing supply security concerns.

That makes the case for targeted and timely government support to scale up production a strong one, both in advanced economies looking to safeguard competitiveness and in countries rich in critical minerals that could emerge as low-cost producers in the longer term. Strategic partnerships with established Asian manufacturers could also help by accelerating technology transfer, driving down costs and encouraging suppliers to localise production. The stakes are high: modern batteries are becoming one of the most important technologies of the 21st century, so secure and affordable access is becoming a matter of economic and national security (Birol, 2025).

Strategic planning, however, must be grounded in reality. Established producers will continue to dominate global supply in the near term, including by operating or supplying much of the capacity located in Europe and the United States. In this context, partnerships with incumbent manufacturers – particularly when ensuring knowledge transfer – can be valuable, aligning strategic goals around investment, learning and innovation.

Innovation offers potential entry points for new players, but it is no shortcut to success. Tomorrow's leaders in next-generation batteries, including solid-state designs, will be those that pair technical breakthroughs with manufacturing efficiency, supply chain strength and a skilled workforce, much as today's lithium-ion industry has done. Skills, suppliers and operational know-how must transfer smoothly across technologies if innovation is to translate into competitiveness.

The size of the overall lithium-ion battery market – about USD 130 billion in 2024 – does create opportunities for newcomers to scale up by first targeting niche segments, such as premium applications where performance outweighs cost. These markets can be large enough to build experience, generate profit and eventually move towards mass adoption. Still, competition will be fierce. The same incumbents that dominate lithium-ion production are also among the most advanced developers of new battery technologies, making it difficult for new entrants to carve out lasting advantages.

6. Has the hydrogen bubble burst?

Why it matters

Hydrogen has been widely hailed as a potential solution to some of the hardest-to-decarbonise parts of the global economy. Hydrogen emits no carbon at the point of use and can be produced from renewables-based electricity through electrolysis of water, with fossil fuels combined with CCUS or using sustainable biomass, offering a pathway for reducing emissions in sectors such as heavy industry, refining, aviation, shipping and long-haul road freight.

Between 2019 and 2023, investor sentiment and policy ambition were buoyant. Hydrogen was seen as a versatile fuel that could help meet net zero commitments, while falling costs for solar PV and wind reinforced the idea that production could quickly shift toward regions with abundant renewable energy. Countries responsible for over 85% of global CO_2 emissions had pledged net zero targets, generating strong expectations of a surge in demand for low-emissions hydrogen.

That perception has since changed significantly. Over the past year, headlines have been dominated by project delays and cancellations, bankruptcies and weakened policy ambitions. Investor sentiment has cooled sharply, prompting questions about whether earlier enthusiasm represented a bubble. This is casting doubts about the long-term roles of hydrogen in the future energy system.

The IEA's annual *Global Hydrogen Review* (IEA, 2025b) offers a reality check. Policy makers, in particular, need clear signals: will hydrogen provide an opportunity to bolster industrial competitiveness or will it undermine energy affordability? Misjudging the moment risks either wasting capital or stalling momentum.

What is happening

Momentum in the sector remains strong, despite the recent uncertainty. Global investment in low-emissions hydrogen production[4] climbed to almost USD 8 billion in 2025, an 80% jump from the year before. Output is expected to have reached about 1 Mt in 2025 – about twice the level in 2020 and accounting for around 1% of total hydrogen supply, which still relies predominantly on natural gas reforming. By 2030, total production is expected to reach more than 4 Mt based on committed projects.

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[4] See IEA (2025b) for a definition of low-emissions hydrogen.

The bulk of low-emissions hydrogen (more than 80%) in 2024 came from gas-based plants equipped with CCUS and around 15% from water electrolysis based on renewables, with the rest having been derived from biomass. Electrolysers have grown larger: the capacity of recently commissioned plants has reached 500 MW, with some under construction set to surpass 1 GW (IEA, 2025b).

However, this expansion has gone hand in hand with a turbulent period for hydrogen company finances. Between 2019 and 2021, over USD 70 billion was added to the total value of listed hydrogen firms specialised in low-emissions production technology, about half of which only went public after 2019. Since then, their combined market capitalisation has collapsed by more than 80%, though the decline now appears to have levelled off. Still, the sector's financial strains remain evident: in early 2025, HydrogenOne Capital Growth, a GBP 105 million (~USD 135 million) fund launched in 2020 to back hydrogen ventures, announced it would wind down after persistent underperformance (H2View, 2025).

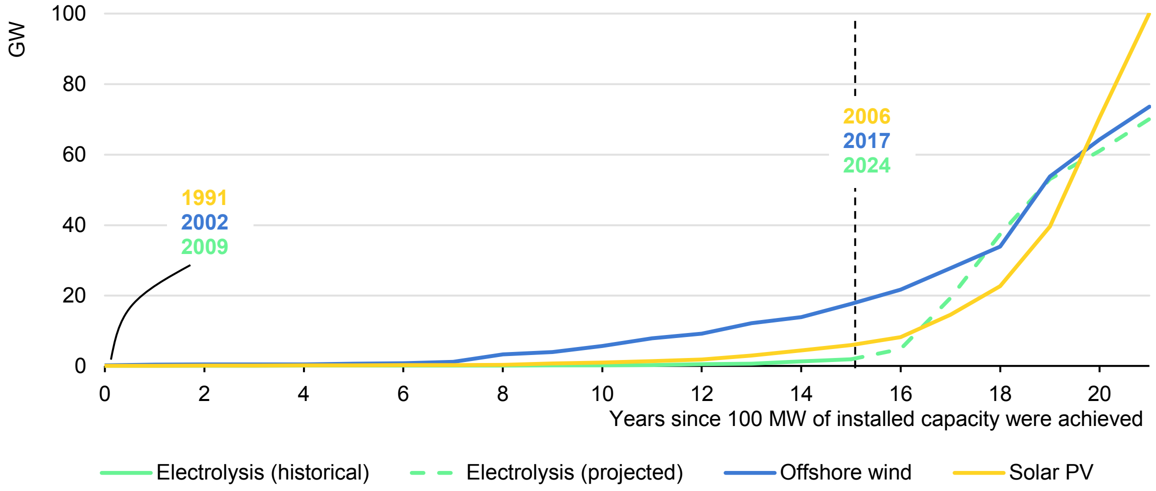
Since 2020, around three-quarters of project investment has been directed towards producing hydrogen for industrial use or for fuels such as ammonia and synthetic hydrocarbons. These areas also account for practically all firm offtake agreements signed over the past 5 years, reflecting lower complexity and existing expertise among hydrogen users. They are likely to remain the backbone of future demand for low-emissions hydrogen. Low-emissions hydrogen and its derivative fuels are particularly well-suited to large-scale applications where hydrogen from unabated fossil fuels is already in use today and alternatives to cutting emissions are absent, such as in refining and chemicals, or to applications where alternative technologies are constrained, as in steelmaking, aviation and shipping.

Investment in low-emissions hydrogen production has been unevenly spread across regions and technologies. Spending on electrolysis is highest in China, where low equipment costs and the ability of state-owned enterprises to implement government plans have driven rapid deployment – from just a few megawatts in 2020 to around 2 GW in 2025. In Europe, the push to cut reliance on Russian natural gas has provided an extra spur for electrolyser installations, unlocking capital for large-scale projects. By contrast, most investment in Canada and the United States has gone to steam reforming plants equipped with carbon capture, driven by access to cheap natural gas, abundant underground CO_2 storage and generous tax incentives.

Most of the recent setbacks for developers and equipment suppliers stem from three sources: the slow conversion of policy targets into workable frameworks; recognition that the slow ramp-up of deployment is preventing the fast reductions on production costs to enable wider adoption; and the sheer complexity of building industrial supply chains and customer confidence from scratch. Unlike solar, wind or batteries, the financial viability of hydrogen projects is tied up with uncertain fuel prices and multiple end-uses, making it a far more complicated business – a factor that investors may have underestimated.

For all the sector's recent troubles, the scale-up of electrolyser manufacturing and deployment over the past 5 years has been closer to the early trajectory of solar PV than to a stalled technology. This growth is mostly a consequence of the push that China has given to electrolysis technology, aiming to replicate previous success in technology manufacturing, as well as the willingness of some investors to gain experience and market position in a sector that is expected to play an important role in meeting climate, energy security and industrial competitiveness goals. Global installed electrolyser capacity reached 100 MW in 2009, but it took another 14 years to clear the 1 GW mark in 2023 (Figure 1.10). Since then, growth has accelerated: in the first seven months of 2025 alone, more than 1 GW was added, and total installed capacity is expected to have reached near 5 GW by the end of the year. Projects already at the stage of a final investment decision (FID) point to 26 GW of total capacity by 2030. If projects with strong potential to be in operation by 2030 are also considered, the potential capacity rises to 65 GW. That pace is similar to the breakneck expansion seen as solar PV and offshore wind started to take off.

Figure 1.10 Global installed capacity of solar PV, offshore wind and water electrolysis at the early stage of adoption



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Notes: Year 0 is the year at which global installed capacity of each technology reached 100 MW: 1991 for solar PV, 2002 for offshore wind and 2009 for water electrolysis. The dotted line in water electrolysis shows the installed capacity that could be achieved with projects that are almost certain or have a strong potential to start operating by 2030 according to the analysis presented in our *Global Hydrogen Review 2025* (IEA, 2025b).

Source: IEA (2025c).

The expected pace of deployment of water electrolysis is not far off the breakneck expansion seen when solar PV and offshore wind first began to scale up.

What it means

Hydrogen is no passing fad. While financial corrections, project delays and cost gaps have cooled investor interest, deployment is accelerating, technology is scaling rapidly, and industrial demand is growing. While stark, the recent market corrections are typical in emerging sectors: technologies often experience cycles of exuberance followed by consolidation before stabilising around the most viable opportunities. In other words, the "bubble" may be weakening, but it is far from bursting – the sector is simply entering a more disciplined and sustainable phase. In this new phase stakeholders will focus efforts on those applications with more solid business cases and higher probability of succeeding, rather than diversifying exploratory effort across a large variety of uses, some of which are more prone to fail.

Nonetheless, the long-term prospects for low-emissions hydrogen and hydrogen-based fuels hinge critically on policy support and technology innovation due to their higher cost relative to conventional hydrogen and other energy sources. If that support falters, the sector could prove more vulnerable than other clean energy technologies. The contrast is clear in the assessment of the likelihood of announced projects in our *Global Hydrogen Review 2025* (IEA, 2025b).

Based solely on projects that are almost certain to proceed under today's policy settings, global low-emissions hydrogen production is set to increase sixfold between 2024 and 2030. Including projects with a strong potential to come online by 2030, output could rise almost fifteen-fold. However, realising these projects would require targeted policy intervention through support schemes that narrow the cost gap with unabated fossil fuel-based hydrogen, stimulate demand in existing industrial applications and scale up enabling infrastructure such as CO_2 transport and storage networks and hydrogen pipelines.

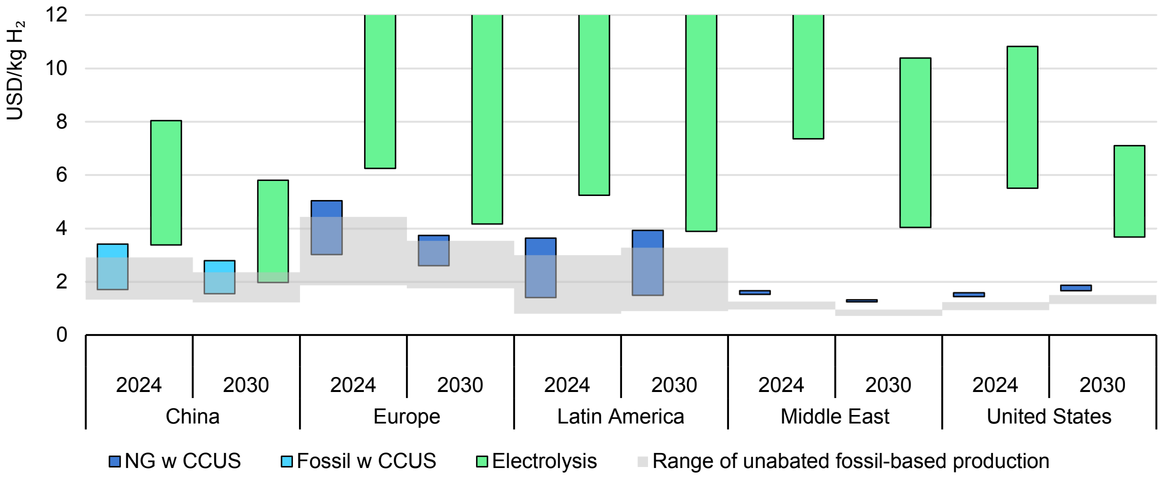
Bringing the full pipeline of announced projects into operation would result in a staggering fifty-fold rise in output, but that appears highly challenging as the end of the decade draws closer. Many proposed projects will also compete with other rapidly growing energy-intensive sectors, such as data centres, for electricity supplies and capital for enabling infrastructure. As a result, a large share of announced projects are more likely to materialise after 2030.

Unlike renewables in the power sector, low-emissions hydrogen still cannot compete on price with unabated fossil fuels without targeted incentives. Producing low-emissions hydrogen requires an additional energy-intensive step – electrolysis or CO_2 capture. Fossil fuels, when used directly in industry or transport, avoid this extra layer of conversion losses. These unfavourable thermodynamics are unavoidable, though they can be overcome when fossil fuel prices are high or when policy support narrows the cost gap.

Another reason to be cautious about the longer-term prospects for hydrogen is that the cost gap has not closed as quickly as many had hoped. Electrolyser costs have risen in recent years due to inflation, supply chain tensions and cost estimates becoming more realistic as projects progress, though this trend is expected to reverse as manufacturing scales and construction experience accumulates. Industrial sectors such as refining and chemicals, along with hydrogen-based fuels, represent a demand base large enough to unlock the economies of scale needed for steep cost reductions. For instance, replacing just one-quarter of today's hydrogen use in refining, ammonia and methanol with electrolytic hydrogen would require about 240 GW of capacity – enough to cut the current capital costs of installing an electrolyser by more than 40%.

At present, producing hydrogen from fossil fuels with CCUS carries a cost gap of USD 0.4-1.2 per kg relative to unabated fossil-based hydrogen, implying a carbon price of USD 30-100 per tonne of CO_2 to level the playing field (Figure 1.11). Electrolytic hydrogen shows wider variation. In regions with good renewable resources and expensive natural gas for industrial end users, the cost gap can be as low as USD 0.5-4.5/kg H_2 (equivalent to CO_2 prices of USD 40-350/t). By contrast, regions with cheap natural gas face a cost gap of more than USD 6/kg H_2, requiring CO_2 prices in excess of USD 550/t to close it.

Figure 1.11 Hydrogen production cost by pathway and region in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Notes: NG = natural gas; CCUS = carbon capture, utilisation and storage. Assumes a capture rate of 95% for technologies using CCUS. The grey shading represents the range of production costs from unabated fossil fuels. The ranges of the fossil-based routes for China include both natural gas reforming and coal gasification. Hydrogen costs are capped at USD 12/kg, although some production routes cost more. Water costs are not included. See the technical annex of the IEA's *Global Hydrogen Review 2025* for further details on technoeconomic assumptions.

Source: IEA (2025b).

Renewable hydrogen production remains far more expensive than unabated fossil-based production, but the cost gap is set to close as early as 2030 in locations such as China.

Some regions are on track to eliminate the cost gap for low-emissions hydrogen entirely by 2030. In markets such as China, where technology and capital costs are relatively low, the economics are particularly favourable. In other regions, notably parts of Europe and Latin America, persistently high natural gas prices, supportive carbon pricing mechanisms and strong renewables potential are expected to bring the cost differential down to less than USD 1/kg.

Low-emissions hydrogen production is not a standardised plug-and-play technology. Whether based on electrolysis or CCUS-equipped steam reforming of fossil fuels, it requires the development of entire supply chains from scratch. Establishing appropriate regulatory frameworks, including standards and certification schemes, is therefore critical to ensure transparency, comparability and investor confidence. Progress in this respect varies widely across regions. Large energy-importing economies such as Europe, Japan and Korea have already devised comprehensive frameworks to mitigate investment risks and facilitate market development. In contrast, progress remains limited in many EMDEs, where institutional capacity and policy alignment are still evolving.

The International Organization for Standardization (ISO) is playing a central role in harmonising approaches. The first part of its lifecycle GHG emissions standard for hydrogen production is expected in early 2026, while additional standards covering conversion into carriers – including liquid hydrogen, ammonia and liquid organic hydrogen carriers – reconversion to hydrogen and transport are scheduled for release later in the year. These efforts will be pivotal in enabling cross-border trade and ensuring that hydrogen contributes effectively to policy goals.

7. Is carbon capture, utilisation and storage finally taking off?

Why it matters

Carbon capture, utilisation and storage (CCUS) is an important suite of technologies needed to complement other means of reducing CO_2 emissions. It captures CO_2 from power plants, industrial facilities or directly from the air, either reusing it or storing it safely underground so that it does not contribute to climate change. As well as cutting hard-to-abate emissions at source, CCUS enables permanent CO_2 removals to balance emissions that cannot be eliminated and lower CO_2 concentrations in the atmosphere. Without it, reaching net zero globally by mid-century is virtually impossible.

Interest in CCUS has surged in recent years, with a wave of projects announced and installed capacity expected to double in the years ahead. Yet past project cancellations, cost overruns and technical challenges are breeding scepticism.

The 2010s saw a similar burst of optimism (IEA, 2021): more than USD 8.5 billion of public funding was pledged globally to projects that, in many cases, never moved far beyond the drawing board. Perceptions of poor operational performance and uncertainty about the financial viability of CCUS investments persist, raising concerns among investors over long-term revenues and returns.

In this context, it is reasonable to ask whether the current momentum will prove any different this time and translate into sustained deployment, or whether we are witnessing another false dawn. At stake are major policy choices in several countries, where governments must decide whether to anchor CCUS as part of their long-term climate strategies. For that debate to be constructive, it is essential to understand if and how today's conditions differ from past episodes – both in the scale of private sector commitment and in the changing role of CCUS within the wider energy transition.

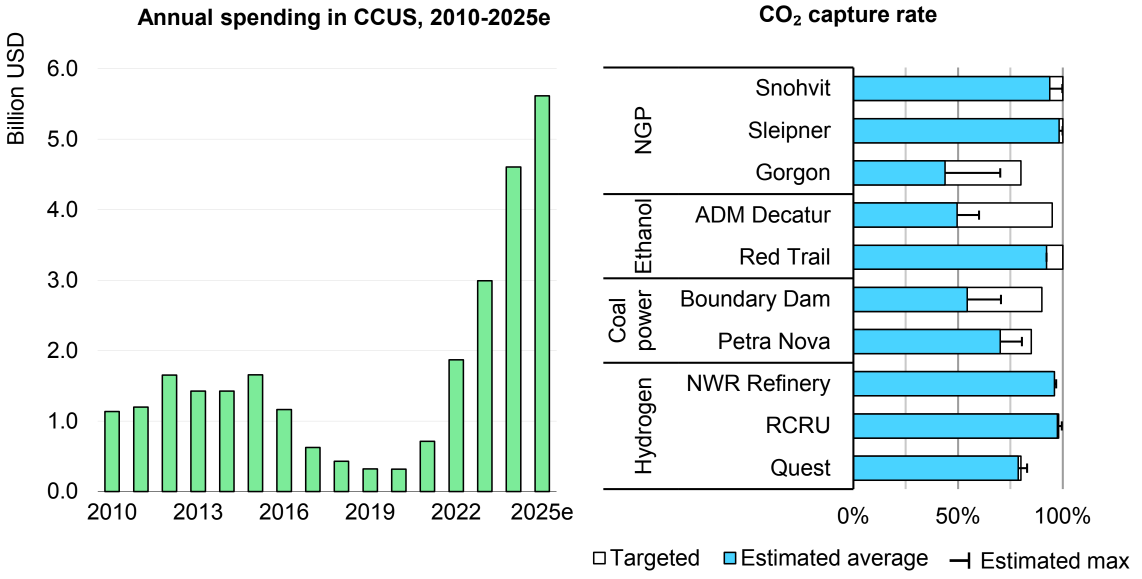
What is happening

There is strong evidence that today's wave is different, but several factors need to align for CCUS to really take off. Global investment in CCUS has grown sharply, from around USD 0.3 billion in 2020 to over USD 5 billion in 2025, far exceeding that in the previous wave of the early 2010s (Figure 1.12). In 2023-24 alone, governments earmarked around USD 50 billion in support. Notably, after two decades of deliberation, the United Kingdom has taken FIDs on several large projects.

The current wave is also broader than before, with projects now spanning multiple sectors, including those that typically involve more dilute CO_2 streams and therefore higher capture costs. The past year has seen several milestones, including FIDs on the first natural gas power plant with carbon capture and storage in the United Kingdom and the world's largest CO_2 removal facility in Sweden. CCUS deployment in the cement sector is also accelerating, with the biggest capture facility ever applied to a cement plant starting operation in Norway and an even larger capture facility reaching FID in the United Kingdom. In addition, two large CO_2 storage projects in Norway and Australia began operations.

Deployment is also widening geographically. In 2020, close to 60% of all projects in operation and under construction were located in North America, but today that share has fallen to around 40%, reflecting the sector's growing international reach. Europe has emerged as a key hub, with major developments underway in the United Kingdom, Denmark and the Netherlands. Indonesia has reached its first FID for a large-scale project, while both the Middle East and China now have as much or more CO_2 capture capacity under construction as Europe.

Figure 1.12 Global investment in carbon capture, utilisation and storage and average capture rates in operating facilities, 2010-2025e



IEA. CC BY 4.0.

Notes: NGP = natural gas processing; CCUS = carbon capture, utilisation and storage. CO_2 capture rates are estimated by dividing the mass of CO_2 separated in the capture plant (and therefore not emitted) by the total mass of CO_2 contained in the gas stream to which capture plant is fitted. Estimated average corresponds to the entire operational period to date. Estimated max corresponds to the highest rate achieved so far in a single a year of operation.

Sources: IEA analysis based on IEAGHG TCP (2019); Alberta Department of Energy (2024); Enhance Energy (2024); US Environmental Protection Agency (2023); IEA Bioenergy TCP (2023); Red Trail Energy (2022); Giannaris, S. et al. (2021); Chevron (2024); Petra Nova Parish Holdings (2020).

The current wave of CCUS investment is bigger than any before it, while operational performance has mostly achieved targeted levels.

More than 50 countries are now represented among the hundreds of projects announced worldwide. If all proceed as planned, global CO_2 capture capacity would increase eightfold, while storage capacity would expand more than thirteen-fold by 2030. As these new projects move from design to operation, gaining real-world experience across different sectors and regions will be essential – not only for improving performance and reliability, but also for driving down costs and accelerating the next wave of deployment.

Operational data suggest that projects are performing better than is often assumed, with most plants operating in line with their original design expectations. It is important to note that few projects were designed to capture the majority of a facility’s total emissions. Instead, they were typically configured to target specific, concentrated CO_2 streams, reflecting the limited economic incentive to capture from more dilute sources. Judged against these design parameters, most projects have achieved their planned capture rates.[5]

Notably, several biofuel and hydrogen plants – where CO_2 concentrations in exhaust gases are high – have achieved capture rates above 90% of their targeted streams during full operation, with some reporting annual averages exceeding 95% (Figure 1.12). While some projects have fallen short of overall CO_2 capture volume targets, this often reflects reduced utilisation of the host facility, such as a power plant or industrial unit, rather than any technical shortcoming of the capture system itself (Clean Air Task Force, 2024). Even so, unplanned downtime at the base plant can undermine project economics by reducing the overall volume of CO_2 captured and raising the levelised cost of capture.

Some projects have nonetheless faced technical hurdles. The Gorgon project in Australia has encountered difficulties in managing reservoir pressure (Chevron, 2024); ADM Decatur in the United States has experienced problems related to CO_2 purity, well clogging and, more recently, corrosion (Reuters, 2024); and Canada's Boundary Dam facility has undergone multiple system modifications to enhance the availability of its capture plant (Giannaris, S. et al., 2021). Importantly, the lessons from these early difficulties have contributed to more robust legal and regulatory frameworks, improving reliability and safety across the industry.

Today's momentum differs markedly from that of a decade ago in both scale and sectoral diversity, but project economics remain a central obstacle to wider deployment. In many industries, the levelised cost of CO_2 avoided for *nth-of-a-kind* projects still exceeds prevailing carbon prices in most jurisdictions (Figure 1.13). Recent inflationary pressures, the first-of-a-kind cost premiums associated with new applications targeting dilute CO_2 streams and high transport and storage fees – particularly for initial emitters connecting to offshore hubs in Europe – are compounding the problem.

Business models are evolving, enabling projects to "stack" multiple revenue streams. By combining policy supports, such as tax credits or carbon contracts for difference (CCfDs), which are designed to bridge the gap between the prevailing carbon price and an agreed strike price with income from the sale of low- or near-zero-emission products or high-quality carbon removal credits, developers are diversifying their sources of revenue. Some removal credits in voluntary markets are fetching over USD 2 000 per tonne, providing a powerful incentive for early

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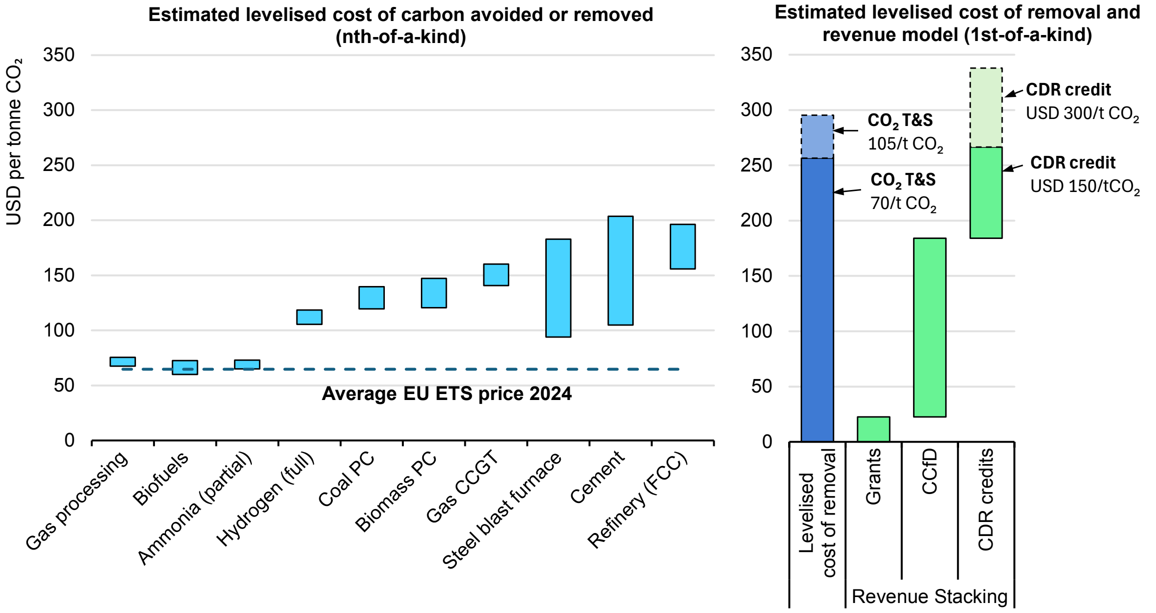
[5] CO_2 capture rates are estimated by dividing the mass of CO_2 separated in the capture plant (and therefore not emitted) by the total mass of CO_2 contained in the gas stream to which capture plant is fitted (i.e. the CO_2 treated by the capture plant).

movers. In Sweden, a mix of government grants and CCfDs cover over half of the cost of Stockholm Exergi's bioenergy-based district heating project. When combined with credit sales, this support package is sufficient to make the project commercially viable (Figure 1.13).

This "revenue stacking" approach has found favour among financers. Banks are now co-funding CCUS projects in both the United Kingdom and Sweden, signalling greater confidence in the sector's financial maturity in some markets. It marks a clear departure from earlier business models that relied on a single revenue stream from selling captured CO_2 for enhanced oil recovery – a model that faltered during periods of low oil prices and led to the temporary shutdown of the Petra Nova project in the United States. It also contrasts with past approaches built solely on expectations of higher future carbon prices, which provides an uncertain foundation for investment.

Figure 1.13 Levelised cost of carbon avoided or removed for selected carbon capture, utilisation and storage applications, and costs and revenues of a first-of-a-kind project, 2024



IEA. CC BY 4.0.

Notes: CCfD = carbon contract for difference; CCGT = combined cycle gas turbine; CDR = carbon dioxide removal; ETS = Emissions Trading Scheme; FCC = fluid catalytic cracker; PC = pulverised combustion; T&S= transport and storage. Left: levelised cost of carbon avoided and removed from previous IEA analysis (see notes on page 63 of (IEA, 2023)), inflated to 2024, and CO_2 transport and storage fee updated to USD 50/t CO_2. Potential reflects levelised costs that could be reached without the cost premiums that are typically associated with first-of-a-kind plants. The first-of-a-kind assessment is based on Stockholm Exergi plant. Model assumptions include 8% weighted average cost of capital, fixed operating expenses at 4% of capital expenses, and an economic lifetime of 15 years.

Revenue stacking is proving crucial to the financial viability of CCUS projects in Europe, such as Stockholm Exergi, for which grants and CCfDs provide over half of its revenue.

What it means

Recent momentum in CCUS reflects growing confidence in the technology’s potential, but interest alone does not equal impact. The surge in announced projects is impressive, yet only facilities that reach operation can deliver real emissions reductions. So far, only around a quarter of the capture capacity announced for 2030 has reached FID and even that milestone does not guarantee delivery: projects can still be delayed, scaled back or cancelled post-FID.

For now, CCUS remains a niche solution, concentrated in North America, China, the Middle East and a handful of Northern European countries. Broader deployment will depend on greater confidence that project risks are both modest and manageable – a conviction that will strengthen only as more facilities move from paper to operation. Beyond high-concentration CO_2 streams, deployment remains limited. Achieving cost reductions in these areas will require scale and accumulated operational experience – progress that can only come with more projects coming into operation.

Attracting larger volumes of private capital would mark a turning point for the industry. Most recent FIDs have relied heavily on public backing, reflecting the early-stage nature of the market. For the market to mature, projects must secure predictable revenue streams that make investment attractive beyond government support. To date, this has been the case for only a few projects. A forthcoming IEA report on leveraging private capital for CCUS will explore how policy frameworks, market design and risk-sharing models can help achieve this.

Whether the current wave of activity becomes a large-scale, durable global industry will depend on turning project announcements into steel on the ground, embedding private finance and extending deployment far beyond today’s early movers.

8. Large, modular and fusion reactors all have renewed momentum: how quickly can nuclear be brought online?

Why it matters

After years of drift, a new era of nuclear energy beckons. More than 70 GW[6] of capacity, equal to 17% of the existing fleet, is now under construction worldwide – one of the fastest build-out rates in the last 35 years. More than 40 countries are planning further expansion. The first small modular reactors (SMRs) are finally moving from blueprint to building site. Energy security, reliability and the need for low-carbon power are all sharpening policy makers' interest, with geopolitics and the global race for leadership in AI adding further urgency.

Nuclear fusion – a very different and as-yet-unproven energy technology – is also generating fresh excitement. The last few years have seen some important advances in fusion technology, while venture capital funding has surged, with tech companies investing in anticipation of long-term offtake contracts, given fusion's promise of constant, emissions-free power.

Yet some of the old obstacles remain. Conventional reactors have a history of delays and cost overruns, while SMRs have been in the works for decades. Fusion, despite the buzz, is still unproven and the old adage about it being "30 years away, and always will be" still resonates with many observers. Whatever the technology, nuclear reactors will always take years to plan and build. Still, many expect timelines to shorten as construction experience accumulates. For governments banking on nuclear, the task now is to separate real progress from hype and to judge when new reactors will actually start delivering electricity to the grid.

What is happening

For conventional nuclear fission, new reactors still take about a decade to build, even before accounting for permitting, which can add another 3-8 years. Despite efforts for streamlining, there is little sign that these timelines are shrinking. In fact, global average construction times for large reactors have roughly doubled since the 1970s, and in Europe and North America, projects launched this century have taken more than 20 years on average to complete (Figure 1.14). Korea used to be

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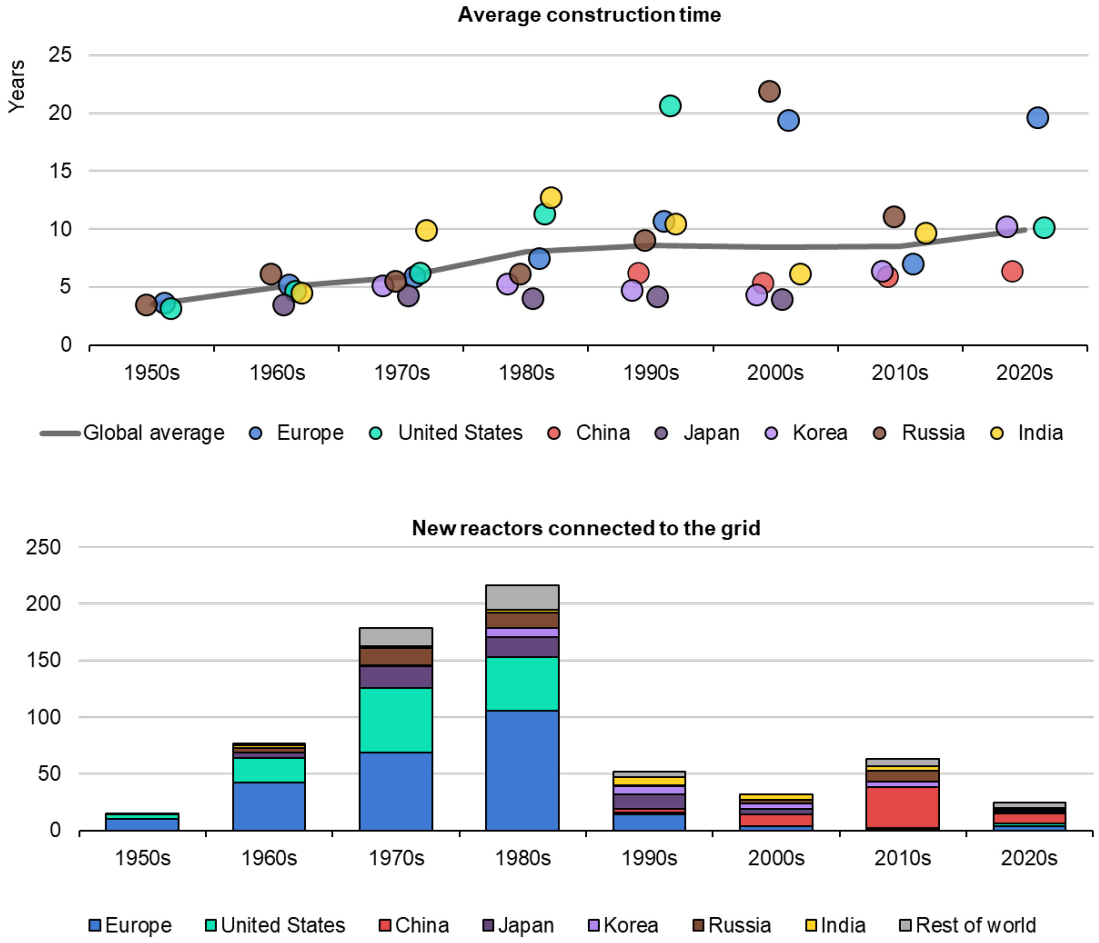
[6] Data on nuclear capacity in this report refer to gross capacity.

able to build a reactor in about 5 years, but that has stretched to 8-10 years over the last decade. The stand-out exception is China, which has managed to hold average construction times below 6 years over the past quarter-century.

Figure 1.14 Construction times for large nuclear reactors and number of reactors connected to the grid by country or region, 1951-2025



Notes: In the upper figure, the construction time of 43 years for Unit 2 of the Watts Bar nuclear power plant is not shown (construction started in 1973 but was halted in 1985 due to decreased power demand before being recontinued in 2007, with the unit being connected to the grid in 2016). Construction time refers to the period from the first pouring of the concrete for the reactor building to the grid connection.

Source: IEA analysis based on International Atomic Energy Agency (2025).

Global construction times for large reactors have doubled since the 1970s, with European and North America projects launched this century taking more than 20 years to complete.

One reason nuclear projects outside China take so long to complete is the collapse in construction that began in the early 1990s: with new orders drying up, much of the industrial base and workforce expertise withered away, and has since had to be rebuilt. Increasing regulatory stringency and rule changes have also made new designs more complex and costly, dragged out permitting procedures and prolonged construction times. As a result, final capital costs and lead times have, in many cases, ended up at least double the original estimates.

China's experience shows how standardisation makes a difference. There, 1 single reactor design accounts for 22 of the 58 units built since 2000, while just 2 designs make up 88% of the 33 currently under construction. China's State Council has also approved a further 21 reactors, out of which 20 rely on just 2 designs (World Nuclear News, 2024), (World Nuclear News, 2025a). Along with a steady stream of orders, this repetition has kept build times under control. The first four Westinghouse AP1000 units installed in China took nearly 9 years on average to complete – only slightly faster than the 10 years required for the first two in the United States. The next wave of eight AP1000s now under construction is moving more quickly, reflecting lessons learned from earlier projects.[7] The installation of the reactor pressure vessel – an important construction milestone – was achieved, on average, after just 21 months from the start of work, compared with 42 months for the initial series (Spangler et al., 2025).

Domestic industrial capacity has expanded in parallel. Whereas China's first generation of nuclear plants in the 1990s depended to a large extent on imported equipment, around 90% of the components used in recent projects are sourced from domestic suppliers (China Atomic Energy Authority, 2018; Nengyuanjie, 2020). These newer reactors also meet international safety standards (International Atomic Energy Agency, 2025), underscoring how localisation has gone hand in hand with technical maturity.

SMRs, typically defined as reactors producing less than 300 MW of electricity, are often seen as the nuclear industry's best bet for faster deployment. Their appeal lies in designs that promise more standardisation, heavier use of off-site manufacturing and serial production. In theory, this should trim construction times, as well as make them easier to integrate into less centralised power systems by slotting into regional grids or industrial hubs where a gigawatt-scale reactor would never fit.

Momentum is building, with more than 90 SMR designs at varying stages of development across more than 30 countries. They make use of a wide range of nuclear technologies, from established light-water reactor technologies to novel approaches, with around 12 designs at advanced development stages. In Canada, an FID was taken in 2025 to build four units, with the first slated for grid connection by 2030 (World Nuclear News, 2025b). The UK government also pledged in 2025 GBP 2.5 billion (around USD 3.2 billion) of public funding, and picked a preferred design, with commissioning due in the mid-2030s (Vallance, 2025). In the United States, data centre operators, hungry for reliable, uninterrupted power

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[7] The localised, Chinese version of the AP1000 is typically named CAP1000.

supplies to support AI, have begun partnering with SMR developers, with one design having already cleared regulatory approval for construction.

Fusion is another story altogether. No power plant yet exists, but interest and money are pouring in. The number of firms researching fusion has multiplied in recent years and global venture capital flows into the sector have risen sharply, led above all by the United States, but followed by China with a surge of investments in the last three years (Figure 1.15). For the first time in 2022, an inertial fusion device in the United States produced more energy than was put into a fusion reaction. The ratio of the energy produced by this device to the energy put into it has since been increased, from 1.5 to 4.1 in April 2025 (National Ignition Facility, 2025). In early 2025, scientists in China and France broke records for sustaining high-confinement plasma, keeping it stable for 17 minutes (Chinese Academy of Sciences, 2025) and then 22 minutes (CEA, 2025) – an important milestone on the path to designing a working reactor. Another fusion device, a stellarator, set a new record for its combination of temperature, plasma density and confinement time (known as the 'triple product'), which is needed for the technology to be viable, over long plasma durations in 2025 (EUROfusion, 2025). The focus of both public and private initiatives is shifting from study of the fundamental physics towards the engineering of first-of-a-kind facilities.

The world's largest fusion experiment is under construction in France. Known as ITER, the intergovernmental project aims to prove that a fusion reactor can produce more energy than it consumes, targeting a net energy gain of ten. However, the effort has been beset by technical setbacks, cost overruns and schedule delays, pushing that milestone back to 2039. If successful, ITER is expected to pave the way for a 500 MW demonstration plant connected to the grid around 2050 at the earliest (EUROfusion, 2018).

Alongside this publicly funded effort, a wave of private companies has entered the fusion race, promising to deliver working reactors far sooner. Dozens of start-ups, many spun out of leading research institutions, are developing alternative technologies that aim to compress timelines and costs, with the majority targeting the commissioning of a first demonstration power plant by the mid-2030s. Commonwealth Fusion Systems, a US-based firm and the sector's largest fundraiser, is pursuing a high-temperature superconducting magnet design and targets achieving a net energy gain of ten as early as 2027. [8] If that target is met, a grid-connected plant could follow in the 2030s.

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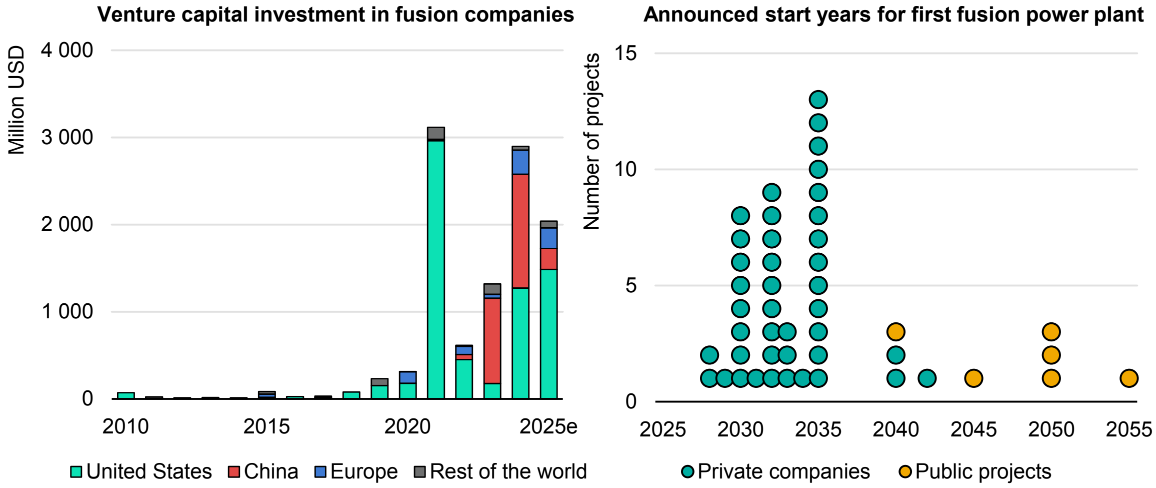
[8] In addition, other companies working on magnetic fusion are developing high-temperature superconducting magnets, which are operating at temperatures of -253°C, such as Helical Fusion in Japan, Tokamak Energy in the United Kingdom or Energy Singularity in China. Low-temperature superconducting magnets, as used in the ITER project, operate at temperatures of -269°C. High-temperature superconducting magnets allow for a more compact fusion reactor design, reducing capital costs and construction time.

Private sector momentum – built on decades of public research – has undoubtedly injected new credibility into fusion's long-promised potential. Whether optimism turns into operating power plants remains to be seen, but the combination of public research and infrastructure and private innovation has given fusion its most realistic path yet toward commercial heat and electricity production within the next two decades.

Figure 1.15 Global venture capital funding for fusion companies, 2010-2025e, and announced start years for electricity-generating fusion plants, 2025-2055



IEA. CC BY 4.0.

Note: Venture capital investment in 2025 only covers the period until August 2025.

Sources: IEA analysis based on Cleantech Group (2025); Crunchbase (2025); Fusion Energy Base (2025); and surveys from Fusion Industry Association (2025).

Cumulative venture capital investment in fusion energy has reached almost USD 11 billion, with the majority of companies aiming to commission power plants in the 2030s.

What it means

The evidence that SMRs will cut lead times for new nuclear power capacity remains mixed. The four demonstration plants in China, Japan and the Russian Federation (hereafter, "Russia") each took 7-9 years to build – hardly a dramatic improvement on conventional projects. China's second SMR, which started construction in 2021, is aiming for grid connection in 2026, but even that would not be a rapid turnaround by industry standards. These first-of-a-kind SMR plants are not yet benefiting from reductions in construction times and costs that their smaller sizes – typically four times smaller than a large reactor – and standardised designs could bring. It is the manufacturing of multiple standardised SMRs in parallel, largely assembled off-site in factories, that is expected to bring down costs and avoid cost overruns.

With first-of-a-kind projects still under construction, the future cost of SMRs remains uncertain. Given their limited economies of scale, it is no surprise that first-of-a-kind SMRs are expected to cost twice as much as conventional large-scale reactors – around USD 10 000/kW in advanced economies (World Nuclear News, 2025b) and less than USD 6 000/kW in China and India (Global Times, 2025). Assuming global deployment reaches 120 GW by 2050, average SMR costs could reach cost parity with large-scale reactors in the 2040s (IEA, 2025d). Developers themselves are more optimistic, targeting a cost range of USD 2 000-3 400/kW.

Fusion raises multiple different questions: the issue is not construction timelines, but how quickly technology developers can shift from experiments in laboratories to the first grid-connected demonstration plant. If realised, the prize will be extraordinary: reactors that generate more energy than they consume require, in principle, no imported fuel (with most reactor designs needing only lithium and water),[9] emit no CO_2 and leave behind no highly radioactive waste. Such attributes would surely attract investors willing to shoulder high upfront costs – provided the plants prove they can run safely, continuously and for decades at a stretch.

Nevertheless, the timeline remains deeply uncertain, given uncertainties about technological progress and costs. There has been steady progress: improved performance in plasma confinement, growing attention to engineering challenges and a surge of private investment supporting competing designs. Even so, the leap from one grid-connected demonstration to a fleet of reliable, commercially operating reactors is likely to remain a long-term endeavour.

9. Can strategic industries in advanced economies restore their competitive edge?

Why it matters

Excess global industrial capacity – especially in steel and chemicals – has depressed prices and squeezed producers in some advanced economies out of export markets. Trade restrictions are compounding the strain, disrupting supply chains and reshaping the competitive landscape. In Europe, the energy crisis has added to these problems, with high and volatile fossil fuel prices arising from imported energy leaving swathes of industry uncompetitive. Yet governments are

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[9] Most proposed reactor designs rely on a combination of deuterium and tritium as fuels. While the production of deuterium from sea water is well established, tritium is extremely rare, with estimated global stocks of 25-30 kg being mostly a by-product of CANDU nuclear reactors in Canada. A single fusion power plant alone may require 10 kg of tritium for commissioning and start-up (Science Business, 2024). Concepts for the production of tritium from lithium using breeding blankets, mostly for use in tokamak reactors, are still at early development stages in terms of materials, coolants and tritium extraction methods (technology readiness levels 2-5).

understandably reluctant to let strategic sectors collapse: industry is too closely tied to skilled jobs, downstream manufacturing and other supply chains, including defence. For instance, in 2025, the UK government stepped in to rescue a loss-making blast furnace – the country's last – rather than see it shut (UK Government, 2025). The US government also stepped in to veto plant closures or relocations the same year, when a US steel company was privately sold to a Japanese investor (Alper, Yamazaki, & Uranaka, 2025).

The longer-term dilemma is harder still. Many advanced economies have pledged to decarbonise industry to reduce environmental impacts, while also seeking to strengthen energy security and industrial competitiveness, and to capture opportunities in growing markets for low-emissions products. Yet the price tag for scaling low-emissions technologies can be daunting, particularly for firms already struggling to compete. Several companies have delayed or reconsidered the investment timeline for building new, low-emissions plants.

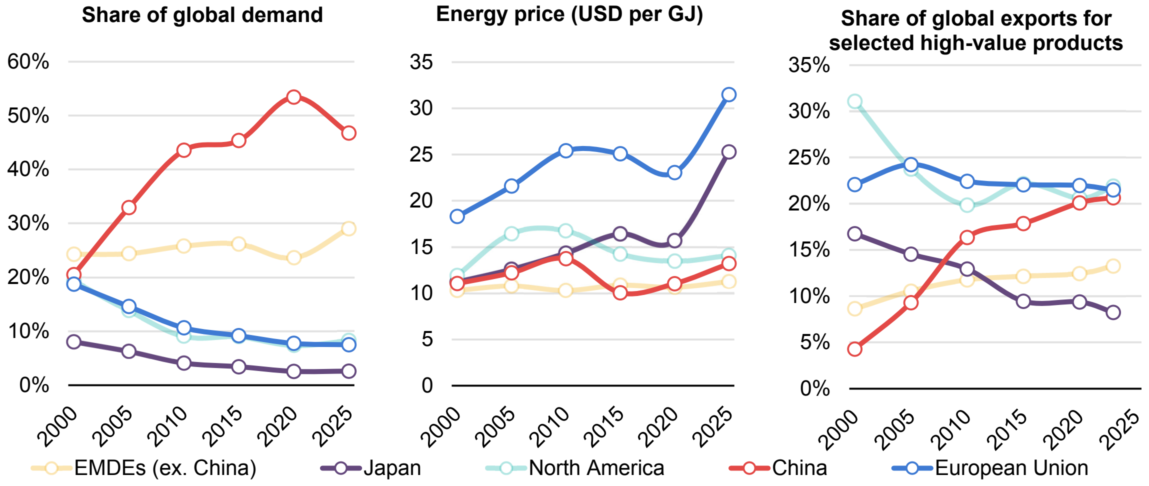
That leaves policy makers and industry searching for a two-track solution: shoring up the competitiveness of today's facilities while finding ways to invest in the technologies that could deliver an edge tomorrow. Innovation can accelerate the development of technologies to boost efficiencies and lower costs in the coming decades. In the meantime, the balance between short-term survival and long-term transformation will define whether energy-intensive industries in advanced economies can reclaim their footing in global markets.

What is happening

For decades, advanced economies dominated energy-intensive industries, supplying local markets with steel, cement and chemicals. Their industrial clusters, located close to centres of demand, were built on formidable comparative advantages: sophisticated technologies, dense capital stock, strong logistics, integration with customers and highly skilled workforces.

However, these advantages are being eroded. Myriad structural pressures – high energy and labour costs, ageing assets, reliance on imported fuels and raw materials, shrinking domestic demand and complex regulation – have steadily undercut competitiveness. Europe has been hit especially hard: the drive to eliminate imports of Russian gas has kept energy prices high. Industrial producers in Europe have faced energy costs about twice as high as in North America and China over the past 5 years (Figure 1.16). They also face carbon prices that add costs not borne by their main competitors overseas. Japan faces intense competition with the burgeoning fleet of new plants elsewhere in Asia, while North America faces new vulnerabilities as shifts in trade policy expose its reliance on cross-border supply chains, especially in steel and aluminium.

Figure 1.16 Industrial sector indicators by country or region, 2000-2025



Notes: EMDEs = emerging markets and developing economies. (Left): Share of global demand is based on value of demand for crude steel, aluminium, ammonia, and cement. Assumed material prices are taken as average global prices from 2000-25. When not available, assumed material prices are derived using the evolution of historical levelised cost of production and demand. (Middle): The energy price for each country/region is the average weighted by demand for each type of energy input. (Right): Share of global exports is based on value of selected traded high-value industrial products (machinery, transport equipment and fertilisers) using bulk material inputs that provide a representative sample across sub-sectors.

Source: IEA analysis based on CEPII (2025).

The competitiveness of materials producers in advanced economies, particularly Europe, has steadily declined in the past 25 years, while Chinese firms have increased their presence.

China and other EMDEs now account for roughly half of gross exports of key bulk industrial materials (steel, aluminium and ammonia) and also meet most of their own development needs. Roughly three-quarters of global demand for bulk industrial materials comes from these countries. Material quality is no longer the competitive differentiator it used to be for advanced economies, with EMDEs – especially China – producing and exporting larger shares of high-value, high-quality goods. Low energy costs remain a key advantage in many EMDEs. Advanced economies therefore face a double squeeze: losing ground abroad while confronting fierce competition at home.

Trade frictions have heightened awareness of the longer-term dilemma: how to balance short-term competitiveness with the transition to innovative, low-emissions production based more on domestic resources in the 2030s. Early movers face daunting economics: new technologies could raise production costs significantly, while markets for more expensive products are still emerging. In the steel sector, for example, initial cost premiums of 20-145%[10] are enough to deter

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[10] Based on comparison of hydrogen direct reduced iron electric arc furnace production compared to conventional iron-based production.

investment, even where public support is strong. ArcelorMittal's decision to shelve its plans for near-zero emissions steel production in Germany (ArcelorMittal, 2025), despite the offer of a EUR 1.3 billion (approximately USD 1.5 billion) public grant (Germany, Federal Ministry for Economic Affairs and Energy, 2024), illustrates these pressures. As energy-intensive sectors are largely driven by operating expenses, capital subsidies alone might not be enough to guarantee long-term competitiveness.

EMDEs may be able to capture emerging opportunities thanks to their growing access to cheap clean energy, abundant raw materials and other enabling factors (IEA, 2024). Realising this potential, however, will depend on progress in financing, infrastructure and regulatory frameworks.

Rapid shifts are difficult, but they can happen when conditions align. In the United States, steelmaking has moved sharply away from coal-based basic oxygen furnaces towards electric arc furnaces. By 2025, output from the latter reached just over 55 Mt (about 70% of total production), driven by federal government stimulus spending in the wake of the 2008 financial crisis, cheap natural gas and rising availability of scrap. This shift has lowered costs and emissions while boosting flexibility, competitiveness and energy security. The United States now has the world's second-largest fleet of electric arc furnaces.

What it means

Advanced economies can no longer count on their traditional strengths to guarantee competitiveness. Those advantages remain important in many cases, but are no longer sufficient to offset structural weaknesses that have been amplified by global market pressures and excess capacity. A carbon border adjustment mechanism, which aims to confirm that a price has been paid for the embedded carbon emissions generated in the production of certain imported goods, may address one source of higher costs but it cannot resolve these deeper issues. Implementing such a mechanism brings its own problems (see Chapter 7). Even if strong markets for near-zero and low-emissions products emerge, some EMDEs are likely to retain their competitive edge over advanced economies. Addressing the underlying problems could take decades.

Maintaining the status quo is a high-risk strategy for the least competitive advanced economies, requiring heavy subsidies with no assurance of restoring competitiveness. An alternative path may lie in strategic partnerships that divide supply chains to maximise each region's strengths. EMDEs with low-cost renewable energy resources could take on the energy-intensive steps of production, while advanced economies retain higher-value activities where they still hold an edge, such as in specialised manufacturing and integration with downstream industries.

Advanced economies could continue to participate in technology development and benefit from their large-scale deployment, while working with EMDEs to establish secure and efficient supply chains. Supply chain security remains a policy priority, meaning that partial relocation of certain domestic production steps – combined with other measures to enhance competitiveness – may be preferable to abandoning them altogether. Shared investment could create more resilient supply chains, lower overall transition costs and capture rising demand for cleaner materials, complementing domestic production that is retained to support security. Experience also suggests that investing in upstream materials production, even when uncompetitive on a cost basis alone, can strengthen downstream industries and domestic supply chains, including for strategic sectors like defence (see Chapter 7).

The potential prize is sizeable, though the opportunities and constraints vary by sector and region, and on how trade policies evolve in the coming years. In the Stated Policies Scenario (STEPS), which takes account of policies that have already been adopted or announced, or are at the advanced planning stage, global markets for low-emissions iron and ammonia for industrial use reach USD 8 billion by 2035. Already, publicly announced agreements for export of these materials, some of which are firm offtakes, have an estimated value exceeding USD 2 billion.

Many of Europe's industrial sites are ill-suited to low-cost near-zero emissions production. Importing intermediate low-emissions inputs and focusing on downstream manufacturing could safeguard the majority of their industry sector jobs (Agora Industry, 2025). For instance, Brazil already has competitive energy resources and existing iron and steel infrastructure, and so if Western European steel producers imported iron from Brazil produced with low-emissions hydrogen rather than producing it domestically, the average steel cost premium over conventional steel would fall from roughly 20% to near cost parity in that scenario (Figure 1.17).[11]

Similarly, Japan faces rising costs in adopting near-zero emissions production, primarily as a result of high energy costs due to geographical constraints. Its competitive advantage, however, lies in value-added industries further down the supply chain. The Middle East, by contrast, benefits from abundant renewable energy resources, making low-emissions ammonia imports from this region a

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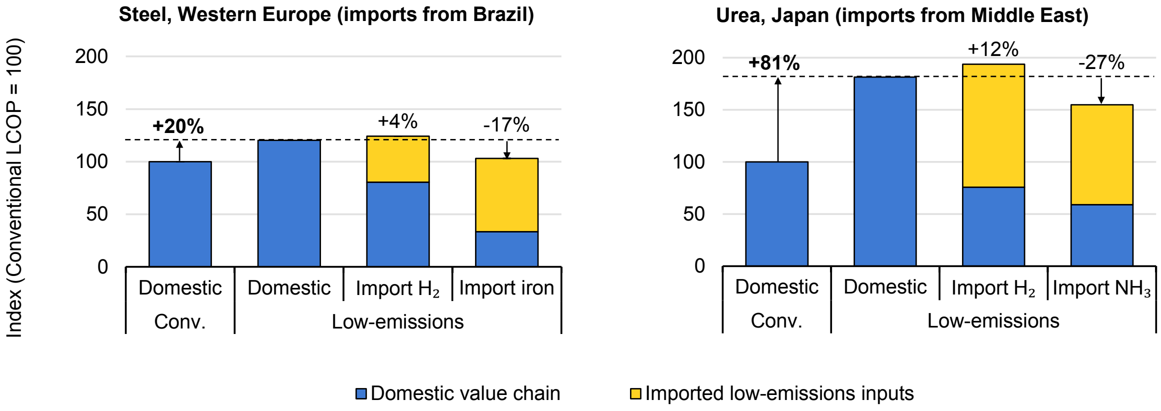
[11] An additional strategy could be to import iron produced with natural gas. Rather than reduce emissions intensity in steel production by roughly 85% compared to today's global average coal-based production, this would lead to a reduction of about 50% (IEA, 2022a), but for a potentially lower premium. Whether it could be attractive depends on there being a differentiated market for low-emissions steel with only partially reduced upstream emissions, among other policy objectives.

more cost-effective option for Japan; urea cost premiums would fall from approximately 80% to 55%. In both cases, importing hydrogen is also feasible, but tends to be more expensive. Its competitiveness will depend on the structure of specific supply chains and the development of international hydrogen markets over the next decade.

Even then, some policy support remains necessary: for example, the cost of producing near-zero emissions steel in Europe from imported iron is still projected to be about 30% higher than the cost of imports from China in 2035. However, these trade-offs may prove acceptable if they preserve jobs, protect domestic capacity and allow advanced economies to specialise in higher-value products. The lesson is clear: by capturing the strategic opportunities provided by low-emissions technologies, advanced economies could proactively shape competitive, cleaner industries for the future.

Figure 1.17 Production costs of steel and urea using conventional and innovative technologies in the Stated Policies Scenario, 2035



IEA. CC BY 4.0.

Notes: LCOP = levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment; Conv. = conventional; H_2 = hydrogen; NH_3 = ammonia. LCOPs are indicative average costs for the selected technology pathways in each region. Indicated percentages show the relative cost premium for the relevant technology and trade scenario (columns) beyond the cost premium of the domestic case for low-emissions technologies (dashed line). All cost premiums are measured relative to the domestic conventional case. For steel production, hydrogen direct reduced iron using an electric arc furnace compared with a conventional blast furnace-basic oxygen furnace is assumed; for the ammonia step of urea production, electrolysis compared with conventional steam methane reforming is assumed. For urea production, biogenic CO_2 is sourced for the low-emissions case and fossil CO_2 is sourced from a co-located steam methane reforming process for the conventional case. Domestic value chain costs are those resulting from the production occurring in the importing region. Imported low-emissions inputs costs are those resulting from production of low-emissions H_2, NH_3, and iron occurring in the exporting region and the transportation of those inputs to the importing country. The cost of carbon pricing is included in the LCOP.

Strategic partnerships that maximise each region's strengths in low-emissions technology supply chains could boost resilience, lower transition costs and capture rising demand.

10. Is there a technology on the horizon that can replicate the explosive growth of solar PV and batteries?

Why it matters

Energy rarely evolves in straight lines. Instead, it lurches forward when a new technology rewrites the rules: coal fuelled the industrial age, while oil reshaped the global economy. More recently, solar panels have revolutionised the way we generate power and lithium-ion batteries have made it attractive to store that energy or use it to power a car. Like the fossil fuels that came before them, they are transforming the global energy landscape, creating entirely new markets for decentralised electricity, backup power and EVs – riding the wider wave of electrification. These are not incremental gains but decisive shifts that are reordering markets, politics, energy security and daily life.

Governments and companies alike are asking whether another breakthrough is waiting in the wings – a technology capable of reshaping markets on the scale of solar and batteries, and unlocking similar wealth for those who design it and master its supply chain. No one wants to miss the "next big thing". The trouble is, in today's crowded field of contenders, it is far from clear which – if any – technology that will be.

What is happening

The boom in solar and batteries over the past two decades is hard to overstate. At the turn of the century, global installed capacity of solar PV was negligible; in 2025, it accounted for more than half of new capacity additions. Since 2015, installed capacity has multiplied eleven-fold. The use of batteries has risen even faster. In 2015, global storage was almost entirely pumped hydro; in 2025, batteries are thought to have overtaken it. Their spread has been turbocharged by the rapid growth of EVs, which rely on the same technologies. Annual investments in solar PV and batteries combined have reached more than USD 500 billion – similar to those in oil supply. Over the past 10 years, the former have more than tripled while the latter have dropped by 30%. In addition, both solar PV and batteries still have a long way to run: competitiveness is improving, costs are falling and their environmental advantages remain compelling.

Yet their success was far from assured two decades ago. Both were considered costly options. Early progress rested on years of research, bolstered by public procurement, feed-in tariffs (for solar PV) and investment support in the first stages of market development, and later by advances in manufacturing. Public backing helped drive down costs, and as innovation, economies of scale and learning-by-doing took hold, the technologies became competitive in their own right.

China emerged in the 2010s as the dominant market and manufacturer for both technologies, drawing on low labour and energy costs, a strong industrial base and sustained policy support – leaving the western countries that had pioneered them far behind. Today, China accounts for nearly two-thirds of both global solar PV module and battery sales. The United States, Japan and the European Union together represent less than 6% of global manufacturing capacity for solar PV panels and components, and less than 13% for batteries.

What it means

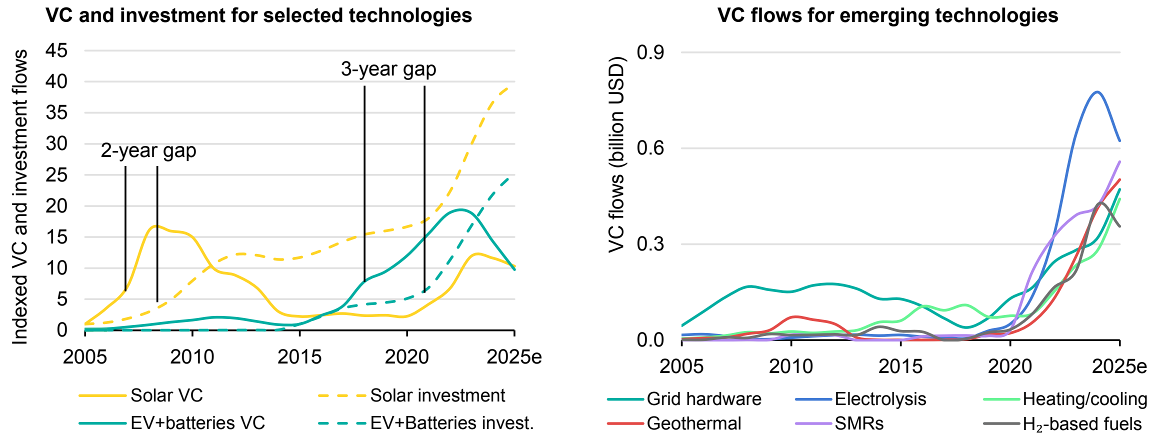
One way to think about which emerging clean energy technologies might be poised for explosive growth is to examine what made solar PV and batteries so successful in the first place. Six features stand out:

- Modularity and manufacturability: Both can be mass-produced by competing firms with variations on a standardised design. This competition has been central to driving down costs: solar PV prices have fallen by more than 85% since 2010.
- Standardisation with flexibility: They slot easily into different end-use products without changing their basic architecture, which in turn enables scale.
- Multiple uses: They serve a range of applications in and beyond the energy sector, allowing early uptake in premium markets before breaking into the mainstream.
- Technological maturity: By the time international policy and economic drivers aligned – demand growth in emerging economies, concerns about climate change and local air pollution, and oil security risks in China – the technologies had already been tested for decades.
- Tradability and ease of deployment: Both can be shipped globally and installed without specialised equipment or highly trained staff. In 2024, almost 20% of PV modules were traded across borders.
- Existing infrastructure: Both can be plugged straight into existing electricity grids.

Some technologies under active research do share several of these traits and promise to address certain problems that solar and batteries cannot, ranging from food security to clean heating and health. Investors are already casting their votes: the past couple of years have seen a steep increase of venture capital flows into six sectors: electrolysers for hydrogen production, geothermal, advanced heating and cooling, small modular nuclear reactors, hydrogen-based fuels and grid technologies. The pattern is strikingly familiar: the same ramp-up in venture capital preceded the solar and battery booms (Figure 1.18).

But no technology in development today ticks all six boxes. Hydrogen lacks transport infrastructure, geothermal is not modular, SMRs still need specialised staff for manufacturing and plant construction. However, this does not mean deployment will not take off. Historical examples show that deployment can take place without some of these conditions. For example, industrial ammonia synthesis started in 1913 and took off in the 1960s driven by population growth and fertiliser demand (Rouwenhorst, Travis, & Lefferts, 2022) – despite the technology not being modular or flexible, and being limited to a single use.

Figure 1.18 Global venture capital flows to selected technologies, 2005-2025e



VC and investment for selected technologies

VC flows for emerging technologies

IEA. CC BY 4.0.

Notes: SMR = small modular reactor; EV = electric vehicle; VC = venture capital; H_2 = hydrogen. Values are indexed to 2005 for solar PV and 2015 for EV and batteries. Values are 3-year moving averages. 2025 estimated based on data until mid-November. Heating/cooling includes mechanical or active systems (e.g. evaporative cooling), solid-state, passive and renewable thermal management systems. Investment refers to ongoing capital spending on assets.

Sources: IEA analysis based on IEA (2025f); Cleantech Group (2025) and Crunchbase (2025).

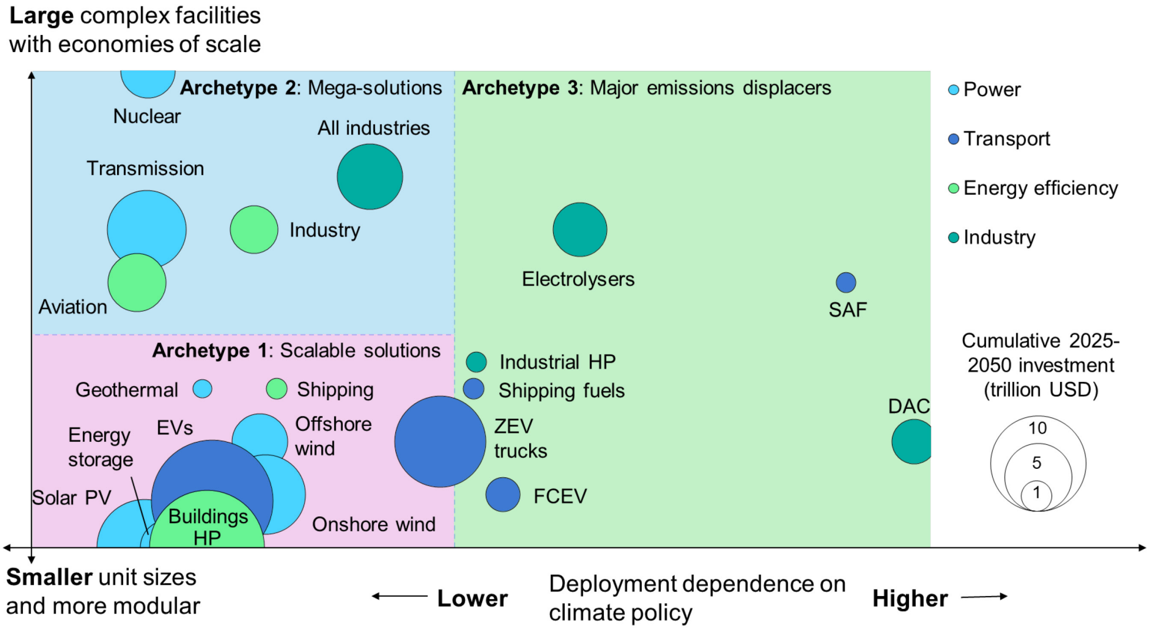
Recent years have seen a jump in venture capital flows into electrolysis, geothermal, heating and cooling technologies, small modular reactors and hydrogen-based fuels.

Another way to gauge potential is to map emerging clean energy technologies against a few key characteristics. Three quantifiable traits were central to the success of solar PV and batteries: unit size (smaller units facilitate rapid cost reduction); reliance on climate policy (diverse market drivers reduce investment risk); and the size of the known addressable market (larger deployment can deliver greater economic impact). Using these criteria, we identify three groups of technologies with the greatest global potential – provided they become proven products and deployment conditions are favourable (Figure 1.19). All are mature enough to scale up and would be deployed rapidly in the context of a faster transition away from unabated fossil fuels, such as in the Net Zero Emissions by 2050 Scenario (NZE Scenario):

- Scalable solutions are deployed in small units, can reduce emissions and have low dependence on climate policies. They could break into mass-market applications if costs fall and attractive consumer products emerge. Examples include heat pumps, energy storage using phase-change materials, advanced batteries, electric trucks and energy management systems for grid flexibility. These technologies see large investments in the NZE Scenario (Figure 1.19).

- Mega-solutions have low reliance on climate policy or new infrastructure and could benefit from the electrification of end-uses, including AI applications. But their large scale limits the speed of cost reduction and installation typically requires site-specific solutions. Examples include long-duration energy storage, industrial electrification, electricity grid infrastructure and next-generation geothermal systems.
- Major emissions displacers are highly dependent on the growth of markets for low-emissions alternatives or complements to today's conventional industrial technologies. Rapid expansion of these markets is needed to sustain high investment over a decade, generating innovation and economic returns. Examples include the production of sustainable aviation fuels and low-emissions shipping fuels, ammonia and primary steel, as well as CO_2 removal.

Figure 1.19 Selected clean energy technologies by asset or project size and dependence on climate policy, 2025-2050



IEA. CC BY 4.0.

Notes: CCUS = carbon capture, utilisation and storage; DAC = direct air capture; EV = electric vehicle; FCEV = fuel cell electric vehicle; HP = heat pumps; SAF = sustainable aviation fuels; ZEV = zero-emission vehicle. Dependence on climate policy is calculated based on the deployment ratio between the Stated Policies Scenario (STEPS) and Net Zero Emissions by 2050 Scenario (NZE Scenario).

Clean energy technologies with strong potential for scale-up can be classified into three archetypes based on typical average size and deployment dependence on climate policy.

In short, solar PV and batteries possess a unique combination of traits – rapid demand growth, investment surges and cost reductions – that will be hard to match, apart from further advances in PV cell and battery design. In addition, to identify the next major opportunities, attention may need to shift towards cross-cutting components used across multiple types of energy equipment. These technologies tend to evolve more incrementally and attract less public attention, yet their leading suppliers stand to capture substantial value as demand expands across several sectors simultaneously. High-performance motors, industrial robots, compressors, heat exchangers, electrodes, membranes, cutting tools, inverters and power-quality controllers are becoming crucial determinants of the competitiveness of a range of products, from next-generation batteries and industrial electrolysers to geothermal energy and high-efficiency air conditioning. Together, these components already represent a global market of over USD 1 trillion.

In addition, a handful of long-term bets could, if successful, tap into markets potentially worth trillions of dollars by mid-century. These include nuclear fusion, solid-state cooling, iron ore electrolysis, limestone-free conventional cement and direct electrochemical ammonia production. Each faces substantial technical and cost barriers and none are expected to have a significant market share within a decade. Their deployment at large scale would require public support in the form of innovation, demand creation and economic incentives. However, history offers a cautionary note: few predicted that solar PV and batteries would take off as fast as they did.

References

Agora Industry. (2025). *The role of green iron trade in accelerating competitive steel transformation.* Berlin: Agora Think Tanks GmbH. Retrieved from https://www.agora-industry.org/publications/the-role-of-green-iron-trade-in-accelerating-steel-transformation

Alberta Department of Energy. (2024). *Quest Carbon Capture and Storage Project Annual Summary Report.* Retrieved from https://open.alberta.ca/dataset/e90a4e6e-2c11-44ee-b198-de244261c585/resource/20fd42f8-6627-44af-82ca-d4af052a040b/download/quest-annual-summary-report-2023-alberta-department-of-energy-and-minerals.pdf

Alper, A., Yamazaki, M., & Uranaka, M. (2025). US will have golden share in Nippon Steel's takeover of US Steel, lawmaker says. Retrieved from https://www.reuters.com/business/us-government-may-hold-some-us-steel-shares-nippon-steel-deal-kyodo-says-2025-05-27/

ArcelorMittal. (2025). ArcelorMittal Europe urges faster implementation of Steel and Metals Action Plan. Retrieved from https://corporate.arcelormittal.com/media/news-articles/arcelormittal-europe-urges-faster-implementation-of-steel-and-metals-action-plan

Birol, F. (2025). *Batteries are crucial technology for the 21st century*. Retrieved from Financial Times: https://www.ft.com/content/874fb936-86de-4fa5-95a1-92afb46e2538

BMI. (2024). *Benchmark Minerals Lithium Ion Battery Gigafactory Assessment*. Retrieved from https://www.benchmarkminerals.com/

BNEF. (2025). *Data service*. Retrieved from https://about.bnef.com/

Brown, C. P. (2025). Trump's trade war timeline 2.0: An up-to-date guide. *PIIE*. Retrieved from https://www.piie.com/blogs/realtime-economics/2025/trumps-trade-war-timeline-20-date-guide

CEA. (2025, February 18). *Nuclear fusion: WEST beats the world record for plasma duration!* Retrieved from https://www.cea.fr/english/Pages/News/nuclear-fusion-west-beats-the-world-record-for-plasma-duration.aspx

CEPII. (2025). *BACI*. Retrieved from https://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37

Chevron. (2024). *Gorgon Gas Development and Jansz Feed Gas Pipeline Environmental Performance Report 2024.* Retrieved from https://australia.chevron.com/-/media/australia/our-businesses/documents/2024-Gorgon-Gas-Development-and-Jansz-Feed-Gas-Pipeline-EPR.pdf

China, Ministry of Finance. (2025). *The State Council Tariff Commission announced adjustments to tariffs on imported goods originating from the United States*. Retrieved from https://gss.mof.gov.cn/gzdt/zhengcejiedu/202505/t20250513_3963685.htm

Chinese Academy of Sciences. (2025). *Chinese "Artificial Sun" Sets Milestone Record towards Fusion Power Generation*. Retrieved from https://english.cas.cn/head/202501/t20250121_899060.shtml#:~:text=The%20duration%20of%201%2C066%20seconds,set%20by%20EAST%20in%202023

Clean Air Task Force. (2024). *Carbon capture and storage: What can we learn from the project track record?* Retrieved from https://www.catf.us/resource/carbon-capture-storage-what-can-learn-from-project-track-record/

Cleantech Group. (2025). Retrieved from https://i3connect.com/front_page

Crunchbase. (2025). Retrieved from https://data.crunchbase.com/reference/getting-started

Diário Oficial da União [Official Diary of the Union]. (2025). *Imprensa Nacional [National Press]*. Retrieved from https://www.in.gov.br/leiturajornal

Enhance Energy. (2024). *Alberta Carbon Trunk Line project : knowledge sharing report.* Retrieved from https://open.alberta.ca/publications/alberta-carbon-trunk-line-project-knowledge-sharing-report-2023

EUROfusion. (2018). *European Research Roadmap to the Realisation of Fusion Energy*. Retrieved from https://euro-fusion.org/wp-content/uploads/2022/10/2018_Research_roadmap_long_version_01.pdf

EUROfusion. (2025). *Wendelstein 7-X sets World record for long plasma triple product*. Retrieved from https://euro-fusion.org/eurofusion-news/wendelstein-7-x-sets-world-record-for-long-plasma-triple-product/

European Commission. (2025). *Publications Office of the European Union*. Retrieved from https://op.europa.eu/en/

EV Volumes. (2025). *Global Electric Vehicle Sales Data, Market Trends & Forecasts You Can Trust*. Retrieved from https://ev-volumes.com/

Financial Times. (2025). *Russia imposes fees to stem flood of low-cost Chinese cars*. Retrieved from https://www.ft.com/content/48cb143e-03ce-4e23-bc6a-7e47d673f1d8

Fraunhofer. (2024). *Whitepaper "Mastering Ramp-up of Battery Production"*. Retrieved from https://www.ffb.fraunhofer.de/en/publications/White_papers_environment_reports_studies/Mastering_Ramp-up_of_Battery_Production.html

Fusion Energy Base. (2025). Retrieved from https://www.fusionenergybase.com/about

Fusion Industry Association. (2025). *The global fusion industry in 2025.* Retrieved from https://www.fusionindustryassociation.org/fusion-industry-reports/

Germany, Federal Ministry for Economic Affairs and Energy. (2024). *Habeck übergibt Förderbescheid über rund 1,3 Milliarden Euro an ArcelorMittal [Habeck hands over funding notice for around 1.3 billion euros to ArcelorMittal]*. Retrieved from https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Pressemitteilungen/2024/05/20240530-foerderbescheid-1.3-mrd-euro-arcelormittal.html

Giannaris, S. et al. (2021). SaskPower's Boundary Dam Unit 3 Carbon Capture Facility - The Journey to Achieving Reliability. *Proceedings of the 15th Greenhouse Gas Control Technologies Conference 15-18 March 2021*, 15. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3820191

Global Times. (2025). *New nuclear technology sees vast export potential*. Retrieved from https://www.globaltimes.cn/page/202307/1295190.shtml

Global Trade Alert. (2025). Retrieved from https://globaltradealert.org/

H2View. (2025). *HydrogenOne fund to return cash to shareholders in managed realisation.* Retrieved September 15, 2025, from https://www.h2-view.com/story/hydrogenone-fund-to-return-cash-to-shareholders-in-managed-realisation/2130274.article/

IEA. (2021). *Carbon capture in 2021: Off and running or another false start?* Retrieved from https://www.iea.org/commentaries/carbon-capture-in-2021-off-and-running-or-another-false-start

IEA. (2022a). *Achieving Net Zero Heavy Industry Sectors in G7 Members*. Retrieved from https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members

IEA. (2022b). *Special Report on Solar PV Global Supply Chains.* Retrieved from https://www.iea.org/reports/solar-pv-global-supply-chains

IEA. (2023). *CCUS policies and business models.* Retrieved from https://www.iea.org/reports/ccus-policies-and-business-models-building-a-commercial-market

IEA. (2024). *Energy Technology Perspectives 2024*. Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2024

IEA. (2025a). *How can innovation help secure future battery markets and mineral supplies?* Retrieved from https://www.iea.org/commentaries/how-can-innovation-help-secure-future-battery-markets-and-mineral-supplies

IEA. (2025b). *Global Hydrogen Review 2025.* Paris: IEA. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2025

IEA. (2025c). *Hydrogen Production and Infrastructure Projects Database.* Paris: IEA. Retrieved from https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database

IEA. (2025d). *The Path to a New Era for Nuclear Energy.* Retrieved from https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy

IEA. (2025e). *The State of Energy Innovation.* Retrieved from https://www.iea.org/reports/the-state-of-energy-innovation

IEA. (2025f). *World Energy Investment 2025.* Retrieved from https://www.iea.org/reports/world-energy-investment-2025

IEA. (2026). Manufacturing and Trade Model Documentation. Retrieved from https://www.iea.org/reports/manufacturing-and-trade-model

IEA Bioenergy TCP. (2023). *Deployment of BECCUS value chains in the United States.* Retrieved from https://www.ieabioenergy.com/wp-content/uploads/2023/03/BECCUS-1.0_US-Case-Study_final_update.pdf

IEAGHG TCP. (2019). Retrieved from https://publications.ieaghg.org/technicalreports/2019-04%20The%20Shell%20Quest%20Carbon%20Capture%20and%20Storage%20Project.pdf

International Atomic Energy Agency. (2025). *PRIS - Power Reactor Information System*. Retrieved from https://pris.iaea.org/PRIS/home.aspx

International Trade Administration. (2025). *International Trade Administration*. Retrieved from https://www.trade.gov/

National Ignition Facility. (2025). Retrieved from https://lasers.llnl.gov/science/achieving-fusion-ignition

Office of the United States Trade Representatives. (2025). *Office of the United States Trade Representatives*. Retrieved from https://ustr.gov/

Petra Nova Parish Holdings. (2020). *Petra Nova Final Scientific/Technical Report.* Retrieved from https://www.osti.gov/servlets/purl/1608572

Red Trail Energy. (2022). *Red Trail Energy Subpart RR Monitoring, reporting, and verification (MRV) plan.* Retrieved from https://www.epa.gov/system/files/documents/2022-04/rtemrvplan.pdf

Reuters. (2024). *ADM pauses CO_2 injection at carbon capture storage site after finding potential leak*. Retrieved from https://www.reuters.com/sustainability/climate-energy/adm-pauses-co2-injection-carbon-capture-storage-site-after-finding-potential-2024-10-02/

Rouwenhorst, K. H., Travis, A. S., & Lefferts, L. (2022). 1921–2021: A Century of Renewable Ammonia Synthesis. *Sustainable Chemistry*. Retrieved from https://www.mdpi.com/2673-4079/3/2/11/review_report

S&P Global. (2025). *Commodity Insights*. Retrieved from https://www.spglobal.com/commodity-insights/en

Science Business. (2024). UK and Canada team up to solve nuclear fusion fuel shortage. Retrieved from https://sciencebusiness.net/news/uk-and-canada-team-solve-nuclear-fusion-fuel-shortage

Sinoimex. (2025). *Global Trade & Industry Growth Lab*. Retrieved from https://www.sinoimex.com/en/index

Sitharaman, N. (2025). *Budget 2025-2026*. Retrieved from https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/feb/doc202521493201.pdf

Spangler, R., Qin, S., Larsen, L. M., Bolisetti, C., Abou-Jaoude, A., Asgari, M. and G. Wilkinson. (2025). *Potential Cost Reduction in New Nuclear Deployments Based on Recent AP1000 Experience.* INL. Retrieved from https://inldigitallibrary.inl.gov/sites/STI/STI/Sort_173162.pdf

The Budget Lab. (2025). *The Fiscal and Economic Effects of the Revised April 9 Tariffs*. Retrieved from https://budgetlab.yale.edu/research/fiscal-and-economic-effects-revised-april-9-tariffs

The White House. (2025). *Briefings & Statements*. Retrieved from https://www.whitehouse.gov/briefings-statements/

UK Government. (2025). Government acts to save British steel production. Retrieved from https://www.gov.uk/government/news/government-acts-to-save-british-steel-production

US Environmental Protection Agency. (2023). *Greenhouse Gas Reporting Program (GHGRP)*. Retrieved from https://www.epa.gov/ghgreporting

US National Archives. (2025). *Federal Register*. Retrieved from https://www.federalregister.gov/

Vallance, P. (2025). *Small Modular Reactor Programme and Site Allocation, Statement made on 13 November 2025*. Retrieved from https://questions-statements.parliament.uk/written-statements/detail/2025-11-13/hlws1050#:~:text=At%20the%20Spending%20Review%20the,government%20approvals%20and%20contract%20signature

World Bank. (2025). *Indicators*. Retrieved from https://data.worldbank.org/indicator

World Nuclear News. (2024). *China approves 11 new reactors*. Retrieved from https://www.world-nuclear-news.org/articles/china-approves-11-new-reactors

World Nuclear News. (2025a). *Ten new reactors approved in China*. Retrieved from https://www.world-nuclear-news.org/articles/ten-new-reactors-approved-in-china

World Nuclear News. (2025b). *Canada's first SMR project: How is CAD20.9 billion costcalculated?* Retrieved from https://www.world-nuclear-news.org/articles/what-is-the-budget-for-canadas-first-smr-project

World Trade Organization. (2025). *WTO Tariffs & Trade Data*. Retrieved from https://ttd.wto.org/en

Part A

Deployment of clean energy technologies, materials and fuels

Technology innovation and commercialisation are behind many new developments in energy markets. Today, the areas of clean energy technologies, near-zero emissions materials and low-emissions fuels are particularly dynamic, albeit to varying degrees. They have become a focus of attention in recent years as the market opportunities are linked to technological leadership and industrial expertise, and not solely to resource endowment. Companies and countries can therefore gain a foothold in these markets by being at the forefront of innovation and commercialisation pathways.

Part A of this report explores the outlook for the deployment of clean energy technologies, near-zero emissions materials and low-emissions fuels on the basis of IEA scenarios. It consists of a discussion of the major trends and factors that explain them in the outlook (Chapter 2) followed by a series of visual dashboards (Chapter 3) with key metrics for each major technology, including market size, cost-competitiveness, technical performance, infrastructure needs and innovation.

Chapter 2. Outlook for deployment of clean energy technologies

Highlights

- Many clean energy technologies are increasingly cost-competitive and growing strongly. Their aggregate market value has grown 20% on average per year since 2015 to reach nearly USD 1.2 trillion. Some 80% of global solar PV and wind generation now occurs at lower levelised costs than for coal or gas. Battery prices have dropped 75% since 2015, pushing electric car sales to around 25% share in 2025. Deployment increases in all IEA scenarios: in the Current Policies Scenario (CPS), their global market value nearly doubles to around USD 2 trillion in 2035, greater than the oil market in 2025. In the Stated Policies Scenario (STEPS), their market value approaches USD 3 trillion, and in the Net Zero Emissions by 2050 Scenario (NZE Scenario), more than USD 5 trillion.
- The market for near-zero emissions materials remains almost non-existent, due to the limited availability of cost-competitive technologies at scale, insufficient policy support and low consumer willingness to absorb cost premiums. Yet momentum is building: 105 Mt of near-zero emissions steel production capacity has been announced since 2020 (equal to around 5% of global production today), roughly double the conventional capacity additions, though only 5% has taken final investment decision (FID). A strong policy push is needed for a large market for near-zero emissions materials: in the NZE Scenario, it reaches USD 500 billion in 2035, far higher than in the STEPS (USD 20 billion) and CPS (USD 5 billion).
- The market for low-emissions fuels grew by an average of 7% annually in the past decade, reaching around USD 215 billion in 2025, but remains small, equal to less than 10% of the market for oil-based transport fuels in 2025. Growth opportunities exist: the market value for low-emissions fuels increases significantly in the STEPS and the CPS to around USD 390 billion in 2035. Higher deployment requires stronger policy support to overcome cost premiums; the market for low-emissions fuels grows fivefold by 2035 in the NZE Scenario.
- The deployment outlook hinges on manufacturing and enabling infrastructure. Investment in production assets for clean energy technologies, near-zero emissions materials and low-emissions fuels is around USD 245 billion today, about three times more than 5 years ago. Investments in infrastructure, primarily electricity grids, total around USD 430 billion, about 40% more than in 2020. While average annual investment in production assets in 2031-35 falls by 60% in the STEPS compared to today, average annual investment in grids is about 60% higher.

Recent market trends

Technology innovation and commercialisation form the basis of any new development in energy markets. Today, the areas of clean energy technologies, near-zero emissions materials and low-emissions fuels are particularly dynamic, even if to varying degrees. They have become a focus of attention in recent years as the market opportunities are linked to technological leadership and industrial expertise, not solely to resource endowment – companies and countries can gain a foothold in these markets by being at the forefront of innovation and commercialisation pathways.

Clean energy technology markets keep expanding

The global market for clean energy technologies has grown rapidly in recent years and continues to develop at pace. The combined market for key technologies[1] expanded at an average rate of close to 20% per year between 2015 and 2024. The market for 2025 is projected to have grown by nearly 25%, pushing the value to nearly USD 1.2 trillion[2] – overtaking the coal market and approaching the scale of the natural gas market (Figure 2.1).

Electric cars have been the main driver of this expansion. The global market for electric cars grew by more than 40% per year on average between 2015 and 2024, accounting for around 90% of total clean energy technology market growth. This surge has been powered by rising sales, which more than offset a 30% decline in average electric car prices – a drop supported by a 75% fall in battery costs – over the same period. Nonetheless, despite this growth, in 2024, the global market for electric cars (around USD 690 billion) was just 30% of the size of the conventional car market. Electric car markets have grown at different speeds across different regions, and for different reasons. In China, electric cars became an industrial policy priority in 2001, and in 2024, they represented close to 50% of its car market, with sales reaching USD 330 billion – the world's largest electric car market. The second-largest market for electric cars is the European Union, where sales have been driven mainly by energy security and climate change priorities, and totalled close to USD 150 billion in 2024. The market for other road vehicles, in particular zero-emission trucks that are powered by batteries or fuel cells, has also grown steadily – by around 25% per year – largely in line with rising sales. However, it remains considerably smaller than the market for electric cars, and

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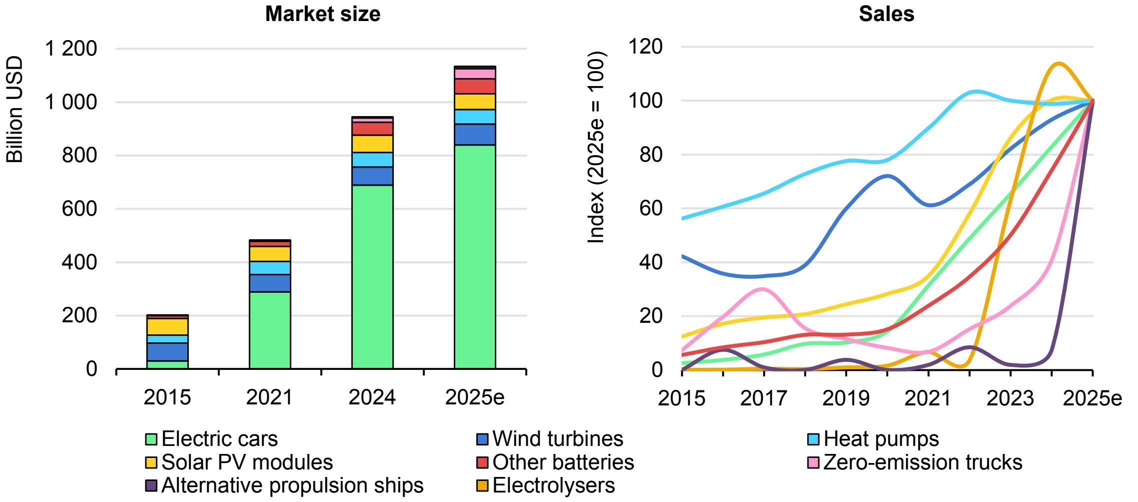
[1] Electric cars, zero-emission trucks, other electric vehicle batteries and stationary batteries, solar PV modules, wind turbines, heat pumps, electrolysers and alternative propulsion ships.

[2] Unless stated otherwise, USD figures are real 2024 dollars in market exchange rate terms throughout this report.

zero-emission truck sales represented less than 2% of all truck sales globally in 2024. To an even greater extent than for electric cars, the market for zero-emission trucks is largest in China, accounting for around USD 13 billion of the approximately USD 16 billion market globally in 2024.

Figure 2.1 Global market for selected clean energy technologies, 2015-2025e



IEA. CC BY 4.0.

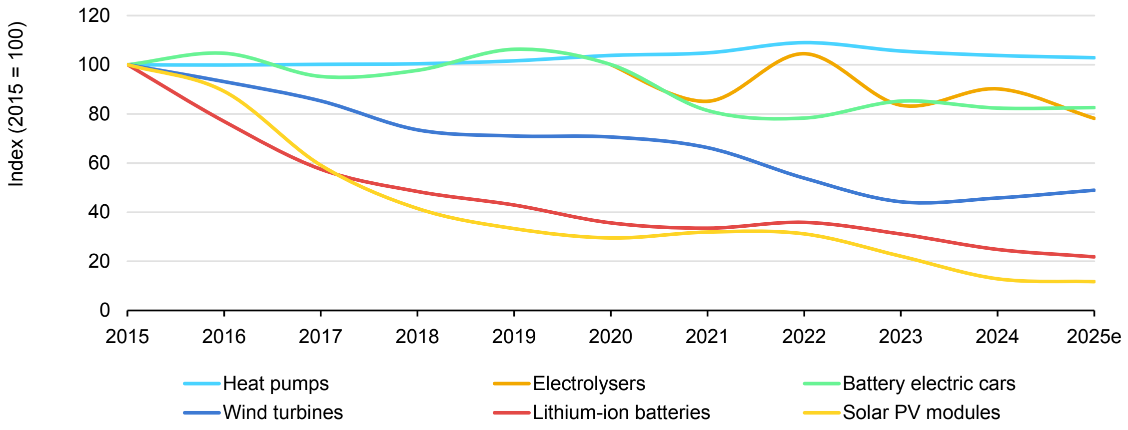
Notes: Heat pumps are residential only (the industrial heat pump market remains negligible). Wind turbines include towers, nacelles and blades. Electrolysers refer to the stack. Other batteries include electric vehicle batteries for vehicles other than cars and trucks, as well as stationary storage batteries. Sales of wind turbines, solar PV modules, heat pumps and electrolysers are measured in terms of GW; sales of electric cars, zero-emission trucks, and alternative population ships are measured in terms of number of vehicles or vessels; sales of other batteries are measured in terms of GWh.

Source: IEA analysis based on BNEF (2025).

The global market for key clean energy technologies has grown strongly over the past decade, at an average of almost 20% per year, driven primarily by electric cars.

In the power sector, the market value for solar PV and wind turbines has grown much more slowly, as plunging costs have offset much of the growth in demand. Solar capacity additions grew tenfold between 2015 and 2024, yet the overall market value rose by only 4%, or less than 1% per year, due to an 85% drop in the cost of PV modules (Figure 2.2). Similarly, while wind turbine costs fell by around 55% over the same period, market growth was more modest. Despite a 75% increase in capacity additions since 2015, the market value in 2024 remained broadly similar over the same period, reflecting the impact of significantly lower prices. In 2024, around 650 GW of solar and wind electricity generation capacity was added, more than eight times the fossil fuel-based capacity additions.

Figure 2.2 Global average clean energy technology price trends, 2015-2025e



Note: Heat pumps are residential only.
Sources: IEA analysis based on BNEF (2025); InfoLink (2025); and S&P Global Mobility (2025).

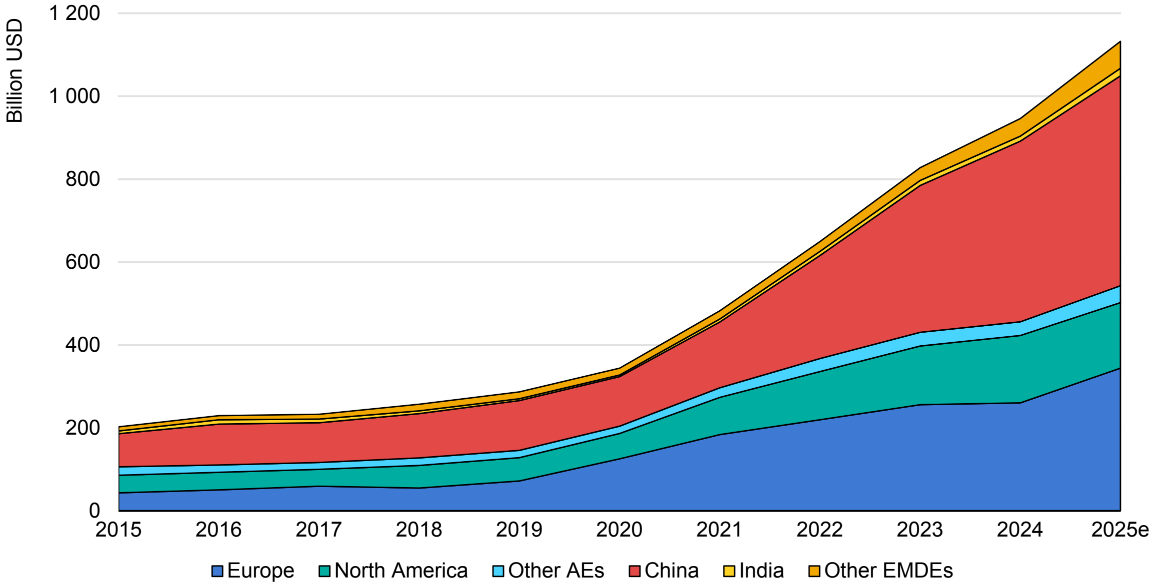
The prices of most clean energy technologies have fallen sharply since 2015, especially solar PV modules, lithium-ion batteries and wind turbines.

The market for heat pumps for heating purposes reached approximately USD 50 billion in 2024, having grown at an average annual rate of more than 5% since 2015. The heat pump market reached about half the size of the gas boiler market in 2024 and is now almost as big as the solar PV market. Market growth has continued despite prices remaining relatively constant since 2015, due to heat pumps increasingly coming with additional features (e.g. quieter operation). While China deployed the most heat pumps (by capacity) in 2024, the United States was home to the largest heat pump market, valued at over USD 17 billion, representing about one-third of the global market that year.

Markets for technologies such as electrolysers for dedicated hydrogen production and low- or zero-emission-capable ships are still in their early stages, and so recent growth patterns are uneven. Electrolyser deployment began to accelerate in the early 2020s, and global installed capacity doubled in 2023 with the addition of nearly 700 MW. Growth then slowed in 2024 but picked up again in 2025. The market for methanol- and ammonia-fuelled ships has also been volatile, due to the wide variation in vessel size and type. In 2024, for instance, the delivery of seven large methanol-fuelled containerships and one large chemical tanker expanded the value of the market to more than USD 1 billion – 13 times larger than in 2023, when only two methanol-powered chemical tankers were delivered. However, methanol- and ammonia-fuelled ships continue to represent a relatively small share of expected new ships (around 6% of gross tonnage to be delivered in 2025); orders for liquefied natural gas ships that could eventually be run on biomethane make up a greater share of planned deliveries.

China has consistently been the largest market for clean energy technologies over the past decade, increasing from slightly less than 40% of the global clean energy technology market in 2015 to close to 45% in 2025. A decade ago, wind turbine components accounted for the largest share – about 35% – of the USD 80 billion clean energy technology market in the country. The market for solar PV modules was slightly smaller, representing almost one-third. Electric cars represented only 10% of the market in 2015, but in 2018 they took the lead, and have remained the largest clean energy technology market in China ever since. In 2025, the electric car market in China is expected to have reached USD 390 billion, accounting for more than 80% of the total clean energy technology market in China.

Figure 2.3 Market value for selected clean energy technologies by region, 2015-2025e



Notes: AEs = advanced economies; EMDEs = emerging markets and developing economies. Selected clean energy technologies include electric cars, zero-emission trucks, other electric vehicle batteries and stationary batteries, solar PV modules, wind turbines, heat pumps, electrolysers and alternative propulsion ships.

Source: IEA analysis based on BNEF (2025).

China has remained the largest market for key clean energy technologies over the past decade, though Europe has experienced a similar annual growth rate of over 20% since 2015.

Europe is the second-largest clean energy technology market today, with market growth averaging more than 20% per year from 2015 to 2025, a rate similar to China. Electric cars were responsible for 85% of the growth in the European clean energy technology market over this period and have represented the majority of the market in Europe since 2017.

In 2015, the North American clean energy technology market was just 1% smaller than the European market but has grown at a slower annual rate since then, increasing on average 15% per year to 2025. In 2025, the North American market for clean energy technologies is expected to have increased by less than 3% compared to 2024, reaching around USD 165 billion, representing less than 15% of the global market.

In India, the market for clean energy technologies is estimated to have grown by around 40% in 2025, compared to 2024. However, this is a recent trend: growth in the Indian market has averaged only 10% per year since 2015, to reach an estimated USD 18 billion in 2025. The total clean energy technology market in emerging economies excluding China is estimated to have reached USD 75 billion in 2025, less than 15% the size of the market for clean energy technologies in advanced economies.

Near-zero emissions materials: a market opportunity or a challenging market?

Near-zero emissions materials are materials produced using processes and technologies that generate very low emissions[3] (IEA, 2024a). The global market for key bulk materials – including steel, cement, aluminium and ammonia – produced through conventional emissions-intensive routes has grown steadily by around 5% annually since 2015, to reach an estimated USD 1.8 trillion in 2025. In contrast, the market for near-zero emissions alternatives remains almost non-existent today. This is primarily due to the limited availability of commercially available or cost-competitive technologies and insufficient consumer appetite to absorb cost premiums in the absence of sufficiently strong policy support.

However, momentum is starting to build around these markets, with demand from end-users playing a key role in helping to accelerate deployment. Some early buyers, including those participating in the First Movers Coalition, have expressed a willingness to pay a higher price – sometimes referred to as the "green premium". In some cases, this premium could be substantial. In the steel sector, for example, Stegra has reported a price premium of 25-35% (Johnson, 2025) for its low-emissions steel, while SSAB expects to charge a premium of EUR 200-300 (USD 235-350) per tonne for its product (SSAB, 2025). Together, these two companies represent 60% of all announced offtake agreements for iron-based near-zero emissions steel.

In parallel, voluntary labels and certifications have emerged in recent years as a way to enable demand for near-zero and low-emissions materials. Existing labelling schemes – which have mainly been developed by the private sector –

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[3] The definition of near-zero emissions materials used is materials that are compatible with the endpoint of a net zero emissions pathway such as the IEA's NZE Scenario.

help to communicate emissions performance, justify price premiums, and create differentiated markets for these materials. While announced certifications for materials on the market remain limited, their potential coverage is significant: the share of total global materials production from companies that are members of the organisations developing these standards is almost 70% for steel and nearly 50% for cement.

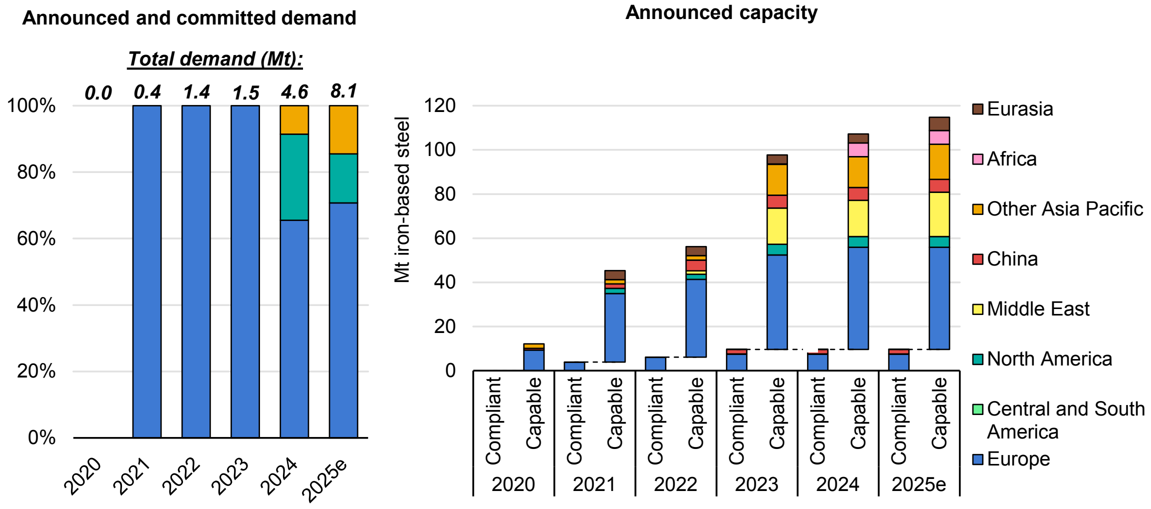
Demand for near-zero emissions materials is growing, driven by such voluntary commitments. In the case of steel, demand has more than doubled each year since 2021, on the back of individual buyer agreements and industry-led demand aggregation initiatives. This has helped advance several first-of-a-kind near-zero emissions projects and demand could continue to grow, especially if pioneering buyers begin to reap reputational or marketing benefits that incentivise broader industry participation. Nevertheless, demand from voluntary commitments makes up only a very small share of the total market: announced offtake agreements (both firm and preliminary) and aggregated demand from both public and private international initiatives currently account for just 0.4% of total global steel demand. For ammonia, the story is similar, although it has been able to attain a larger market share: low-emissions offtakes from industrial users could fulfil almost 4% of global ammonia demand for industrial applications.

In addition, the project pipeline for near-zero emissions materials production has expanded significantly in recent years. Announced steel capacity has grown at an average annual rate of 55% since 2020 (Figure 2.4) and cement projects at 50%. The first small-scale aluminium project has also been launched. Production capacity for conventional materials has grown much more slowly (<1% for steel and cement, 3% for aluminium), albeit from a larger base. Since 2020, announcements of new capacity for near-zero emissions steel have reached around 105 Mt – roughly double the growth in conventional capacity (of around 50 Mt). For cement, growth in announced near-zero emissions capacity (around 55 Mt) contrasts with a decline of nearly 300 Mt in conventional production. Regional growth trends vary: Europe and the Middle East lead on near-zero emissions steel projects (Figure 2.4), North America and Africa on ammonia, Europe and North America on cement, and Canada on aluminium. However, many of these projects remain at early stages of development, with only a small share having reached FID, equivalent to 5% of announced capacity for steel and 10% for cement.

In the steel sector, near-zero emissions steel production capacity announced to date is sufficient to produce just over 5% of the world's overall steel demand. More than 90% of this capacity is considered "near-zero emissions capable", meaning that it would operate using the same core process equipment as near-zero emissions capacity – achieving a substantial reduction in emissions intensity from the start, compared to current conventional technologies – but it would initially fall short of the emissions intensity required for near-zero emissions. However, these projects have plans to reduce emissions to a level consistent with near-zero emissions at a later date, and would be designed with technical capabilities that enable near-zero emissions production in the future without substantial additional capital investments in core process equipment.

Much of the project pipeline for near-zero emissions steel is in Europe, where recent growth has been driven by government emissions targets and broader market signals that are building momentum for the transformation of heavy industry despite higher costs (see below). Projects that have reached FID status have typically benefited from significant public subsidies to help bridge the cost gap. Nevertheless, despite some progress, there has been a wave of project delays and cancellations over the past year, due to difficult market conditions and withdrawal of government support.

Figure 2.4 Near-zero emissions steel demand and production project pipeline by region, 2020-2025e



IEA. CC BY 4.0.

Notes: Announced and committed demand refers to estimated offtake for near-zero emissions steel based on preliminary and firm announcements from individual companies and private sector demand aggregation initiatives. Compliant refers to projects that operate as near-zero emissions from the start; have achieved a final investment decision (FID) or provided strong certainty that FID will be achieved; and include clear information confirming near-zero emissions production. Capable refers to "near-zero emissions capable" projects; projects that have not achieved an FID, or are not near achieving one, are also included in this category due to greater uncertainty. For further information, see the definitions of these terms in Chapter 3. Production from announced projects shown here excludes near-zero emissions steel from 100% scrap.

Source: IEA analysis based on publicly available announcements.

While significant capacity capable of producing near-zero emissions steel has been announced, much of it is not expected to operate as fully near-zero emissions at the outset.

Box 2.1 Major steel producing markets are approaching the new market opportunity differently

China (52% of global steel production today): Announcements of near-zero emissions projects have been slower than in other major steel producing countries but co-ordinated action through the China Iron and Steel Association has led to a draft standard for near-zero emissions steel with a threshold that is aligned with the IEA's proposed definition from the report *Achieving Net Zero Heavy Industry Sectors in G7 Members* (IEA, 2022). This aims to build market foundations and support premium pricing and export access. Several hydrogen-ready projects have been announced and successfully brought into operation, with the aim of switching to hydrogen later.

European Union (7%): Following a wave of early announcements, few projects have reached FID, with some delayed, postponed or cancelled. Producing near-zero emissions steel from hydrogen in the European Union is projected to be 25-70% more expensive than in regions with cheaper energy, such as the United States or the Middle East, by 2035. Despite available subsidies and other mechanisms helping to narrow this cost gap, the resulting price premiums remain too high for most buyers. Mechanisms to address this include the Emissions Trading Scheme, the Carbon Border Adjustment Mechanism, proposed contracts for difference, and a new low-emissions product label under the Clean Industrial Deal.

North America (6%): Demand is emerging: RMI's Sustainable Steel Buyers Platform identifies 1 Mt of demand from North American firms (RMI, 2024). Early projects continue to need subsidies, and some US projects have been cancelled or defunded. Canada is supporting deployment through several mechanisms, including Clean Economy Investment Tax Credits targeting carbon capture, utilisation and storage (CCUS) and low-emissions hydrogen production facilities that reduce emissions from conventional steel plants.

Japan (4%): Few near-zero emissions steel projects have been announced, as efforts focus more on incremental emissions reductions than full decarbonisation. Companies are adopting the "Green Steel for GX" label, which uses a mass balance approach to allocate emissions reductions to select steel products, allowing them to be marketed as "green steel." The government offers subsidies to support this strategy and incentivises low-emissions steel procurement, including through subsidies for carmakers producing electric vehicles (EVs) and public procurement rules.

Middle East (3%): Several projects plan to begin using natural gas and switch to hydrogen as it becomes available. While this approach means the emissions reductions are lower initially, it can stimulate market development. However, without clear hydrogen transition timelines, there is a risk of carbon lock-in and missed opportunities to expand the market for near-zero emissions steel.

The small low-emissions fuels market is dominated by established biofuels

The market for low-emissions fuels[4] remains relatively small today. Between 2015 and 2024, the combined market for selected biofuels and low-emissions hydrogen-based fuels – including biodiesel, bioethanol, biogas, hydrogen, ammonia, methanol and synthetic fuels – grew at an average rate of about 7%. It is expected to have continued to expand in 2025, reaching roughly USD 215 billion. Despite this growth, the sector represents less than 10% of the market value of fossil diesel and gasoline used in transport today, as sustainable fuels continue to account for only a limited share of global energy consumption. In 2024, liquid biofuels made up around 5% of energy use in road transport and around 0.1% of jet fuel demand. Low-emissions hydrogen supplied less than 1% of total hydrogen use, while demand for low-emissions ammonia and methanol in shipping remains limited, awaiting the delivery of additional new vessels.

Conventional biofuels such as biodiesel, bioethanol, and biogas make up the bulk of the market for low-emissions fuels today. The value of the market for biodiesel and bioethanol has grown relatively steadily over the past decade, at an 8-10% annual average growth rate, supported by blending mandates, while growth for biogas has been more marginal, at 2% per year.

Overall growth in hydrogen and hydrogen-based fuels has not met the ambitious goals set by project announcements in recent years, hampered by high costs, uncertain demand and regulatory environments, and slow infrastructure deployment. It is nonetheless considerable: the value of the low-emissions hydrogen market for fuel applications has grown at an average of 7% per year since 2020, albeit from a low base. In the short term, demand for low-emissions hydrogen for fuel applications is being driven mainly by its use in refining. New applications still represent a small share of demand, but demand for hydrogen-based fuels (ammonia and methanol) for shipping (and to a lesser extent for power generation and aviation) stands out. These applications account for around 40% of the volume included in firm offtake agreements for low-emissions hydrogen. Despite these signs of early progress in the market, current offtakes remain too limited in volumes to secure large investments, which is compounded by them often being non-binding. Some firm offtakes in these applications have, however, led to investment decisions for production, such as at a synthetic methanol plant in Denmark. In 2025, production of low-emissions hydrogen-related fuels is

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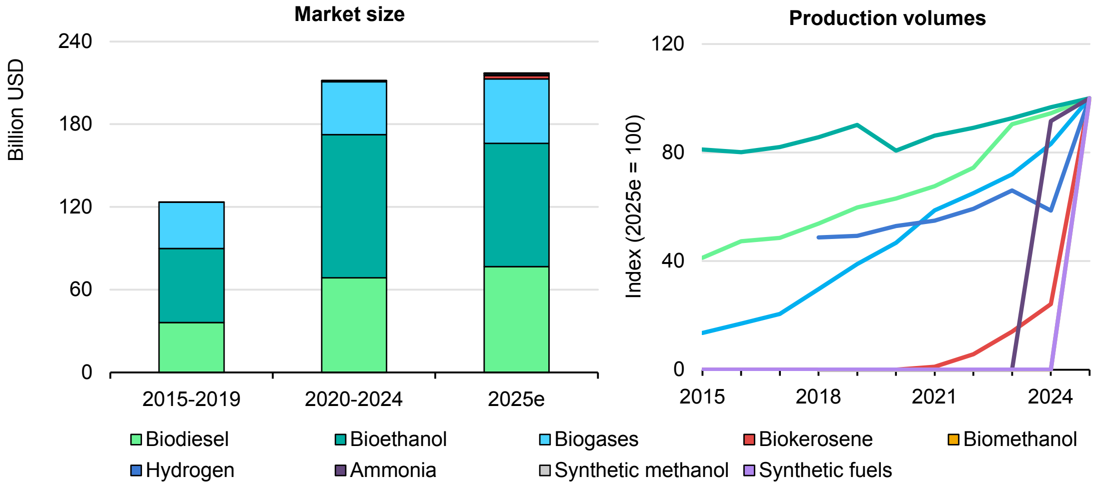
[4] Low-emissions fuels designate fuels and chemical feedstocks that can be produced from plants, which absorb CO_2 from the atmosphere as they grow, or through industrial processes that generate very low emissions, for example renewable-powered and/or using CO_2 captured from the air or biogenic sources. These can include both gaseous – biogas, hydrogen, synthetic methane – and liquid – biofuels, ammonia, synthetic hydrocarbon fuels – products.

expected to have risen by 30%, with around 60% of the increase from electrolytic hydrogen, driven by China, which benefits from low-cost renewables and domestic equipment, and 40% from CCUS projects in the United States, spurred by the 45Q tax credit on CO_2 storage.

Sustainable aviation fuels (SAFs) make up a very low share of the low-emissions fuels market but are growing faster than all other low-emissions fuels. The value of the market for biokerosene – mostly produced from waste and residue oils feedstocks today – grew at an average annual rate of 150% between 2021 and 2024. This uptick was primarily driven by blending mandates, for example in the European Union, United Kingdom and Brazil, as well as by regulatory targets, despite significantly higher costs (see Chapter 3).

Figure 2.5 Low-emissions fuels market size trends, 2015-2025e



Notes: Market size is calculated based on fuel production volumes and prices, allocated to the point of demand. Market size excludes the use of hydrogen, hydrogen-based fuels, and biofuels as feedstock in industry. The market for hydrogen, ammonia and methanol used as fuels and feedstock in industry was around USD 1 billion in 2024. For hydrogen and hydrogen-based fuel production, fuel production costs are used as proxies for prices. Biogases include biogas and biomethane. Synthetic fuels include synthetic methane and kerosene. Hydrogen and hydrogen-based fuels are only included from 2018 onward. While small volumes of synthetic kerosene are produced, the market pre-2025 is negligible and has been removed from the indexed chart (right).

Low-emissions fuels markets remain dominated by conventional biofuels, while emerging fuels like biokerosene and low-emissions hydrogen are growing from a small base.

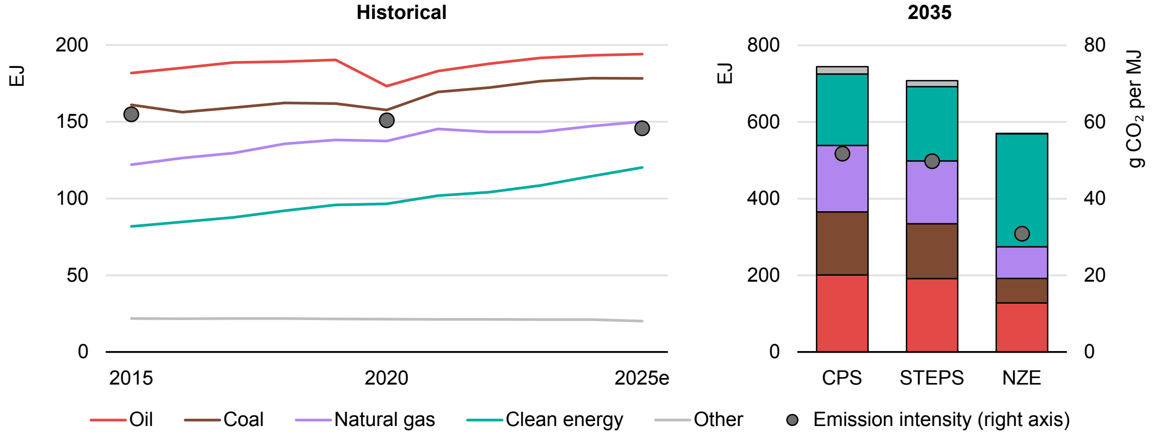
Global outlook

Growth in the development and deployment of clean energy technologies, near-zero emissions materials and low-emissions fuels has been strong over the past decade. The extent and pace at which these developments continue, however, is in no small part linked to government policy and the extent to which it enables deployment hurdles linked to infrastructure, cost premiums and regulatory barriers to be overcome. This section explores the outlook for the deployment of clean energy technologies, near-zero emission materials and low-emission fuels through the lens of IEA scenarios. The analysis begins with an overview of energy trends under different scenarios before examining the market prospects for each of the three areas in turn, as well as providing an overview of the investments required.

The use of clean energy grows across all scenarios

Today, clean energy represents 18% of the global energy mix, up from less than 15% in 2015. This share is set to continue growing in all the outlooks discussed in this report, reaching 27% in 2035 in the STEPS, 25% in the CPS and 52% in the NZE Scenario. Clean energy demand increases more than 60% from now to 2035 in the STEPS, reaching around 195 EJ – a level similar to today's oil demand. The increase is not much lower in the CPS, at 55%, whereas the trajectory of the NZE Scenario requires an increase of 145%. The use of solar PV grows particularly strongly, almost quadrupling over the next decade in the STEPS, while use of wind energy grows by 150%. As a result, the use of unabated fossil fuels falls by 7% to 2035 (mostly at the expense of coal) in the STEPS, even as total energy demand increases. By contrast, unabated fossil fuel use grows slightly to 2035 in the CPS, by around 1%. In the NZE Scenario, total energy use declines by 14%, with unabated fossil fuel demand almost halving.

Figure 2.6 Global energy mix by scenario, 2015-2035



IEA. CC BY 4.0.

Notes: CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. Oil, coal and natural gas refer to unabated uses as well as non-energy use. Clean energy includes renewables, modern bioenergy, nuclear, abated fossil fuels, low-emissions hydrogen and hydrogen-based fuels. Other includes traditional use of biomass and non-renewable waste.

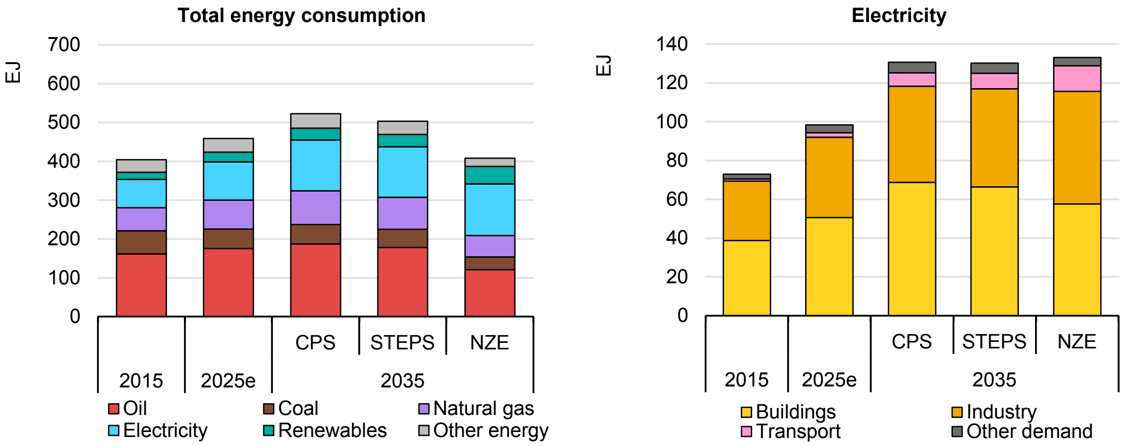
Clean energy demand grows in all scenarios; in the STEPS, it increases over 60% by 2035, reaching a level similar to today's oil demand.

The extent of clean energy growth has direct implications for emission trajectories. In the NZE Scenario, energy sector emissions in 2035 are around half the level projected in the STEPS and 45% of the level in the CPS in the same year. More than a quarter of the increase in clean energy over the next decade in the NZE Scenario comes from growing demand for solar PV. This has a significant impact on the emissions trajectory: about one-fifth of the cumulative emissions savings to 2035 in the NZE Scenario relative to the STEPS are associated with solar PV. Growth in modern bioenergy and wind each represent close to 20% of the growth in clean energy over the next decade in the NZE Scenario, and abated fossil fuels almost 10%.

The growing electrification of end-use sectors is a common feature across all scenarios. The share of electricity in final energy demand increases from about 20% today to around 25% in 2035 in the STEPS and the CPS, and above 30% in the NZE Scenario. Thanks in part to the efficiency gains brought about by electrification, total electricity demand in the NZE Scenario in 2035 is just 2% higher than in the STEPS and the CPS, meaning electricity demand grows by more than 30% over the next decade in all scenarios. Uptake of heat pumps contributes to electricity reaching almost 50% in the final energy demand mix of buildings in 2035 in the STEPS and in the CPS, and over 55% in the NZE Scenario, from close to 40% today. Electricity consumption for transport also grows, albeit from a lower base. Electricity represents 6% of transport energy consumption in the STEPS in 2035, 5% in the CPS and more than double that in the NZE Scenario, up from less than 2% today. The electrification of industry grows from 24% today to 26% in 2035 in the STEPS, remains at 24% in the CPS, and increases to 32% in the NZE Scenario. Electrification in industry over the next decade is mainly driven by the electrification of low-temperature heat in non-energy intensive industries and growth of electricity-intensive scrap-based steel production.

From 2025 to 2035, the demand for liquid biofuels grows by about 30% in both the STEPS and CPS, but their share of total energy demand grows only slightly to reach around 1% in 2035. Biofuels, including biomethane, play a larger role in the transport sector, increasing from around 4% of transport energy demand in 2025 to over 5% in 2035 in the STEPS. A third of the increase in the demand for biofuels from 2025 to 2035 in the STEPS comes from increased demand for road transport; just under 20% is for aviation. In the NZE Scenario, demand for liquid biofuels more than doubles from 2025 to 2035, reaching 3% of total energy demand and 10% of transport energy demand.

Figure 2.7 Total energy consumption per fuel and electricity demand per end-use sector and by scenario, 2015-2035



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Notes: CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. Renewables include modern bioenergy and renewable waste.

Demand for electricity is set to grow more than 30% over the next decade based on the stated policy direction; at the same time, renewable energy supply grows 70%.

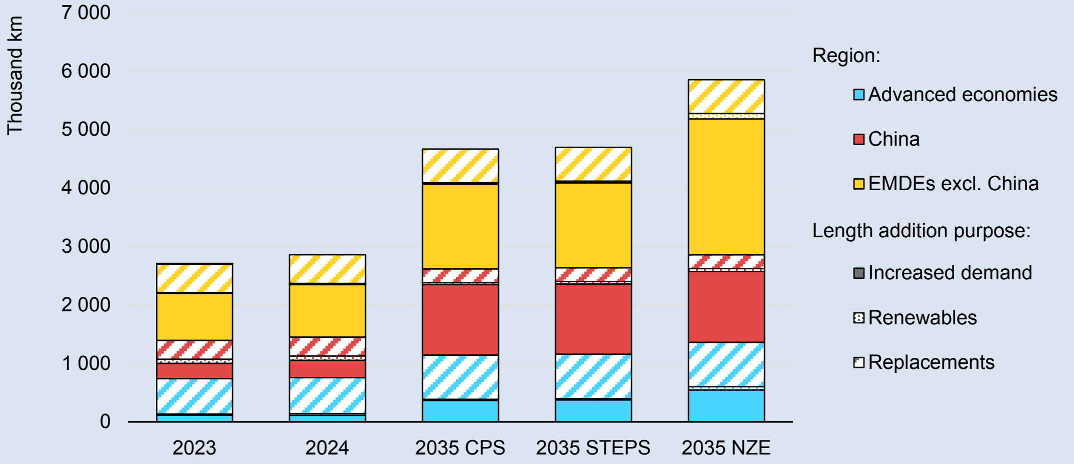
Demand for low-emissions hydrogen and hydrogen-based fuels in 2035 in the STEPS is more than 20 times the demand estimated for today. Nevertheless, hydrogen and hydrogen-based fuels represent just 0.1% of global energy demand in 2035 in the STEPS, a marginally higher share than in the CPS. Demand in 2035 in the NZE Scenario is more than ten times higher than in the STEPS, driven mostly by increased consumption for transport, especially for the shipping sector. Still, hydrogen and hydrogen-based fuels represent less than 1.5% of energy consumption in the NZE Scenario in 2035.

Box 2.2 Enabling infrastructure: electric grids in the spotlight

As the world moves into the age of electricity, with an increasing reliance on distributed energy sources and growing electricity demand from various dispersed end-uses, grids are becoming ever more critical to the functioning of the energy system. Electricity demand grows sharply over the next decade in all outlooks discussed in this report: by more than 30% in both STEPS and CPS and by 35% in the NZE Scenario. The upgrades and expansion of electricity grids required to meet and maintain the growing demand for electricity will, in turn, require more grid components, such as cables, inverters and transformers. Beyond sheer expansion, grids will also face increased capacity constraints and growing system complexity as variable renewables, distributed resources and increased electrification reshape power flows and operational requirements. To tackle these challenges, grids will need enhanced dynamic control capabilities to manage rapid voltage fluctuations and dynamic line rating to unlock additional capacity and reduce the need for costly new infrastructure.

Global demand for cables grew by 6% in 2024, mainly driven by growing demand in China and other emerging markets and developing economies (EMDEs). In advanced economies, more than 80% of new cable line length was used for replacements, while growing electricity demand was responsible for 40% of total new cable length in China, and 60% in other EMDEs. The overall length of the cables in the grid is set to grow by roughly 3.9 million kilometres per year on average from 2025 to 2035 in the STEPS, by 3.8 million kilometres in the CPS and by roughly 4.3 million kilometres per year in the NZE Scenario. The larger needs in the NZE Scenario stem from higher deployment of renewables and increased electrification compared to other scenarios.

Figure 2.8 Cable additions by region, purpose and scenario, 2023-2035



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Notes: EMDEs = emerging markets and developing economies; CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. **"**Increased demand" refers to additions due to an increase in demand, "Renewables" refers to additions due to an increase in renewables and "Replacements" refers to additions due to replacements of existing lines.

Inverters, which are necessary to convert the direct current generated by solar PV into alternating current that is compatible with the existing grid, are another important component in the context of grid upgrades and expansion. In 2024, demand for PV inverters grew by over 20%, reaching more than 400 GW.

Transformer demand has also surged in the past 5 years, outpacing supply and resulting in increased prices and lead times. Average annual transformer capacity additions and replacements reached 3 GW between 2015 and 2024, driven by increased electrification, large new electricity-consuming facilities (such as data centres and EV charging networks), rapid expansion of distributed electricity generation and ageing infrastructure. As these trends accelerate between 2025 and

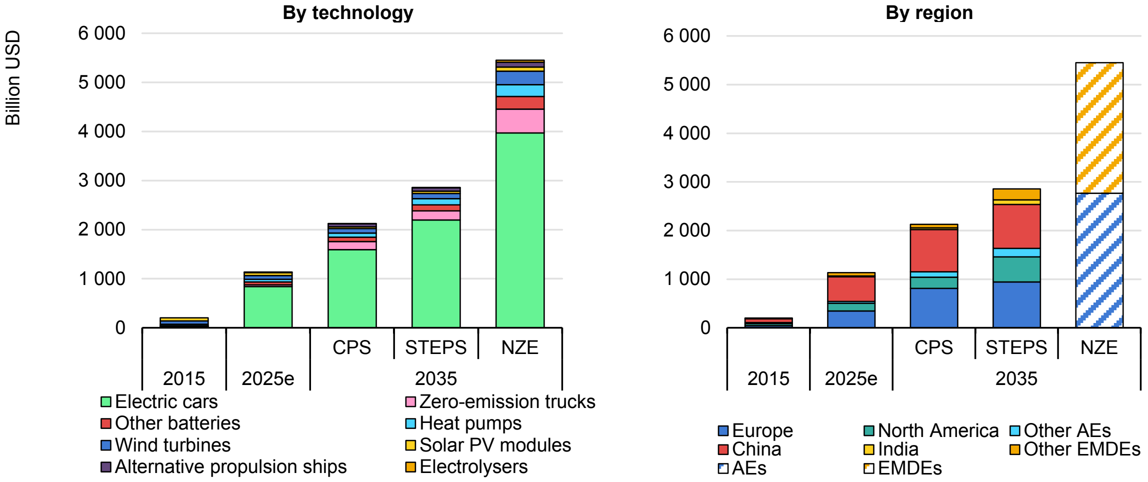
2030, annual average transformer capacity is set to reach around 6 GW in the STEPS and CPS, with China alone representing roughly 70% of total additions in both scenarios. It reaches more than 7 GW in the NZE Scenario.

Manufacturing is critical to meet this increasing demand for grid technologies and to counter any possible bottlenecks or supply chain risks. Clear visibility on investments, long-term procurement signals and harmonised technical standards are important to enabling manufacturing expansions at a pace that encompasses demand growth. See Chapter 6 for further investigation of these risks.

Market opportunities are not evenly distributed

Over the next decade, the value of the global market for clean energy technologies is set to grow in all IEA scenarios. In the STEPS, the market for clean energy technologies grows almost two-and-a-half times to approach USD 3 trillion (in real 2024 dollars) by 2035, while it almost doubles to reach around USD 2 trillion in the CPS. The value of the market for clean energy technologies reached in 2035 across all scenarios is greater than the value of the global oil market in 2025.

Figure 2.9 Global and regional market size of selected clean energy technologies by scenario, 2015-2035



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Notes: CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. AEs = advanced economies; EMDEs = emerging markets and developing economies. Wind turbines include towers, nacelles and blades. Electrolysers refer to the stack. Heat pumps include residential and industrial. Alternative propulsion ships refer to methanol- and ammonia-fuelled ships. Other batteries include electric vehicle batteries for vehicles other than cars and trucks, as well as stationary storage batteries.

The value of the market for clean energy technologies grows two-and-a-half times over the next decade in the STEPS.

Electric cars remain by far the largest clean energy technology market in 2035 in all scenarios; as such, they are also the main driver of the differences in market value growth across the scenarios. In the STEPS and the CPS, they account for 75-80% of total growth of the value of the market between 2025 and 2035. Zero-emission trucks contribute close to 10% of total growth in both scenarios, becoming the second-largest clean energy market by the end of the decade, with sales increasing almost sixfold. Batteries for other EVs and for stationary storage also represent close to 5% of the increase in the market size for clean energy technologies in the STEPS.

While installed solar PV capacity more than triples over the period in the STEPS, its market size in 2035 is about 25% lower than in 2025, reflecting declining technology costs. Global installed solar PV capacity also triples in the CPS from 2025 to 2035, yet annual additions in 2035 are about 10% lower than in 2025, and therefore the market for solar PV is about 40% lower in 2035 in the CPS. In both the CPS and STEPS, wind capacity more than doubles over the same timeframe. As a result, its market grows over 2% per year in the STEPS, and by roughly 1.5% in the CPS. The value of the market for heat pumps grows at around 2.5% annually to 2035 in the CPS and 6.5% annually in the STEPS. The growth in the market for electrolysers is higher, but starts from a lower base. Over the next 10 years, the value of the market for electrolysers grows 10% annually in the CPS and slightly faster in the STEPS.

Sales of methanol- and ammonia-fuelled ships in 2035 in the STEPS are 12 times higher than in 2025, with vessel types diversifying beyond chemical tankers and containerships to include cargo ships and bulk carriers. In the CPS, sales in 2035 are just 10% lower than in the STEPS, marking an 11-fold increase in sales compared to 2025. As a result, the market size for alternatively fuelled ships increases at least ninefold by 2035 in the two scenarios, reaching over USD 60 billion in the CPS and about USD 70 billion in the STEPS – greater than today's solar PV market.

The value of the global market for clean energy technologies grows two-and-a-half times more to 2035 in the NZE Scenario compared with the STEPS. As in the STEPS and in the CPS, electric cars and zero-emission trucks remain the two largest markets. The electric car market grows at an average annual rate of around 15% in the NZE Scenario. By 2035, the market reaches nearly USD 4 trillion in the NZE Scenario, more than four times its size in 2025. The market for zero-emission trucks expands even more rapidly, growing nearly 13-fold between 2025 and 2035, with an average annual growth rate close to 30%. Sales increase slightly faster – by around 15 times – supported by falling production costs and vehicle prices.

Other clean energy technologies also grow more rapidly in the NZE Scenario than in the STEPS and the CPS. In particular, the market size for electrolysers in the NZE Scenario in 2035 is about six times the size of the electrolyser market in the STEPS in that year.

The geographic distribution of clean energy technology deployment to 2035 varies between scenarios. Currently, the market size for clean energy technologies is roughly equal between advanced economies and EMDEs, largely due to China's dominant role in EV sales and solar PV installations. In 2025, China's market alone, valued at approximately USD 510 billion, is estimated to account for nearly half of the global clean energy technology market. In the STEPS, stronger regulations in some of the largest advanced economies drive faster market growth (more than 10% per year to 2035) compared with EMDEs. For example, the market for clean energy technologies reaches USD 950 billion in Europe in 2035 in the STEPS. In the CPS, the market value for clean energy technologies in 2035 in advanced economies is 30% lower than in the STEPS, and 65% lower in emerging economies other than China. For example, the market for clean energy technologies in India grows by 7% from 2025 to 2035 in the CPS, while it grows 18% over the same period in the STEPS. In both the STEPS and CPS, China's market continues to expand at around 5% per year, surpassing USD 800 billion by 2035. In the NZE Scenario, the value of the clean energy technology market grows by over 15% annually in both advanced and emerging economies.

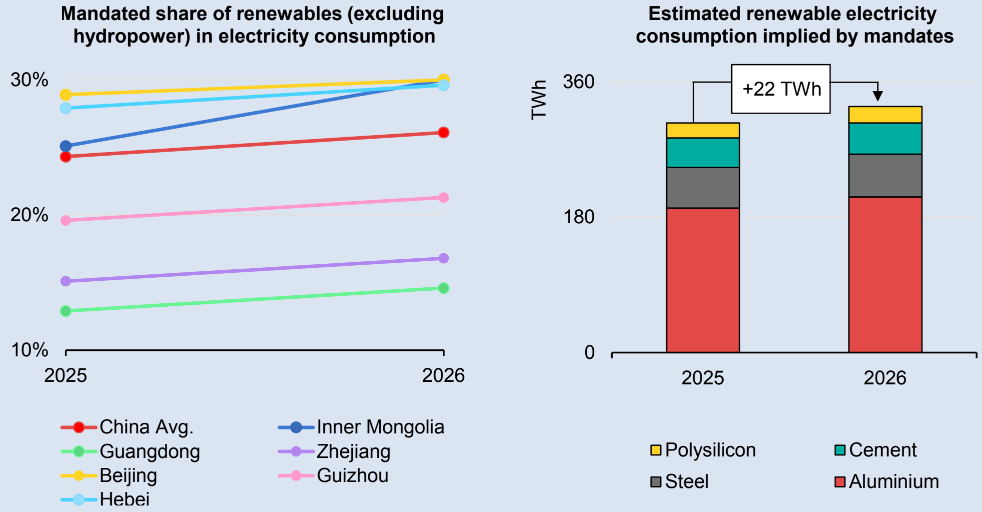
Box 2.3 China's expanded Renewable Electricity Mandates are driving new markets for clean energy technologies in heavy industries

In July 2025, China's National Development and Reform Commission expanded its Renewable Electricity Mandates to cover steel, cement, polysilicon and certain types of data centres, alongside the aluminium industry, which has been covered since 2024 (Howe, 2025). The mandates stipulate province-level shares of renewable electricity in the total electricity consumption by these sectors, alongside a further stipulation for renewables excluding hydropower generation (i.e. mainly solar PV and wind) (National Development and Reform Commission, 2025).

China's solar and wind electricity generation has grown rapidly, from 10% of final electricity demand in 2020 to nearly 20% in 2024. As China phases out its feed-in tariffs, the Renewable Electricity Mandates reflect a broader shift towards a more market-oriented support framework for renewables. To date, China's heavy industries have played a limited role in driving renewable electricity demand. However, coupled with China's ambitious industrial decarbonisation and electrification targets, the extended mandates have the potential to significantly increase renewable electricity demand across these sectors.

Province-level thresholds for renewables excluding hydropower for 2025 range from 10.7-30%. In 2026, this range is elevated to 12.4-30%. In hydro-rich Sichuan, where the overall share of renewables in electricity generation is already high, the 2026 mandate will require heavy industry to increase its non-hydropower renewables share from 11.9% to 13.6%. Some provinces that have rapidly increased their electricity generation from solar and wind in recent years – including Hebei, Jilin and Liaoning – will see their targets remain largely stable at around 30% through 2026 (Myllyvirta, 2025).

Figure 2.10 Mandated shares of solar and wind generation in Chinese heavy industry, 2025-2026



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Notes: In the left-hand graph, the China average is weighted by consumption. In the right-hand graph, electricity consumption estimates for the steel and aluminium industries exclude any consumption downstream of casting.

In 2024, the aluminium, steel, cement and polysilicon industries together accounted for more than 1 600 TWh of electricity consumption, which is about 15% of China's total. Just the incremental tightening of the Renewable Electricity Mandates in 2026 relative to 2025 would see the weighted national average share for solar PV and wind in heavy industry consumption increase from 24.3% to 26.1%. This increase would lead to an estimated 22 TWh of additional renewable electricity demand nationally – more than the total electricity demand of Croatia. If all of this was generated from solar PV, it would require installation of 26 GW, which corresponds to 8% of China's total annual installations in 2024. Wind turbines could be used in combination with – or instead of – solar PV, and demand for electrolysers is likely to be stimulated in instances where electrolytic hydrogen is a useful intermediate (e.g. chemically reducing iron in the steel industry, or for long-duration energy storage).

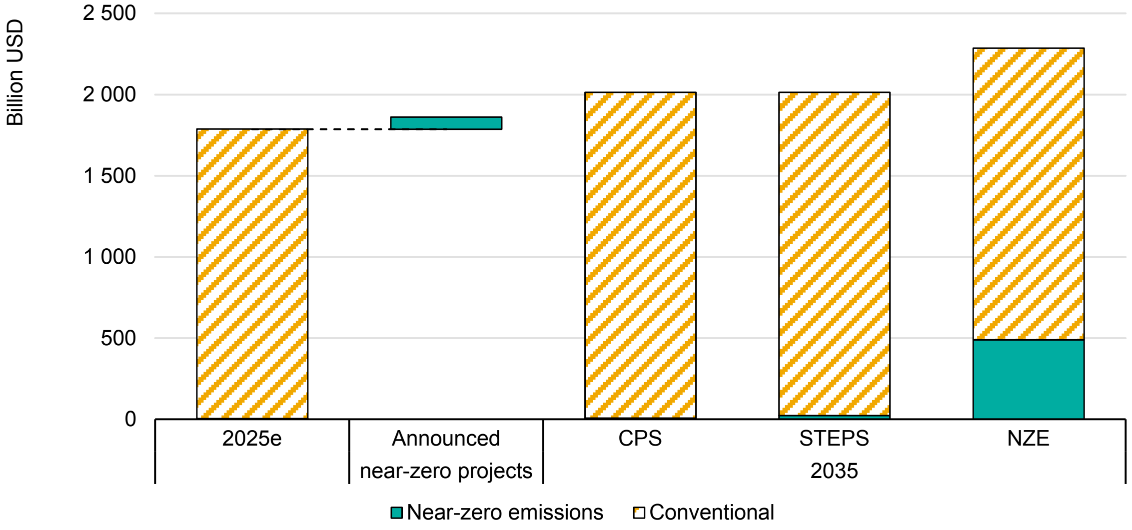
Power purchase agreements and other instruments can be used to alleviate difficulties with building-out solar PV and wind generation in certain provinces (e.g. densely populated Beijing). At the same time, province-level mandates can help target industrial decarbonisation efforts in coal-rich provinces that account for the majority of production in these industries, which often make extensive use of emissions-intensive captive coal power plants. Under the current targets, Inner Mongolia would see the most rapid increase in its mandated renewable electricity consumption, with its target rising by five percentage points (Figure 2.10). Achieving this will require more than 8 TWh of additional renewable electricity by 2026.

The size of the global market for bulk materials produced using near-zero emissions technologies grows only modestly in the STEPS and the CPS, reflecting limited announced projects and the strong policies needed to drive rapid deployment of those technologies. It grows far more quickly in the NZE Scenario, reaching USD 500 billion in 2035 (20% of total market for conventional routes), compared with just USD 20 billion in the STEPS (1% of the total market) and USD 5 billion in the CPS (0.3%).

Steel contributes more than three-quarters to the total near-zero emissions materials market in 2035 in the NZE Scenario, cement 15%, aluminium 5% and ammonia for non-fuel uses 3%, roughly in proportion to their current market sizes. Compared to the overall market for materials, the market opportunity for near-zero emissions materials in the NZE Scenario is slightly skewed towards advanced economies. This reflects the design of the scenario, which assumes a faster pace of decarbonisation in these regions. However, many EMDEs have potential to produce near-zero emissions materials at lower cost, thanks to low-cost renewable energy resources.

Under advantageous circumstances, projects producing near-zero emissions materials might already be able to compete with conventional alternatives in the near-term (see Chapter 7), although this has not yet been the case. Achieving the market scale of the NZE Scenario would require a far larger number of projects to be launched than have been announced to date. Project deployment at this scale would only happen with strong policy support, in areas such as internationally interoperable emissions standards, action on demand creation and transparency and certainty on related cost premiums. Availability of low-emissions electricity at low cost, and enabling infrastructure such as low-emissions hydrogen transport and storage, electricity grids and CCUS would also be necessary, requiring multi-year planning and co-ordinated investments.

Figure 2.11 Global market size of conventional and near-zero emissions bulk materials by scenario, 2025e-2035



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Notes: CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. Represents the market size for steel, cement, aluminium, and ammonia for non-fuel applications. Assumed materials prices are derived using the evolution of levelised cost of production and demand in each scenario. Near-zero emissions steel includes both iron-based and scrap-based production.

The near-zero emissions materials market is worth USD 500 billion in 2035 in the NZE Scenario, but to reach this size, far more projects would need to be announced – and soon.

The global market for low-emissions fuels roughly doubles in size by 2035 in both the STEPS and the CPS, expanding from around USD 215 billion in 2025, to around USD 390 billion, or about 15-20% the current size of the diesel and gasoline markets in transport.

In the STEPS and CPS, 60% of this growth comes from the continued expansion of relatively mature biofuels such as biomethane, bioethanol and biodiesel in transport, particularly road. Biodiesel and bioethanol are expected to grow at an average annual rate of 2-3%, while biomethane could grow at an average 7-8%, with the three biofuels accounting for an 80% share of the low-emission fuels market in 2035. Another 20% of market growth comes from hydrogen, ammonia and methanol, driven primarily by increasing use of low-emissions hydrogen as a fuel in industry, road transport and shipping. Growth in these sectors reflects early corporate offtake commitments and targeted tax incentives.

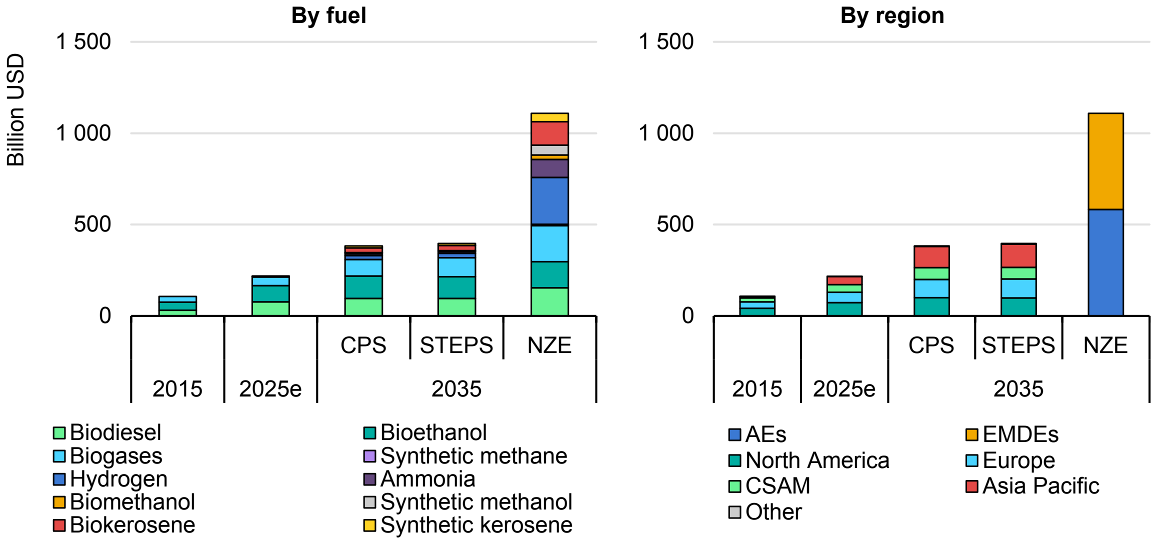
The remainder of the increase is driven by sustainable aviation fuels (SAFs), which stand out for their high relative growth, albeit from a small base. In both the STEPS and CPS, SAFs are projected to grow by about 30% per year, boosted by blending mandate requirements, with biokerosene making up two-thirds of the growth. By 2035, SAFs are expected to meet about 4% of total jet fuel demand, while some regions have set substantially higher mandates – such as the European Union's target of 20% by 2035.

In the NZE Scenario, low-emissions fuels play a far greater role, with the market expanding fivefold between 2025 and 2035, approaching half of the current size of diesel and gasoline markets in the transport sector. Emerging low-emissions fuels – hydrogen, ammonia, methanol and SAFs – account for over half of the total low-emissions market by 2035, reflecting a structural shift away from existing biofuels, which are increasingly constrained by sustainable feedstock availability. The low-emissions hydrogen, ammonia and methanol markets grow more than twice as fast as in the STEPS, underpinned by rising demand for low-emissions fuels in industry and shipping.

Achieving this faster scale-up will require significant cost reductions, robust policy support and strong demand signals. SAFs produced using the prevailing route today – hydroprocessed esters and fatty acids (HEFA) – currently cost some two to three times more than fossil jet fuels, and face limitations on sustainable feedstock. Synthetic kerosene, which is still at demonstration phase, can cost over nine times more. While investment in these emerging pathways will be needed to reduce costs, including in other biomass-based SAFs, the resulting impact on average flight ticket prices could be relatively limited (see Chapter 3). As of September 2025, only 15% of hydrogen and hydrogen-based fuel production that could be operational by 2030 had offtake agreements, and just one-quarter of those contracts are on firm, long-term terms.

Regionally, the market for low-emissions fuels is currently slightly larger in advanced economies, which account for about 60% of global demand. This reflects early adoption of climate policies such as blending mandates. In all scenarios, the regional distribution becomes more balanced over time, as emerging economies scale up low-emissions fuels use.

Figure 2.12 Low-emissions fuels market size by fuel, region and scenario, 2015-2035



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Notes: AEs = advanced economies; EMDEs = emerging markets and developing economies. CSAM = Central and South America; CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. Market size is calculated based on fuel production volumes and prices, allocated to the point of demand. Biogases include biogas and biomethane. Hydrogen refers to low-emissions hydrogen. For hydrogen and hydrogen-based fuel production, fuel production is used as a proxy for price. Market size excludes the use of hydrogen, hydrogen-based fuels, and biofuels as fuel or feedstock in industry. The market for low-emissions hydrogen and hydrogen-based fuels, as well as low-emissions hydrogen, ammonia and methanol used as feedstocks in industry and biorefineries, is around USD 55 billion in 2035 in the STEPS, USD 45 billion in the CPS, and USD 550 billion in the NZE Scenario.

The market for low-emissions fuels doubles and diversifies by 2035 in the STEPS, with hydrogen-based fuels and biokerosene making up almost 20% of the value of the market.

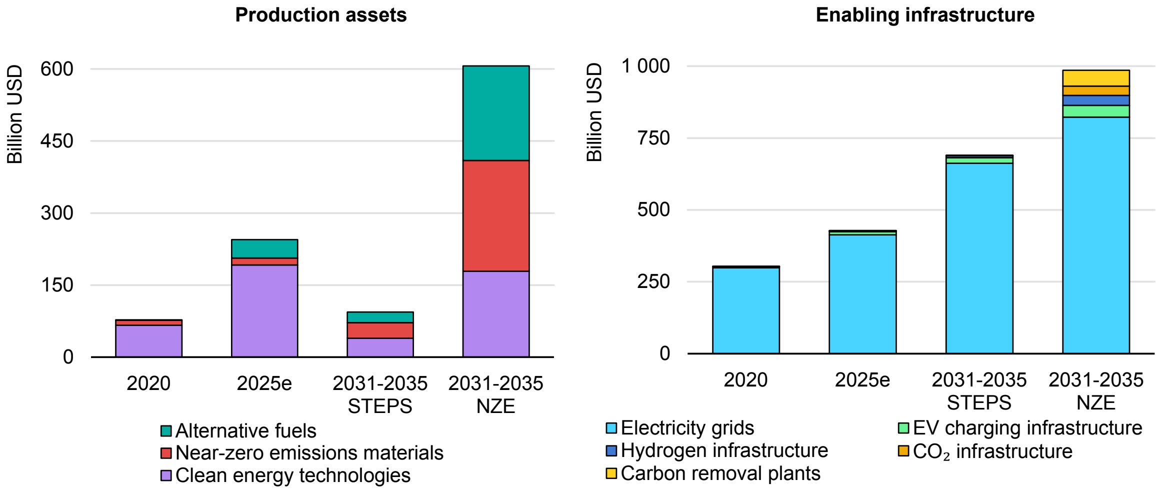
Investment needs

Developing and maintaining markets for clean energy technologies, materials and fuels requires investments in production assets and infrastructure. For example, a growing market for electric cars triggers investment in new or retooled assembly plants, EV charging infrastructure, and eventually electricity grid upgrades or expansions to power the growing stock. In particular, investment in electric grids can help avoid delays in grid reinforcement and interconnection, which could otherwise limit the speed at which new electricity-related clean energy technology projects can be deployed and connected to the grid, notably for solar, wind and battery storage.

Investment in production assets for clean energy technologies, near-zero emissions materials and low-emissions fuels is estimated to have reached around USD 245 billion in 2025, about three times the investment 5 years earlier. To put this in perspective, global investment in low-emissions fuels production facilities alone in 2025 is estimated to be the same as that expected in oil refineries (USD 30 billion) (IEA, 2025a).

Investment in enabling infrastructure, primarily electricity grids, is estimated to have approached around USD 430 billion in 2025, about 40% more than in 2020. The level of investment in production assets and enabling infrastructure combined in 2025 is estimated to be around half of the size of the market for these clean energy technologies, near-zero emissions materials and low-emissions fuels.

Figure 2.13 Average annual investments in production assets and enabling infrastructure by technology category in the Stated Policies Scenario and Net Zero Emissions by 2050 Scenario, 2020-2035



Notes: STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; EV = electric vehicle. Investments in production assets refers to manufacturing or production equipment. Clean energy technologies include battery cells, anodes and cathodes; electric cars; solar PV modules, cells, polysilicon and wafers; wind towers, blades and nacelles; heat pumps; and electrolysers. Alternative fuels include advanced biofuels, low-emissions hydrogen and hydrogen-based fuels.

Investment in production assets for clean energy technologies and low-emissions fuels falls to 2035 in the STEPS, but grows for near-zero emissions materials and enabling infrastructure.

Average annual investment in production assets for clean energy technologies, materials and fuels combined falls by 60% in the STEPS from 2031-35, compared to 2025 levels. This is mainly driven by a drop in investment needed for manufacturing capacity for clean energy technologies to cope with demand, given the big expansion observed in recent years. For example, manufacturing capacity for battery cells expanded more than fivefold from 2020 to 2025. In the STEPS, however, battery manufacturing capacity only doubles to 2035. For solar PV module manufacturing, capacity has increased more than fourfold over the last 5 years, yet it increases only 5% over the next decade in the STEPS (see Chapter 5 for more details).

In the CPS, investments to enable markets for clean energy technologies, materials and fuels are lower than in the STEPS, but are still needed to bring both production capacity and enabling infrastructure above 2025 levels. The annual investments in the production of near-zero emissions materials are about 60%

lower on average from 2031-35 than in the STEPS. By contrast, annual investments in alternative fuel production assets in the CPS are only around 15% lower than in the STEPS on average over the same period. In the NZE Scenario, average investment in clean energy technology production assets between 2031-2035 is similar to 2025 levels, though investments for near-zero emissions materials are more than 15 times 2025 levels, and those for alternative, low-emissions fuels production assets are five times 2025 levels.

Average annual investment in electricity grids between 2031-35 in the STEPS is about 60% higher than in 2025. Investment in public EV charging infrastructure increases by a greater percentage (80%) but reaches just USD 20 billion in average annual investment from 2031-35, compared to around USD 660 billion for electricity grids. In the CPS, the average annual investment from 2031-35 for electricity grids is only 2% lower than in the STEPS; for EV chargers, the investment level is about one-third of that in the STEPS. Investment in electricity grids and EV charging infrastructure during this timeframe are much higher (25-100%) in the NZE Scenario. The NZE Scenario also sees higher annual investments in carbon removal plants (USD 55 billion), CO_2 transport and storage infrastructure (USD 30 billion), and hydrogen infrastructure (USD 35 billion) from 2031-35.

Drivers of deployment

The adoption of new technologies and fuels in the energy sector is driven by multiple factors including cost-competitiveness, direct or indirect policy support, affordability, energy and environmental performance and consumer appeal, among others. However, technologies vary widely in terms of their target users, which affects both the expected value of the service provided to the consumer and how production costs are ultimately passed on to end-users.

Some clean energy technologies, such as EVs and heat pumps, are consumer goods and compete directly with conventional alternatives, such as oil-fuelled cars and gas-fired boilers. Others, like solar PV plants, heavy-duty trucks, near-zero emissions materials manufacturing, or low-emissions ships, are typically deployed by businesses or public entities to support the delivery of other goods or services. These distinctions influence how sensitive adoption is to cost, which economic or financial indicators – e.g. upfront equipment or installation costs, running costs, total cost of ownership (TCO) – matter most in decision-making, and which policy instruments are likely to be most effective in supporting deployment.

Cost-competitiveness

Utility-scale solar PV and wind are among today’s most cost-competitive clean energy technologies. Since 2010, the levelised cost of electricity (LCOE) has declined by 90% for solar PV and 70% for wind generation. In 2024, approximately 80% of all wind and solar electricity generation took place in countries where these technologies offered a lower LCOE than coal- or gas-fired plants. Climate and energy security policies have played a critical role in helping solar and wind compete with fossil fuels in those countries. China, in particular, has provided extensive support for both large-scale and distributed solar and wind systems. Combined with its ability to manufacture components cheaply, this has enabled renewable generation costs that are competitive with coal. In the wind sector, ongoing reforms in auction design (e.g. through two-sided contracts for difference and the inclusion of qualitative criteria), permitting processes, and grid access – notably in Europe, India and several emerging and developing economies – are improving the bankability of new projects. This is helping the industry bounce back from recent supply chain disruptions and macroeconomic headwinds.

Costs are projected to decline further through to 2035 – by about 40% for solar PV, and about 10% for onshore wind. In the STEPS, projected LCOEs show that new solar PV and onshore and offshore wind have similar or lower average generation costs than new coal, gas and nuclear in the United States, European Union and China. Even when accounting for technology dispatchability, analysis shows that the value-adjusted levelised cost of electricity (VALCOE)[5] of a solar or wind plant operating at a 95% capacity factor could be comparable to dispatchable sources in major markets in 2035 (IEA, 2025g).

The economics of mass market technologies, such as EVs and heat pumps, are also improving in some markets. In China, battery manufacturing cost reductions, a high degree of vertical integration in supply chains, and intense competition have driven down electric car prices to match – or even undercut – those of conventional cars in most market segments. In 2024, two-thirds of electric cars sold in China were priced lower than their internal combustion engine (ICE) counterparts, compared to half in 2021. These cost advantages have had global ripple effects, with the affordability of Chinese EVs contributing to their rising adoption in other regions. In 2024, the share of electric cars in total car sales in other emerging markets and developing economies in Asia, Latin America and Africa nearly doubled, reaching 4%, largely due to the availability of competitively priced imports from China. However, this trajectory could shift amid uncertainty over future import tariff policies.

In the world's second and third leading electric car markets – the European Union and United States – progress on making EVs more affordable is, however, lagging behind China. In Germany, for example, the average price premium for small battery electric cars remained almost unchanged between 2021 and 2023, reaching just over 40% higher than equivalent small ICE models in 2024. In the

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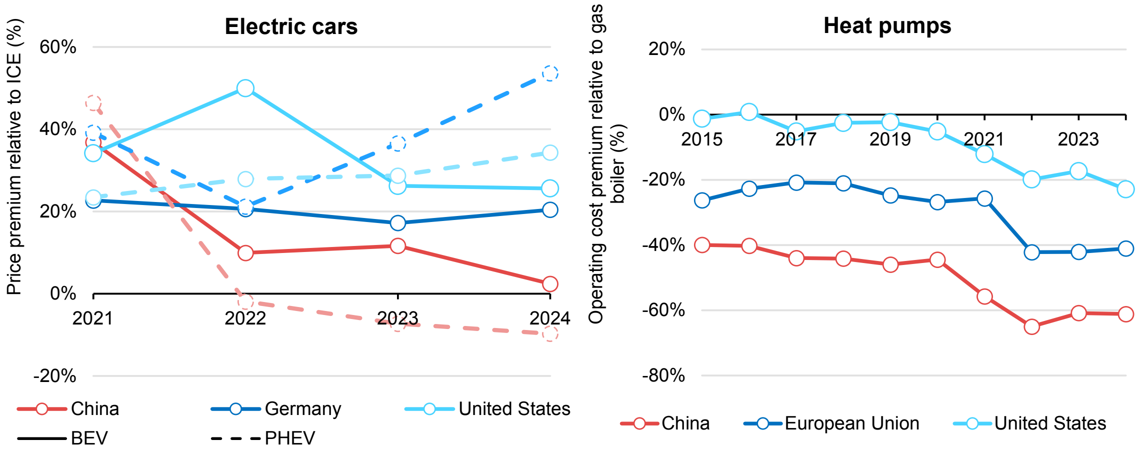
[5] The VALCOE, developed for the IEA Global Energy and Climate Model, accounts for a technology's intermittency, its contribution to a system's adequacy and stability, and its ability to provide flexibility.

United States, the price premium has fluctuated, reaching just over 40% for medium battery EVs in the same year, and just over 25% for electric SUVs.

Figure 2.14 Evolution of cost-competitiveness for electric cars and heat pumps, 2021-2024



Notes: ICE = internal combustion engine; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle. Electric car price premium is calculated for sport utility vehicles (SUVs) relative to ICE equivalents. Operational cost premium is calculated based on annual spending on heat pump operation relative to gas-fired boilers.

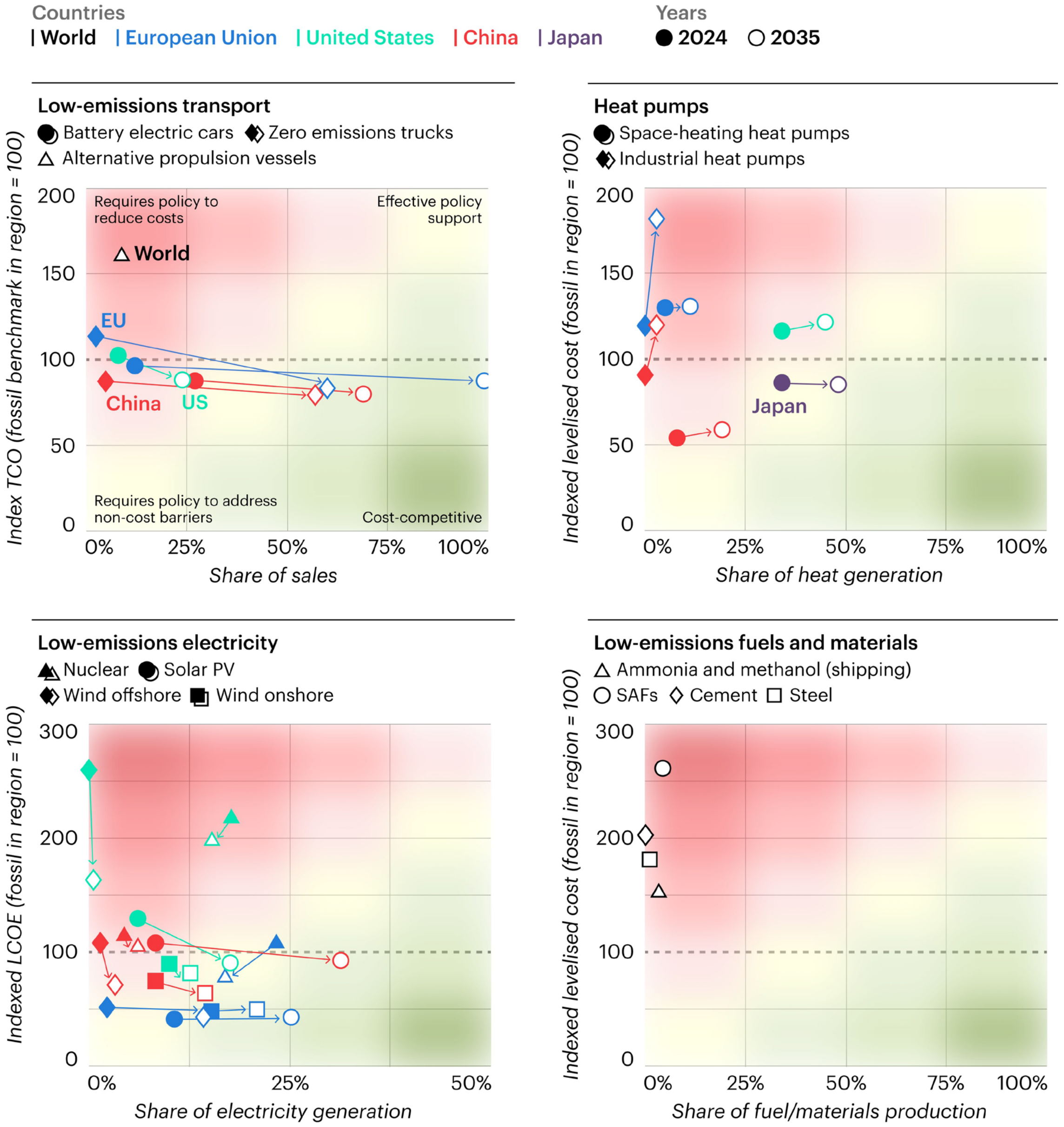
The competitiveness of mass market technologies such as electric cars and heat pumps is improving in some markets, although barriers to adoption remain.

In an increasing number of countries, space-heating heat pumps are becoming the most economical choice compared with fossil fuel-based systems, especially when accounting for their higher energy efficiency and ability to provide both heating and cooling. In regions with milder winters and a strong demand for cooling, such as the southern United States, southern Europe, central China, and Japan, air-to-air heat pumps offer a clear economic advantage, thanks to their dual (heating and cooling) functionality and lower operating costs. In colder regions like central and northern Europe, Canada, and the northern United States, the cost-competitiveness of heat pumps is more dependent on the relative prices of electricity and natural gas, highlighting the need for balanced energy pricing and targeted policy support to level the playing field. In some northern European countries, annual operating costs are lower than for gas-fired boilers due to long-standing cheap electricity prices relative to natural gas and have been steadily decreasing in the past 10 years thanks to efficiency improvements. This has boosted heat pump adoption, especially when accompanied by long-term policies that removed much of the uncertainty for households and installers. However, higher upfront costs relative to gas-fired boilers may still prove to be a barrier to adoption in many regions without a similar level of long-term confidence.

The situation is quite different for industrial heat pumps, a market still in its early stages but with significant untapped potential. Today, electricity supplies less than

5% of total industrial heat demand globally. Installed industrial heat pump capacity is expected to grow in the coming years, making up 2% of industrial heat in light industries in 2035 in the STEPS. However, higher electricity to gas price ratios could increase the cost premium, pointing to the need for policy to support cost reductions.

Figure 2.15 Relative cost and market share for selected clean energy technologies and low-emissions products by market in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: SAFs = synthetic sustainable aviation fuels based on electrolytic hydrogen; VALCOE = value-adjusted levelised cost of electricity; TCO = total cost of ownership; Near-zero emissions cement: production weighted average cost of production of low-emissions pathways indexed on unabated cement production.

While clean energy technologies are becoming increasingly affordable, in many instances policies are required to address cost and non-cost barriers.

Electric trucks have also become more affordable, thanks to falling battery prices and improvements in energy density, particularly in China, where the price gap between diesel and electricity (on an energy-equivalent basis) is relatively wide. In certain applications in China, battery electric trucks already offer a lower TCO due to the higher energy efficiency of electric powertrains compared with ICE. While TCO remains higher than for fossil-fuelled alternatives in many other regions, cost parity is expected to be reached across a growing number of applications over this decade.

By contrast, emerging low-emissions fuels still face a considerable cost disadvantage compared with unabated fossil-based alternatives, which continues to be a barrier to widespread adoption. Electrolytic hydrogen, for instance, is currently 1.2 to 7.5 times more expensive to produce than fossil-derived hydrogen even in locations with low-cost renewables. Similarly, SAFs remain uncompetitive because of high production costs (see above) and limited feedstock availability. Methanol- and ammonia-powered ships cost about twice as much to own and operate as conventional vessels, though this gap should narrow as fuel production expands and ships become more efficient.

Near-zero emissions materials also continue to struggle to compete with conventional alternatives (see Chapter 7). Although the materials themselves are often identical in quality, the deployment of near-zero emissions production technologies depends heavily on cost-competitiveness, as well as the willingness of buyers to pay a price premium and policy drivers such as public procurement of near-zero and low-emissions materials.

Nevertheless, a subset of buyers are willing to pay a price premium for near-zero emissions materials and fuels. For instance, a recent survey of buyers indicated that around half of respondents might accept a 25% price premium for near-zero emissions steel and concrete (Climate Group, 2024) (IEA, 2025b). However, most near-zero emissions production cannot currently meet that price point without substantial subsidies. For instance, in the STEPS, the cost of producing near-zero emissions hydrogen-based steel is estimated to remain 20-145% higher than conventional steel even by 2035, in the absence of policy support. This translates to an additional cost of USD 125-600 per tonne of crude steel in this scenario, depending on the region. As the price premium increases, the share of willing buyers declines significantly, limiting the size of the market and slowing broader commercial adoption.

Low-emissions fuels and materials are typically inputs further up in the value chain than many clean technologies destined for mass market consumers. This creates an opportunity for their cost premiums (including profit margins) to be absorbed along the supply chain, resulting in only modest price increases for end consumers. For example:

- Low-emissions fuels: switching to fertilisers based on low-emissions hydrogen in wheat production would lead to only a minimal impact on final retail prices. Similarly, the use of SAFs would have a relatively small impact on airfares: in Europe, for instance, under the European Union's 20% SAF blending mandate by 2035, average ticket prices would rise by around 10%, since fuel accounts for around 30% of airline costs on average. In shipping, fuel costs represent only a small share of overall freight rates, with the latter typically being a minor component of final consumer prices. Nonetheless, even marginal increases can be significant, given the strong competition in the shipping industry.
- Materials: use of near-zero emissions materials would lead to only a minor impact on final price in a variety of key applications. In the automotive sector, full substitution of conventional steel with near-zero emissions steel would increase car prices by just 1-2%. In the construction sector, the price of a typical house would rise by a similar amount – roughly 1-3% – if near-zero emissions steel and cement were to be used. In both examples, partial substitution of these materials in the final product would have an even smaller impact on the price.

Nevertheless, the current production cost premiums for low-emissions fuels and materials remain a major barrier for project developers. Without stronger policy intervention, these premiums are unlikely to fall significantly.

Policy drivers

Policy support remains essential to the cost-competitiveness and market potential of new energy technologies and fuels. This is especially true for those that continue to face significant cost gaps compared with conventional alternatives or are hampered by non-cost barriers such as social acceptability or regulatory hurdles.

In transport, targeted measures such as purchase subsidies, tax credits, fuel economy standards and EV mandates have significantly boosted EV adoption, even in regions where affordability of EVs remains a challenge. For example, despite electric cars being on average 20-25% more expensive (from a purchase price) than their ICE equivalents in the European Union and North America, EV market shares in those regions rose from under 1% in 2015 to 12% and 8%, respectively, in 2024. This trend has been reinforced by large-scale legislative packages, like the EU Fit for 55 package, which combine consumer incentives with industrial policy to strengthen domestic supply chains (see Chapter 7).

Similar dynamics are visible in the buildings sector. Heat pump deployment has increased in all major heating markets, supported by building codes requiring or encouraging their installation in new buildings, subsidy schemes, and other policy measures that steadily raise the bar for heating systems. Over the last decade, sales have increased 80% globally (in capacity terms), with stronger growth in Europe and the United States. Recent efforts such as the REPowerEU plan in the European Union and US state-level electrification mandates have helped to accelerate heat pumps adoption. Meanwhile, countries including Japan and Korea are expanding subsidy programmes to overcome upfront costs. Despite these advances, heat pumps still only cover about 15% of global heating needs in buildings.

Policy remains particularly critical for earlier-stage technologies that struggle to scale. Low-emissions fuels and materials, and alternative propulsion vessels, for example, require robust demand-side incentives to complement supply-focused policies (see Box 2.4). For example, international frameworks like the International Civil Aviation Organization scheme have so far had limited impact in driving adoption of SAFs, prompting several governments to introduce national blending mandates (e.g. in the European Union (European Commission, 2025), United Kingdom (UK Department for Transport, 2025), Brazil (Argus, 2025), and Japan (Argus, 2024)).

Box 2.4 Designing an effective policy framework for near-zero emissions materials

A strong and well-designed policy framework can transform a difficult market environment for near-zero emissions materials into a viable commercial opportunity. Governments have a wide range of policy tools at their disposal to support the development and scale-up of markets. For a detailed overview of policies for materials, see the IEA's *Demand and Supply Measures for the Steel and Cement Transition* (IEA, 2025b) paper and the *Policy Toolbox for Industrial Decarbonisation* (IEA, 2025c).

Key policy levers include:

- **Bridging the price gap** for near-zero emissions products through supply-side support to make early-stage investments financially viable.
- **Stimulating demand** by helping to secure buyers or creating markets for near-zero emissions products, even when they come at a premium, both through public procurement and other instruments that create private sector demand.
- **Shifting the competitive landscape** through broader market signals – such as carbon pricing or regulatory standards – that reward lower-emission production pathways.
- **Establishing enabling conditions**, including clear definitions, certifications, and standards, to underpin market confidence and support other policy measures.

- **Co-ordination of enabling infrastructure** that near-zero emissions technologies depend on – namely, low-emissions hydrogen, low-emissions electricity, biofuels and CCUS – to avoid delays in deployment.

There is no single "correct" policy formula; what matters most is that policies are sufficiently strong to make a tangible impact. Governments can and should tailor their policy mix to reflect domestic circumstances, market maturity and industrial structure. In many cases, a comprehensive framework combining supply-side support, demand stimulation and enabling measures will be most effective. However, one well-designed and robust policy can sometimes outperform several weaker ones, especially when administrative simplicity and regulatory clarity are critical to success.

At the same time, technologies that are already cost-competitive with fossil-based alternatives continue to face systemic barriers that hinder their market penetration. For example, solar PV is, on average, cheaper than fossil generation in the European Union and the United States, but remains constrained by permitting hurdles, grid bottlenecks and public acceptance, making up 11% and 6% of the regions' electricity mixes in 2024, respectively. The same is true to a lesser extent for onshore wind, with generation reaching 15% and 10% the same year, respectively. In China, the adoption of medium- and heavy-duty electric trucks is similarly limited – not by cost, but by infrastructure readiness. While charging networks for passenger EVs and electric buses are well established, public and depot charging stations, especially for long-haul freight, are still in the process of being scaled up.

Regulatory reforms to address legal or regulatory barriers in some sectors are also increasingly being put in place. For example, the use of low-emissions ammonia in ship engines is currently prohibited in many jurisdictions, requiring changes in safety regimes before deployment can begin at scale. The recent introduction of pilot safety frameworks for ammonia vessels illustrates how governments are beginning to adapt legal systems to enable their wider deployment. Similarly, current building codes can include prescriptive rules on cement composition and building design, in some cases precluding the use of lower-emissions clinker substitutes or innovative building designs that could reduce the use of emissions-intensive clinker. Revision of these building codes could facilitate greater uptake of near-zero and low-emissions cement. The European Union's revised Construction Products Regulation is an example of supportive regulatory reform.

Innovation

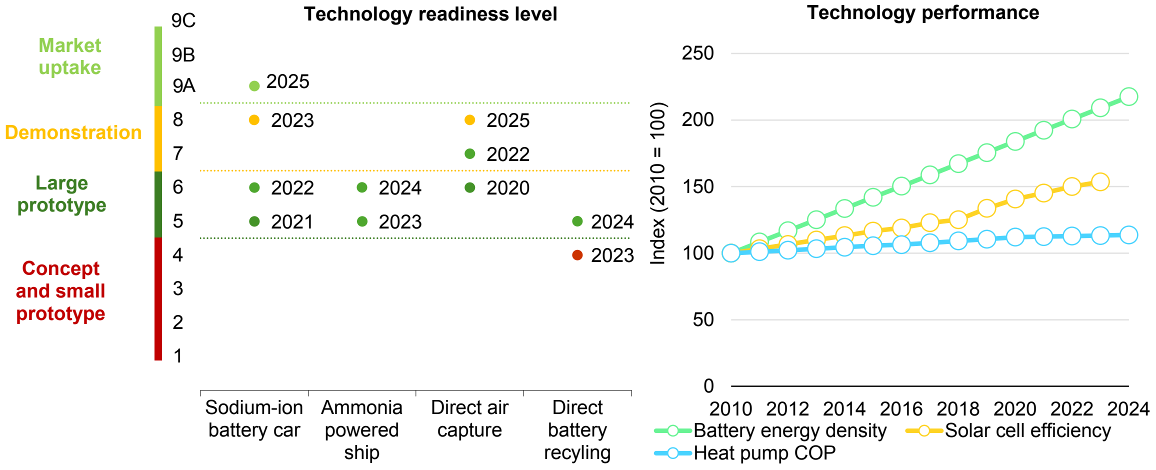
Innovation is central to improving competitiveness across the board and boosting technology adoption by lifting technical barriers to adoption and bringing new solutions to market. It can also contribute to improving the operational performance of existing technologies, alleviating non-cost factors, and facilitating the recuperation of valuable materials. Innovation in manufacturing techniques is a crucial strategy for countries aiming to become or to remain major players in an increasingly competitive global clean technology market (see Chapter 7). Governments have a critical role to play in supporting energy innovation, a sector marked by high barriers to entry such as capital intensity, long lead times, safety standards, and the need for extensive physical infrastructure (IEA, 2025d).

Recent years have seen strong momentum in bringing entirely new solutions to market. The development of alternative energy conversion methods (such as thermochemical, biological, or electrochemical processes), the design of new equipment and systems to accommodate alternative fuels or low-emissions production pathways, and the use of emerging materials like nanomaterials or solid-state electrolytes has allowed for the achievement of performance levels beyond those possible with conventional technologies. In shipping, ammonia as a marine fuel shows strong potential to support deep decarbonisation due to its scalability and competitive TCO compared with other low-emissions options. However, engines capable of running on low-emissions ammonia are still at the prototype stage, with commercial deployment expected in the coming years. In a milestone for the sector, in 2024, a ship belonging to Australian mining firm Fortescue became the first to use ammonia for marine propulsion at the Port of Singapore. It had been retrofitted with two dual-fuel engines to run on both ammonia and diesel (Maritime and Port Authority of Singapore, 2024). Engine manufacturers such as Everllence (formerly MAN), Wärtsilä, J-Eng, WinGD, and Hyundai have also begun offering ammonia-capable engines, contributing to a noticeable increase in ammonia-fuelled vessels on shipyard order books.

Another area in which innovation has played a significant role in bringing new technologies to market is carbon dioxide removal (CDR), a sector that is important to meeting net zero goals, particularly in direct air capture (DAC) (IEA, 2025d). Currently, DAC faces high energy requirements and steep first-of-a-kind costs, estimated at between USD 500 and USD 1 900 per tonne of CO_2 captured. Around USD 1 billion of RD&D funding has been made available to fund DAC first-of-a-kind and pilot projects, in the hope that advanced capture materials and improvements in process efficiency, along with economies of scale, could bring these costs down to around USD 300/t CO_2 by mid-century.

In parallel, innovation continues to play an important part in enabling performance gains in existing clean energy technologies. Lithium-ion batteries have doubled in average energy density since 2010, enabling lighter battery packs and longer ranges for EVs, while more affordable chemistries – such as lithium iron phosphate (LFP) and sodium-ion – are broadening market options. Heat pumps have achieved significant improvements in seasonal performance factors, expanding their competitiveness in colder climates, while record solar cell efficiencies have been demonstrated through tandem perovskite–silicon designs, now being piloted at industrial scale in China and Europe.

Figure 2.16 Evolution of technology readiness levels, 2021-2025, and performance for selected clean energy technologies, 2010-2024



Notes: COP = coefficient of performance. Technology performance is based on sales-weighted average.
Sources: IEA (2025e) and IEA (2023).

Continued innovation is bringing emerging clean energy technologies closer to market and improving their performance, helping to support market uptake.

System integration is another frontier that innovation efforts are tackling. This includes grid-responsive solutions such as virtual power plants (a network of decentralised, medium-scale power generating units combined with flexible power options for consumers and storage systems) and vehicle-to-grid interfaces, as well as digital tools that co-ordinate decentralised assets and manage variability. Infrastructure upgrades like hydrogen-ready pipelines and fast-charging networks for EVs also enable the broader deployment of clean technologies such as variable renewables. The rollout of smart grids, first commercialised in the late 2000s, has played a central role in managing variable renewable energy inputs. These technologies are becoming increasingly important as the share of renewable electricity in total generation grows and as more end-uses become electrified. Efficient EV charging is another key enabler of adoption. For example, cars equipped with bidirectional chargers, first brought to market in the early 2020s, now account for more than one in eight new electric cars sold, offering both greater grid flexibility and enhanced user value (IEA, 2025f).

Finally, materials innovation is increasingly focused on sustainability and recyclability. As demand for critical minerals and materials grows alongside accelerating clean energy technology deployment, innovation could also play a central role in enabling the recovery of valuable resources from end-of-life equipment and industrial waste. This includes more efficient material recovery methods, such as hydrometallurgy or electrochemical separation, AI-powered sorting systems for complex waste streams like electronic waste and composites, and product designs that incorporate disassembly and recycling considerations from the outset (closed-loop approaches). For example, improved recycling processes for lithium and nickel could reduce global demand by around 25% by 2025 and, similarly, could reduce demand for cobalt by 40% by the same year (IEA, 2024b). However, significant technological advances are needed across all stages of the recycling chain for recycled materials to compete with mined equivalents and to comply with emerging regulatory frameworks. Based on current trends, recycled lithium and nickel are projected to meet only around 5% of demand by 2035, with the primary constraint being that the increase in demand far outpaces the number of batteries reaching end-of-life (see Recycling section in Chapter 3).

References

Argus. (2024). *Japan aims to tighten SAF supply regulations*. Retrieved from https://www.argusmedia.com/en/news-and-insights/latest-market-news/2582074-japan-aims-to-tighten-saf-supply-regulations

Argus. (2025). *Brazil SAF industry set to take off in 2027*. Retrieved from https://www.argusmedia.com/en/news-and-insights/latest-market-news/2674362-brazil-saf-industry-set-to-take-off-in-2027

BNEF. (2025). *Data service*. Retrieved from https://about.bnef.com/

Climate Group. (2024). *Report: Nearly half of global companies are ready to pay a premium for lower emission steel and concrete*. Retrieved from https://www.theclimategroup.org/our-work/news/report-nearly-half-global-companies-are-ready-pay-premium-lower-emission-steel-and

European Commission. (2025). *ReFuelEU Aviation*. Retrieved from https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en

Howe, C. (2025). China sets its first renewable standards for steel, cement and polysilicon. *Reuters*. Retrieved from https://www.reuters.com/sustainability/boards-policy-regulation/china-sets-its-first-renewable-standards-steel-cement-polysilicon-2025-07-11/

IEA. (2022). *Achieving Net Zero Heavy Industry Sectors in G7 Members.* Retrieved from https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members

IEA. (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*. Retrieved from https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach

IEA. (2024a). *Definitions for Near-Zero and Low-Emissions Steel and Cement, and Underlying Emissions Measurement Methodologies*. Retrieved from https://www.iea.org/reports/definitions-for-near-zero-and-low-emissions-steel-and-cement-and-underlying-emissions-measurement-methodologies

IEA. (2024b). *Recycling of Critical Minerals*. Retrieved from https://www.iea.org/reports/recycling-of-critical-minerals

IEA. (2025a). *World Energy Investment 2025.* Retrieved from https://www.iea.org/reports/world-energy-investment-2025

IEA. (2025b). *Demand and Supply Measures for the Steel and Cement Transition*. Retrieved from https://www.iea.org/reports/demand-and-supply-measures-for-the-steel-and-cement-transition

IEA. (2025c). *Policy Toolbox for Industrial Decarbonisation*. Retrieved from https://www.iea.org/reports/policy-toolbox-for-industrial-decarbonisation

IEA. (2025d). *The State of Energy Innovation*. Retrieved from https://www.iea.org/reports/the-state-of-energy-innovation-2025

IEA. (2025e). *ETP Clean Energy Technology Guide*. Retrieved from https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

IEA. (2025f). *Global EV Outlook 2025*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2025

IEA. (2025g). *World Energy Outlook 2025*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2025

InfoLink. (2025). *InfoLink Consulting*. Retrieved from https://www.infolink-group.com/

Johnson, S. a. (2025). Green steel firm Stegra secures half of $1.1bn funding. *BusinessDay*. Retrieved from https://www.businessday.co.za/world/2025-11-06-green-steel-firm-stegra-secures-half-of-11bn-funding/

Maritime and Port Authority of Singapore. (2024). *World's First Use of Ammonia as a Marine Fuel in a Dual-Fuelled Ammonia-Powered Vessel in the Port of Singapore*. Retrieved from https://www.mpa.gov.sg/media-centre/details/world-s-first-use-of-ammonia-as-a-marine-fuel-in-a-dual-fuelled-ammonia-powered-vessel-in-the-port-of-singapore

Myllyvirta, L. (2025). *China's north cleans up its power mix as the south lags.* Retrieved from CREA: https://energyandcleanair.org/chinas-north-cleans-up-its-power-mix-as-the-south-lags/

National Development and Reform Commission. (2025). *Notice on Renewable Energy Power Consumption Responsibility Weights and Related Matters in 2025 (NDRC Energy Office [2025] No. 669).* Retrieved from NDRC: https://www.ndrc.gov.cn/xxgk/zcfb/tz/202507/t20250711_1399141.html

RMI. (2024). *Amazon and Johnson Controls Join Major Corporations in Launching Tender to Accelerate Deployment of Near-Zero Emissions Steel*. Retrieved from https://rmi.org/press-release/amazon-and-johnson-controls-join-major-corporations-in-launching-tender-to-accelerate-deployment-of-near-zero-emissions-steel/

S&P Global Mobility. (2025). *Global New Vehicle Registrations*. Retrieved from https://www.marketplace.spglobal.com/en/datasets/global-new-vehicle-registrations-(248)

SSAB. (2025). *SSAB Capital Markets Day 2025 – Accelerating premium leadership*. Retrieved from https://www.ssab.com/en/news/2025/11/ssab-capital-markets-day-2025--accelerating-premium-leadership

UK Department for Transport. (2025). *Sustainable Aviation Fuel (SAF) Mandate*. Retrieved from https://www.gov.uk/government/collections/sustainable-aviation-fuel-saf-mandate

Chapter 3. Technology deployment dashboards

Highlights

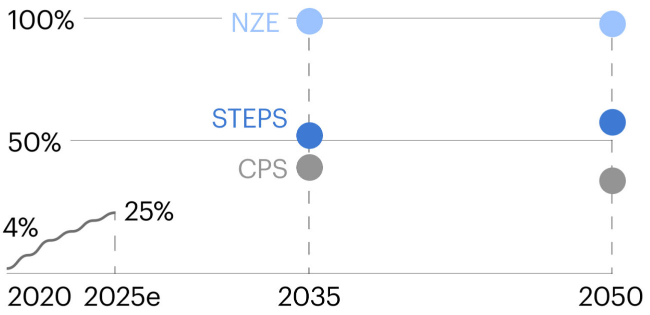
- Clean energy technology deployment advances in all IEA scenarios. How fast it will advance is linked to the capacity of individual technologies and technology groups to support the achievement of multiple policy objectives, the extent to which they benefit from effective policy support, and their relative abilities to reach technology maturity and cost-competitiveness.
- For example, clean energy technologies that underpin the age of electricity, like batteries or solar PV, are increasingly cost-competitive and expanding rapidly, supported by their modularity and mass manufacturing. While there is evidence of progress for energy technologies still under development or entering markets, it has been less steady. This is the case for low-emissions hydrogen production; carbon capture, utilisation and storage (CCUS); and near-zero emissions material production, all of which tend to involve large-scale engineering projects and rely on policy support to scale up and lower costs. Other technologies at earlier stages of development, such as nuclear fusion, solid-state cooling, iron ore electrolysis or conventional cement made without limestone could be transformative, but their viability remains unproven.
- This chapter analyses trends on deployment, cost-competitiveness and enabling factors for clean energy technologies across different sectors, including technologies that both produce and consume energy directly, as well as those used to produce low-emissions fuels and materials:
  - **Transport:** electric cars, zero-emissions trucks and ships powered by ammonia or methanol.
  - **Buildings:** heat pumps for space heating, air conditioning systems and zero-carbon ready building envelopes.
  - **Industry:** industrial heat pumps, near-zero emissions steel and cement, and recycling technologies.
  - **Power generation:** solar PV, wind power, nuclear, geothermal and stationary energy storage.
  - **Other energy transformation:** production of low-emissions hydrogen, ammonia and methanol, and sustainable aviation fuels.
  - **Carbon dioxide removal:** bioenergy with carbon capture and storage and direct air capture.

❶ ELECTRIC CARS

Increasing affordability bolsters the outlook

Market

Global sales share



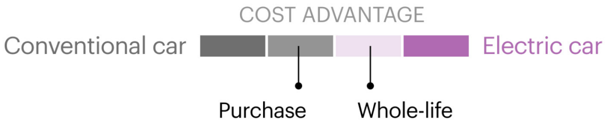
Market status

Global market size (USD)

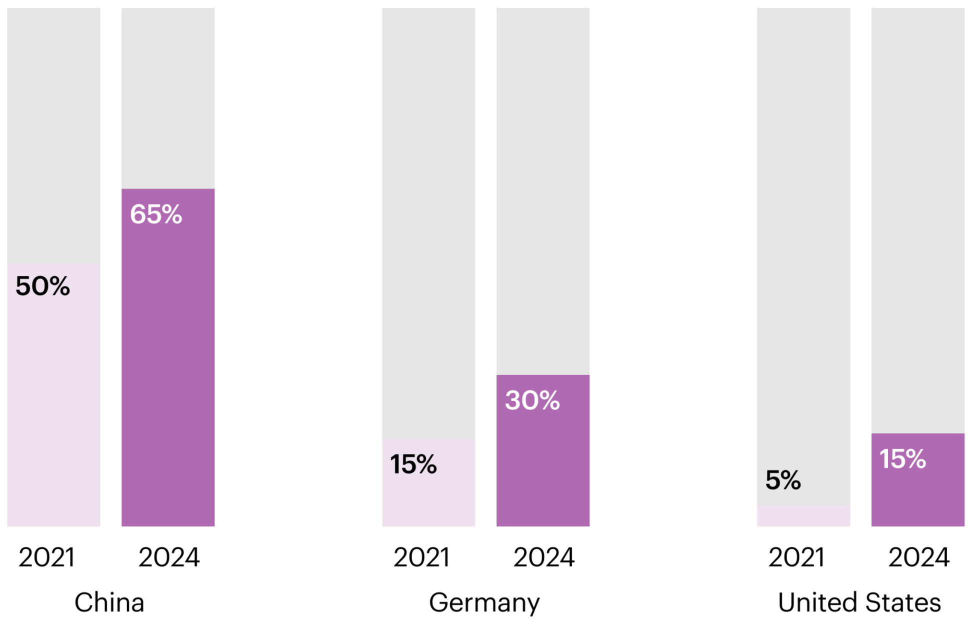
	2025e	2035	2050
NZE		4.0 tn	3.7 tn
STEPS	0.8 tn	2.2 tn	2.6 tn
CPS		1.6 tn	1.7 tn

Competitiveness

Electric cars have become more competitive



Share of battery electric car sales cheaper than conventional equivalents



Annual fuel cost for an electric car today

2–6x

lower than petrol cars

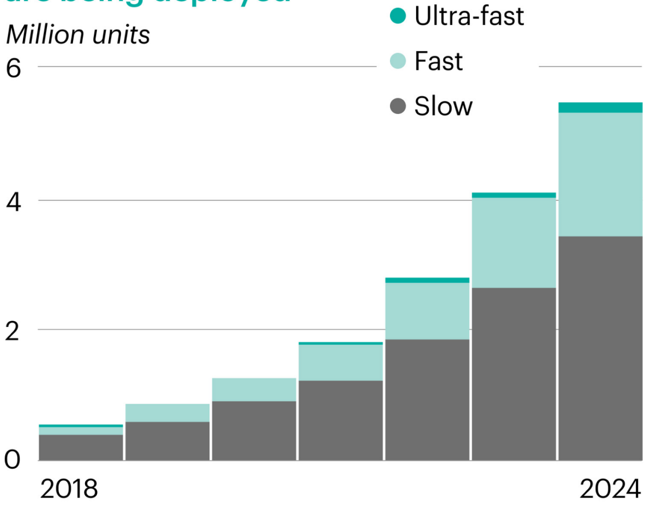
Falling battery pack prices

-30%

global average since 2020

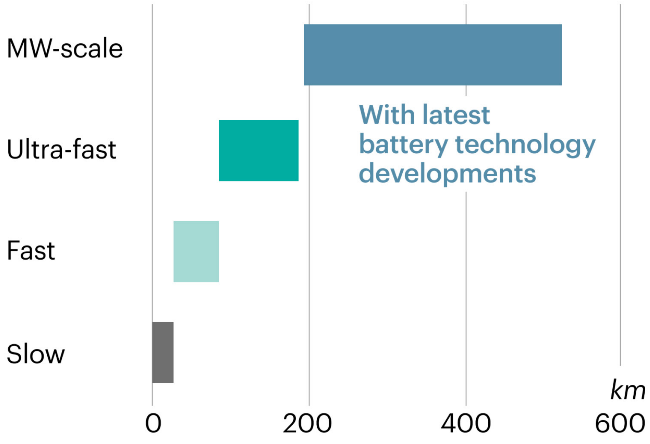
Enabling factors

More and faster public chargers are being deployed



High-power chargers and improved batteries are reducing charging time

Electric range added in 5 minutes of charging



Electric cars

Lower electric car prices mean less policy support is needed

Global sales of electric cars have grown every year over the past decade, largely driven by supportive policies such as financial incentives and fuel economy standards. In 2024, global sales of electric cars rose by more than 25% and they are estimated to have risen by around 20% in 2025. Battery technology improvements, notably higher energy density, better manufacturing efficiency and a shift toward chemistries with lower critical mineral content, have also helped reduce production costs, increased driving range and made electric cars more attractive to consumers. The average range of new battery electric cars has increased by more than 75% since 2015.

Government subsidies have recently been scaled back in several countries due to budget constraints. For instance, in Germany, where battery electric cars are still around 20% more expensive on average than internal combustion engine (ICE) cars, sales declined by more than one-quarter in 2024 when subsidies were no longer available. In some cases, subsidies were phased out because of the increasing affordability of electric cars. In the People's Republic of China (hereafter, "China"), the phase-out of national purchase subsidies at the end of 2022 had little impact on sales in 2023, partly because more than 60% of electric cars sold in China that year were cost-competitive with equivalently sized ICE cars.

Imports of affordable Chinese-made electric cars have boosted sales in some emerging markets, including Brazil, Indonesia, Mexico and Thailand. In Brazil, for example, the price gap between battery electric and ICE cars dropped from over 100% in 2023 to just 25% in 2024, as the share of Chinese imports in electric car sales rose from 60% in 2023 to more than 80% in 2024. Despite continued growth in sales, total government spending on electric cars worldwide accounted for only around 7% of total electric vehicle (EV)-related spending in 2024, down from 20% in 2017.

Industry plans, such as announcements of more affordable models, combined with continued battery cost declines and policy support in many countries, point to growing electric car sales in the coming years, which is reflected in IEA scenarios.

Priority policy actions

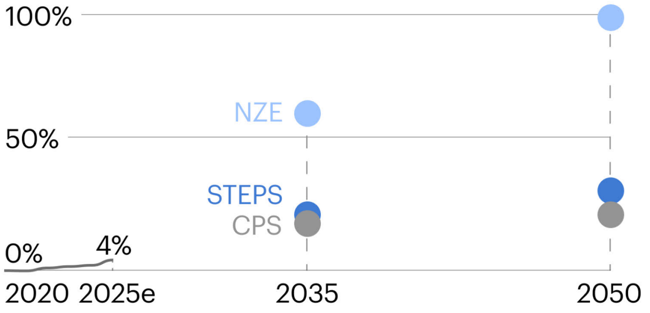
- Adapt support for electric cars as prices become more competitive.
- Expand publicly accessible EV charging infrastructure and support the installation of home chargers.
- Ensure secure, resilient and sustainable EV supply chains.

❷ ZERO-EMISSIONS TRUCKS

Electric trucks are increasingly competitive, including for long-haul

Market

Global sales share



Market status

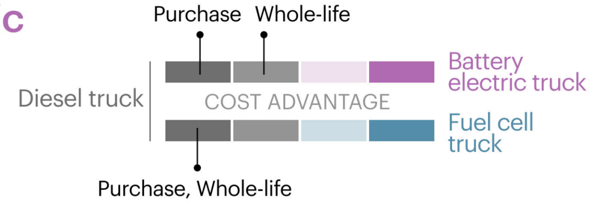
Pre-commercial	Awaiting adoption	Building momentum	Strong growth	Consolidation
	● Fuel cell	● Battery electric		

Global market size (USD)

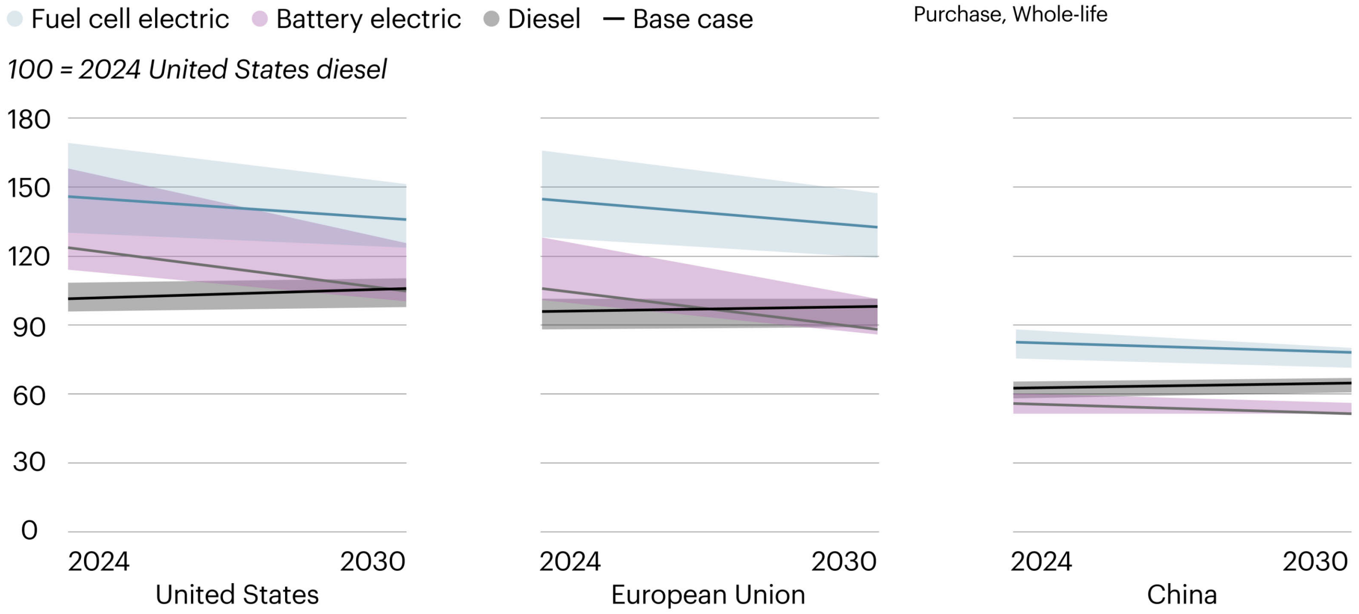
	2025e	2035	2050
NZE		490 bn	970 bn
STEPS	16 bn	200 bn	350 bn
CPS		160 bn	230 bn

Competitiveness

Competitiveness is in reach for battery electric trucks this decade across major EV markets

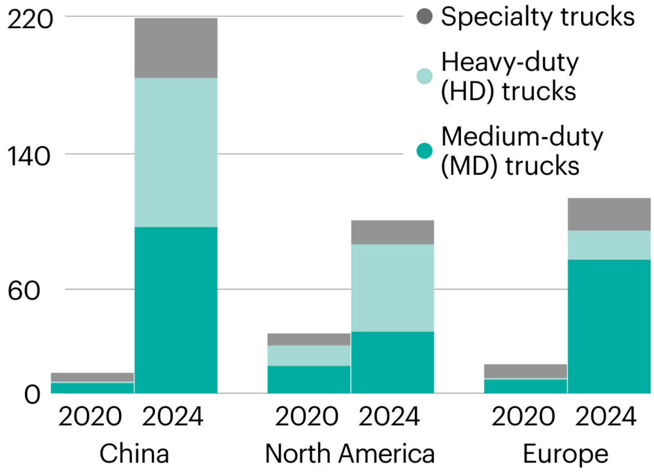


Total cost of owning heavy-duty trucks driving 500 km per day in the STEPS

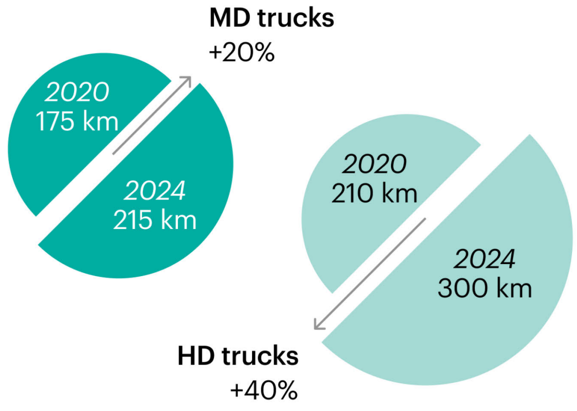


Enabling factors

The number of zero-emission truck models available continues to expand



The driving range of battery electric trucks has improved



Zero-emissions trucks

Cheaper batteries have reduced electric truck ownership costs

Interest in zero-emission trucks, including battery electric and fuel cell electric trucks, has been rising in recent years, though deployment remains limited. In 2024, battery electric truck sales surpassed 90 000 units globally, with over 4 000 fuel cell electric trucks also being sold. Government-funded pilot and demonstration projects have shown that zero-emissions trucks can fulfil driving requirements for logistics operations, but their uptake is being driven primarily by emissions regulations. Declining battery prices and improvements in energy density have made electric trucks more cost-competitive.

China currently accounts for around 80% of global zero-emissions truck sales. Domestic efforts to cut emissions from heavy industry have spurred investment in heavy-duty electric trucks, and battery swapping, which allows for quicker turnaround times, has also boosted adoption, with around one-third of electric trucks sold in the country in 2024 being battery swap capable. In China, a relatively wide gap between diesel and electricity prices (per unit of energy), combined with the higher energy efficiency of electric powertrains compared with internal combustion engines, means that battery electric trucks already offer a lower total cost of ownership (TCO) for some applications. TCO parity is expected to be achieved in more regions and applications later this decade.

The deployment of high-power chargers for heavy-duty vehicles has so far been limited, including in China. While several major markets have installed thousands of charging points in the 300-350 kW range, the world's first megawatt-scale (MW) chargers for trucks were only deployed in 2024, in the United States and Europe. In addition, although some governments have been investing in hydrogen refuelling infrastructure for over a decade, most existing stations were designed for cars and buses. As a result, many may not be suitable for refuelling fuel cell trucks, either due to insufficient hydrogen dispensing pressure or physical space constraints. However, in recent years, stations designed to serve trucks have been built in regions such as Europe and the United States.

In 2035, zero-emission truck sales reach over 20% of total global truck sales in the STEPS, around 15% in the CPS, and close to 60% in the NZE Scenario.

Priority policy actions

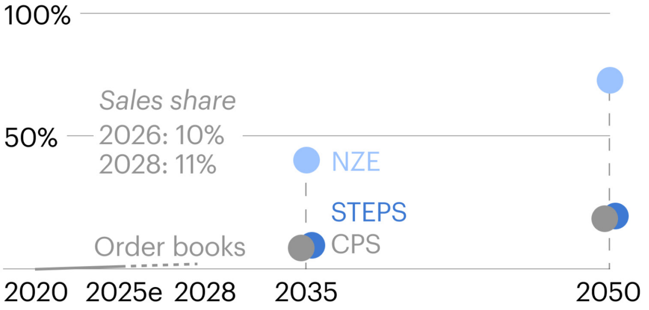
- Implement targeted fiscal policies and innovative financing models.
- Leverage national and regional air quality regulations.
- Support co-ordinated public-private deployment of high-power electric charging with grid upgrades, and roll-out of hydrogen refuelling infrastructure.

❸ AMMONIA AND METHANOL PROPULSION SHIPS

Orders for alternative propulsion ships are starting to increase

Market

Share of ammonia + methanol propulsions in the fleet



Market status

Pre-commercial	Awaiting adoption	Building momentum	Strong growth	Consolidation
Ammonia *(TRL 6)*		Methanol		

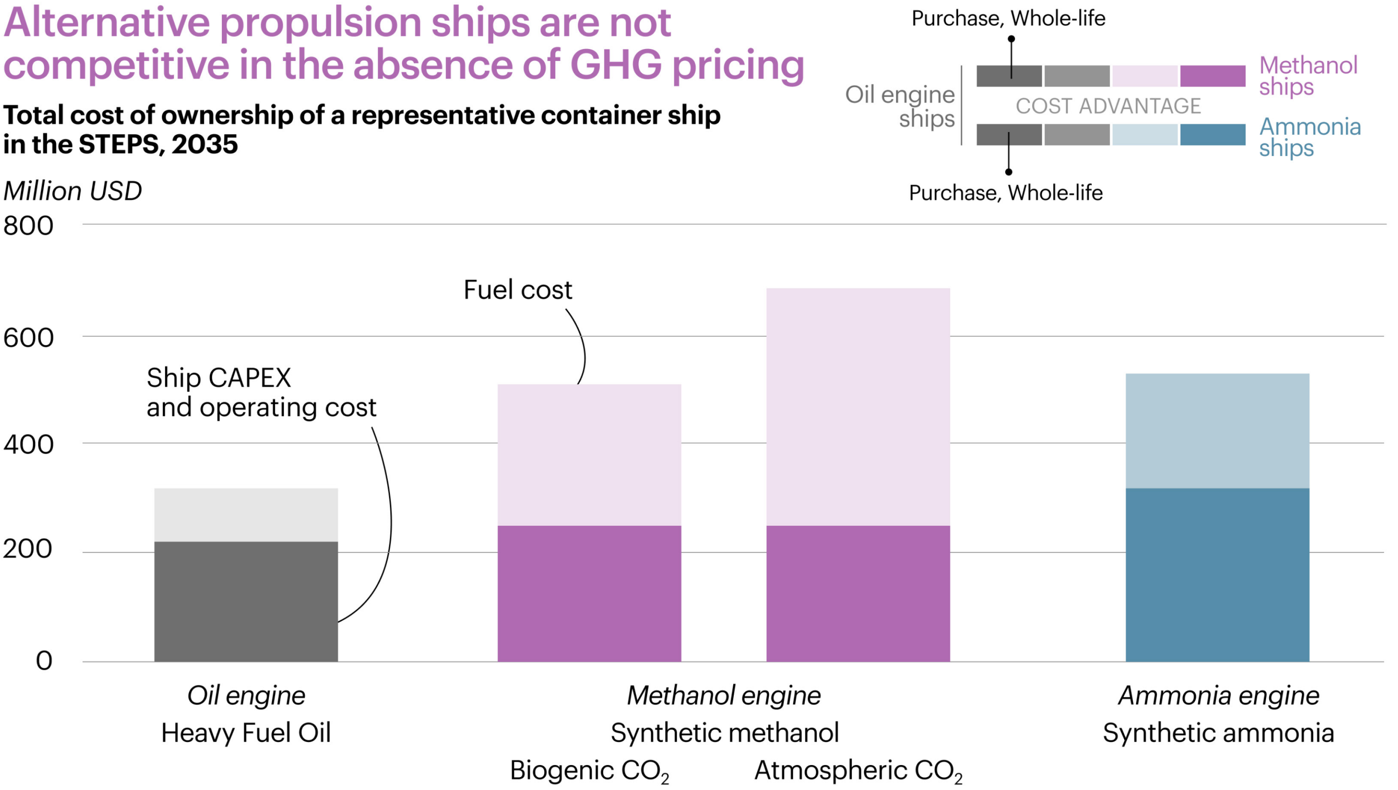
Global market size (USD)

	2025e	2035	2050
NZE		95 bn	153 bn
STEPS	6 bn	73 bn	46 bn
CPS		67 bn	44 bn

Competitiveness

Alternative propulsion ships are not competitive in the absence of GHG pricing

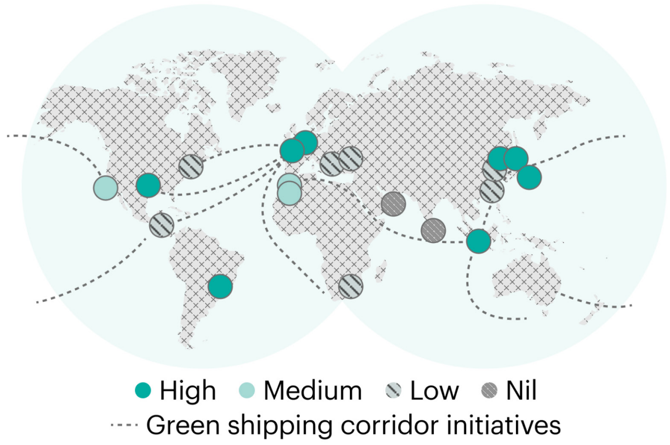
Total cost of ownership of a representative container ship in the STEPS, 2035



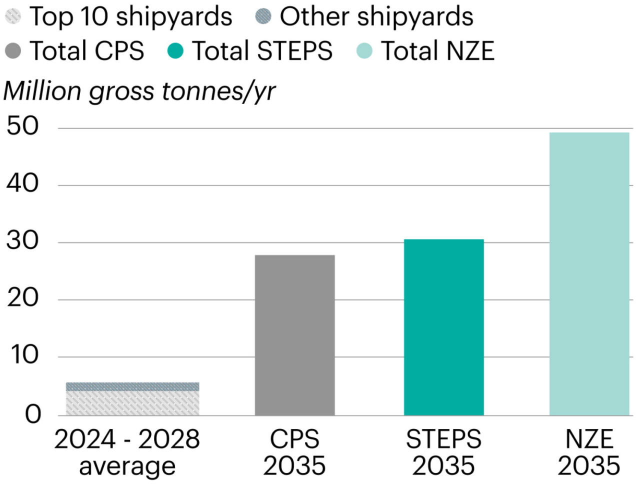
Enabling factors

Under half of the 20 major bunkering ports of the world are alternative-fuel ready

Alternative fuel readiness in 2024



The construction of alternative propulsion ships needs to increase significantly



Ammonia and methanol propulsion ships

Policy support is needed to level the playing field with conventional fuels

Large ocean-going vessels often travel for several weeks, which makes electrification difficult. Drop-in biofuels can be used in existing ships without major modifications, but their long-term potential is constrained by the availability of sustainable biomass. Synthetic fuels derived from low-emissions hydrogen are alternatives that can be further scaled up; synthetic methanol and ammonia appear the most cost-competitive on a TCO basis, but they require new propulsion systems and enhanced safety measures.

As a result of the expansion of Emission Control Areas (IMO, 2025a) and GHG emissions limits from the European Union (European Commission, 2025a) and International Maritime Organization (IMO, 2025b), conventional ships represent only around a third of planned deliveries for 2028 (by gross tonnage); liquefied natural gas-propulsion ships make up more than half. Methanol propulsion ships make up some 10% of orders, but these have levelled off for deliveries for 2026 and 2028, with shipowners noting difficulties in securing long-term offtake agreements with fuel suppliers (WSJ, 2024). Development of ammonia engines for large vessels has accelerated, with leading engine manufacturers reporting successful pre-commercial trials, some at full load. At least 30 ammonia-propulsion medium to large vessels are expected to be delivered from 2026 (United Nations Statistics Division, 2025). The TCO of methanol- or ammonia-powered ships is today up to twice as high as that of oil-fuelled vessels, but this cost gap is expected to narrow as fuel production scales up and energy efficiency improves. Fuel costs per unit of cargo are typically small compared to freight rates, and freight itself is often just a minor component of end-consumer prices, but competition in the shipping industry is intense. Some cargo owners are willing to pay a green premium, but not yet at the levels required for alternative fuels (Boston Consulting Group, 2025).

In 2035, alternative propulsion ships reach more than one-third of total sales gross tonnage in the STEPS and CPS, and 80% in the NZE Scenario.

Priority policy actions

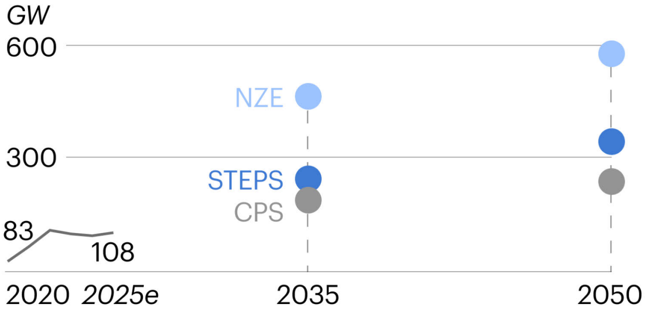
- Continue to foster international collaboration and ensure timely implementation of internationally agreed pathways.
- Provide financial support to shipyards producing alternative propulsion ships and encourage knowledge-sharing on design and manufacturing.
- Accelerate development of international green shipping corridors and investment in alternative fuel production and bunkering at key ports.

④ HEAT PUMPS

Heat pumps are gaining ground; lower electricity prices would push them even further

Market

Global heat pump sales



Market status

Pre-commercial
Awaiting adoption
Building momentum
Strong growth ●
Consolidation

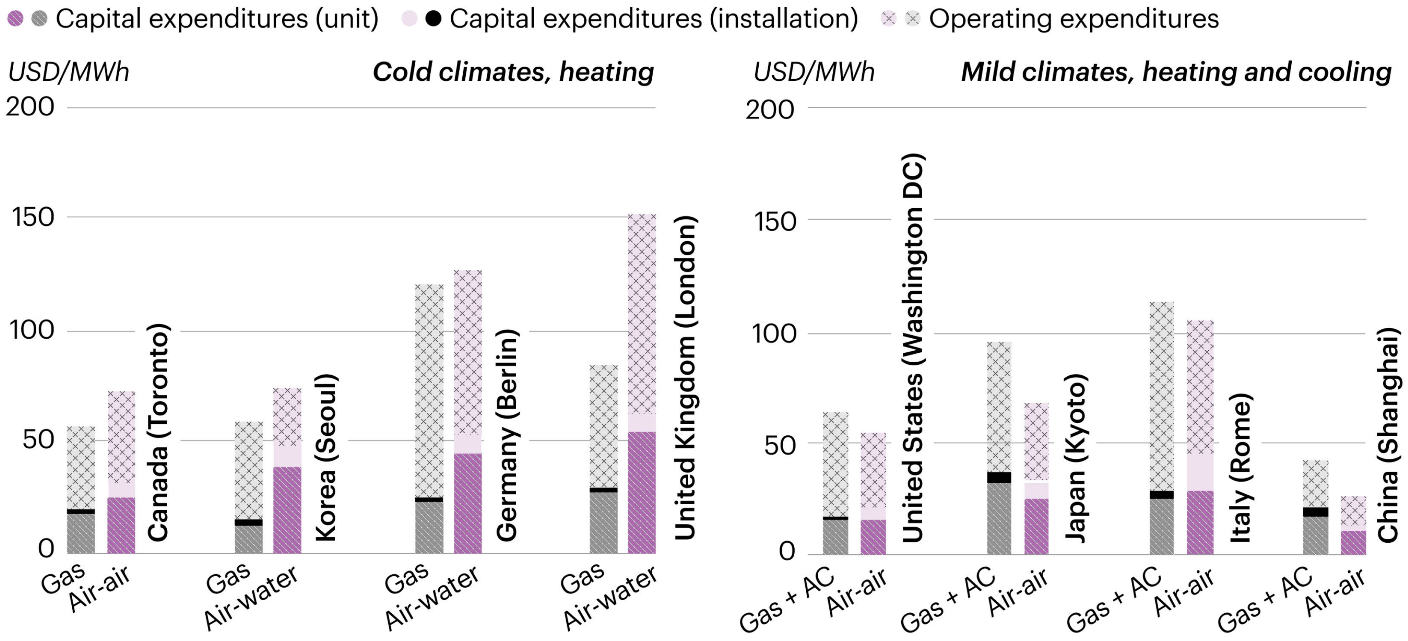
Global market size (USD)

	2025e	2035	2050
NZE		225 bn	260 bn
STEPS	50 bn	120 bn	165 bn
CPS		95 bn	115 bn

Competitiveness

Heat pumps are most competitive in mixed-climate regions

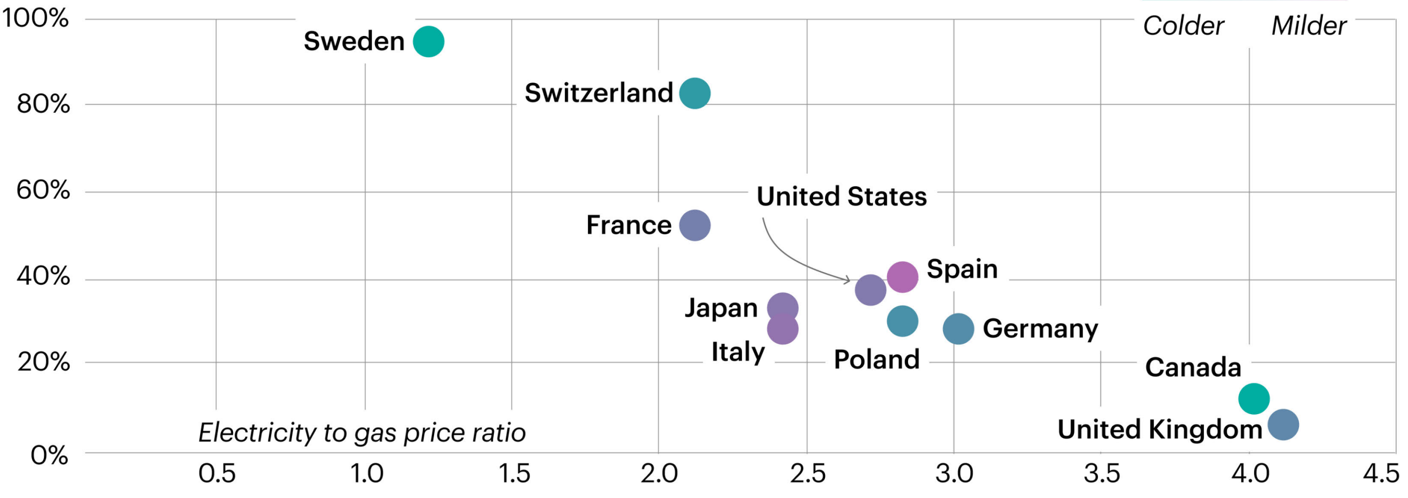
Levelised cost of heating, 2024



Enabling factors

Markets with lower electricity prices see increased heat pump adoption

Heat pump market share, 2023



Buildings heat pumps

Heat pumps return to growth as sales increase in all scenarios

Global sales of heat pumps for heating slowed in 2023 and 2024, after a record surge in 2022. This dip came against the backdrop of high interest rates, inflation, higher energy prices, policy uncertainty and a weaker construction sector. China remains the world's largest market, accounting for one in three installations in 2024, followed by the United States and the European Union.

Despite this recent slowdown, the longer-term view is more encouraging: global sales have more than doubled over the past decade. Heat pumps are increasingly cost-competitive in countries where the ratio of electricity to fossil fuel prices is favourable, or where milder winters and high cooling needs make air-to-air models appealing thanks to their potential for year-round operation.

However, cost remains an important barrier. In many regions, electricity prices remain higher than natural gas, weakening incentives to switch. In the United Kingdom, electricity prices are roughly four times higher than natural gas prices; in Germany, they are about three times higher. Even in Canada and the United States, where electricity is relatively cheap, low gas prices mean that the cost gap remains wide. This is often due to taxes and levies that disproportionately affect electricity. In addition, while lifetime costs are often lower, upfront costs can be two to three times higher than for fossil fuel alternatives, which acts as a barrier to uptake, especially for low-income households. Sudden changes to subsidies or regulations can disrupt supply chains and erode consumer confidence, as seen recently in Italy, Germany and parts of the United States.

In the STEPS, annual heat pump sales double by 2035 compared to today. In the CPS, sales increase by 85%, driven by improvements in affordability. In the NZE Scenario, sales are almost double those in the STEPS by 2035, unlocking the full potential for heat pump adoption across all markets.

Priority policy actions

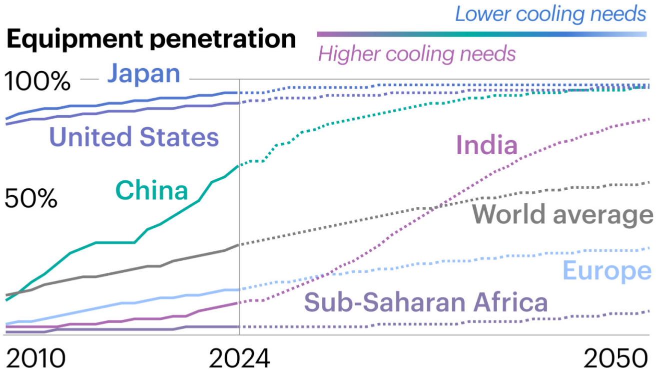
- Adjust energy taxes and levies while encouraging flexible demand, including via targeted R&D support.
- Avoid abrupt changes to incentives or regulations.
- Expand fast-track reskilling programmes and integrate heat pump training into vocational education.
- Establish one-stop-shops for advice and installation, streamline permitting processes and encourage innovative business models (e.g. leasing).

5 AIR CONDITIONING SYSTEMS

Increasing temperatures are boosting demand for cooling

Market

Equipment penetration



Market status

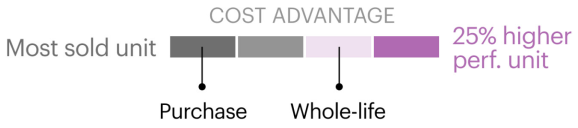
Pre-commercial | Awaiting adoption | Building momentum | **Strong growth** ● | Consolidation

Global market size (USD)

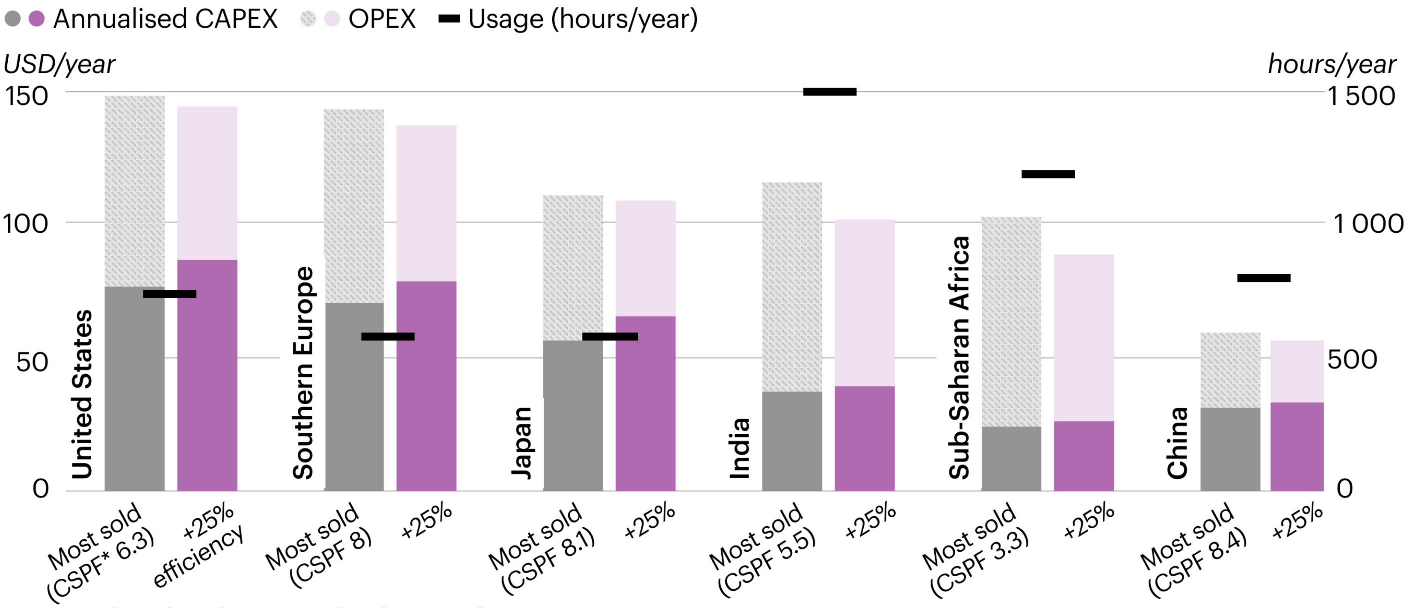
	2024	2035	2050
	120 bn		
NZE		165 bn	230 bn
STEPS		150 bn	200 bn
CPS		140 bn	180 bn

Competitiveness

Higher performance models pay back over their life cycle



Yearly cost of an air conditioning system for selected countries, 2024

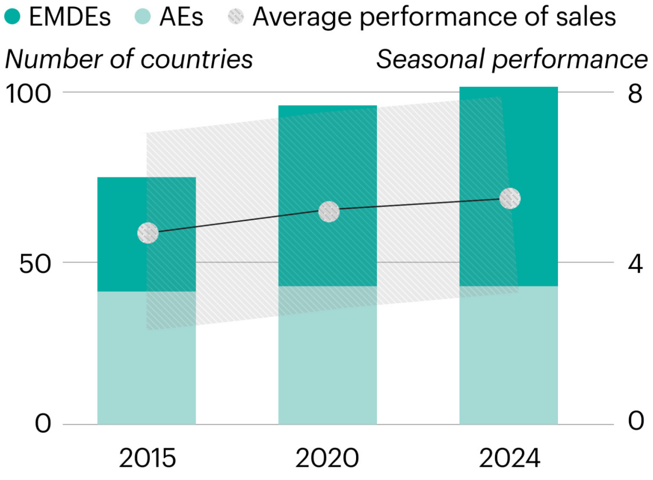


*(CSPF) Cooling seasonal performance factor

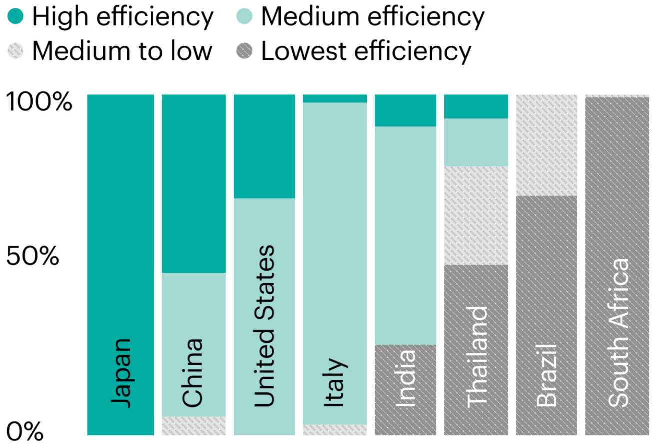
Enabling factors

MEPS are key for energy savings, impacting domestic and trade markets

Number of countries with MEPS



Shipments of air conditioning systems from China, 2023



Air conditioning systems

Policy is key to enable access to affordable, high-performance units

Rising temperatures and improving living standards are driving a surge in global demand for air conditioning (AC) – now one of the fastest-growing uses of electricity in buildings and the dominant means of indoor cooling. Since 2000, the number of households owning AC has nearly tripled worldwide, rising from less than 15% to about 40%, pushing up electricity use for space cooling by more than two-and-a-half times. Penetration is highest in wealthier, temperate regions – reaching around 90% in the United States and Japan, and over 70% in China. Uptake remains lower in hotter, more humid regions, largely due to affordability constraints – reaching more than 30% in Brazil, about 20% in India and less than 10% across much of Africa.

Improving AC efficiency is critical to limiting the impact of rising demand on electricity use, peak loads and refrigerant-related emissions – a major contributor to global warming. More than 100 countries now have minimum energy performance standards (MEPS) in place for AC, covering around 90% of global cooling energy demand, up from about 75% in 2015. These standards have steadily raised average efficiency, but major gaps persist. The most efficient models sold today are up to four times more efficient than the least efficient, and about three times as efficient as the global average. However, high-efficiency units frequently carry a capital cost premium due to added features such as quieter operation, improved design and smart functionality.

In the STEPS, AC efficiency improves gradually, with around 2 billion units sold between 2025 and 2035. In the CPS, efficiency improvements are more muted. In the NZE Scenario, all units sold by 2035 are assumed to match today's best available models.

Priority policy actions

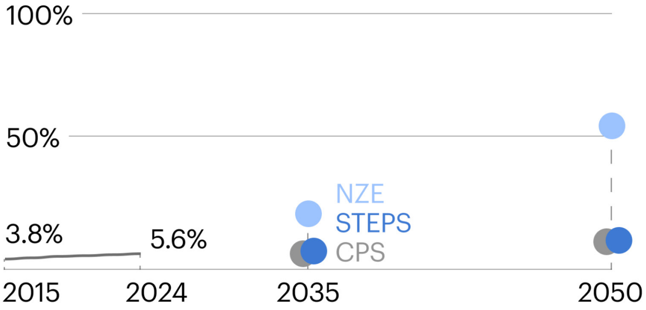
- Expand and tighten MEPS to improve access to high-efficiency units and accelerate the phase-out of inefficient models, such as fixed-speed models.
- Encourage innovative business models (e.g. cooling-as-a-service) and support R&D (e.g. on solid-state cooling or desiccant-based systems).
- Prioritise passive cooling solutions and introduce targeted financial incentives for high-efficiency units, especially for low-income households in humid and temperate climates.
- Align national and local cooling strategies with building energy codes, design regulations and broader urban and energy planning frameworks.

❻ ZERO-CARBON-READY BUILDING ENVELOPES

Stringent codes and better disclosure are the missing catalysts for zero-carbon-ready market growth

Market

Share of built floor area



Market status

Pre-commercial · Awaiting adoption · **Building momentum ●** · Strong growth · Consolidation

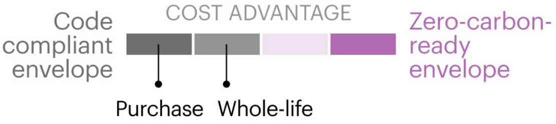
Global market size (USD)

	2024	2035	2050
NZE		5.2 tn	4.7 tn
STEPS	0.7 tn	0.8 tn	0.7 tn
CPS		0.6 tn	0.5 tn

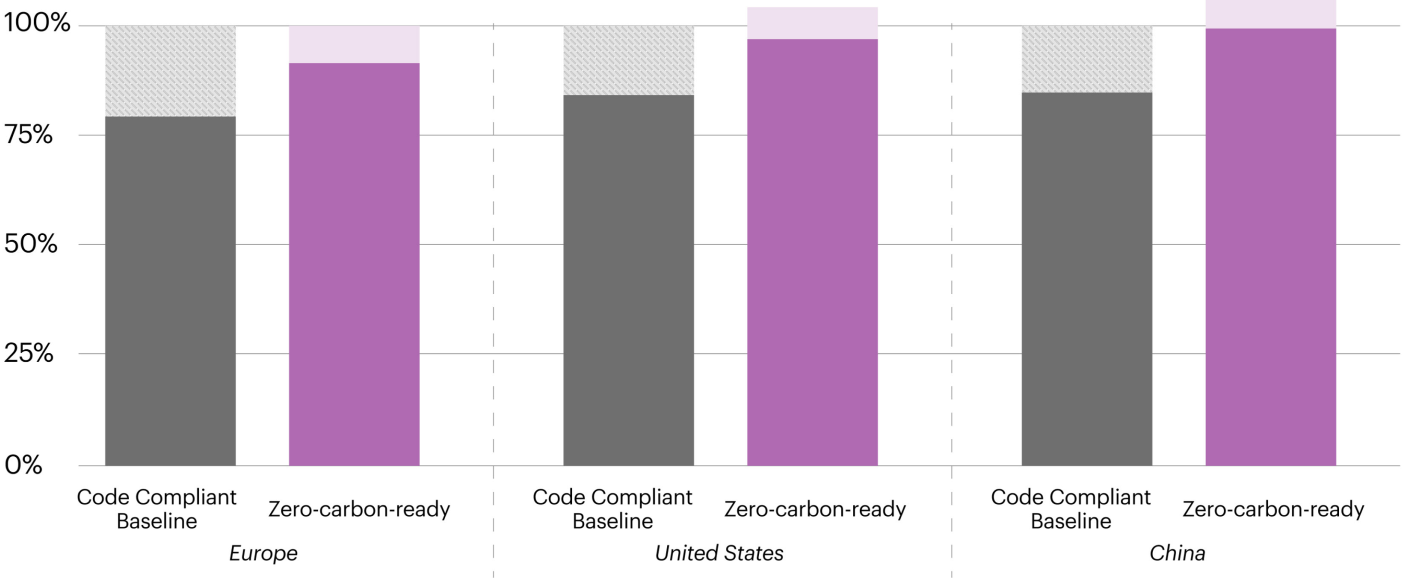
Competitiveness

Long payback, but high value proposition

Total construction and energy expenditures for buildings by selected region in the STEPS over 50 years, with a 3% discount rate



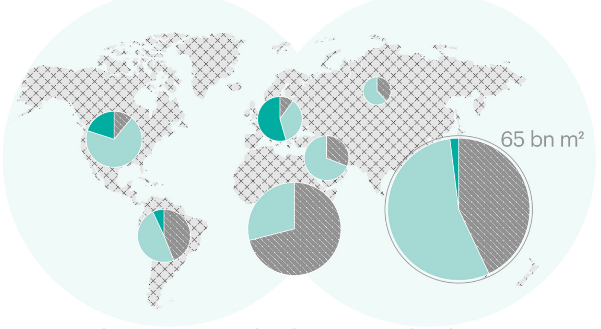
▨ ● Heating and cooling bills ● ● Construction costs



Enabling factors

Building energy codes are lacking or not stringent enough in some regions

Circle sizes proportional to new floor area to be built to 2050



● ZCR *Subject to very high EE standards*
● Compliant *Subject to some EE standards*
▨ Non-compliant *Not subject to any known EE standards*

Established technologies, with context-specific innovation options

Widely adopted (Technology Readiness Level 9C)
Mechanical ventilation ⑨ Natural ventilation ⑨
External shading ⑨ Mineral/foam insulation ⑨

Building momentum (TRL 9B)
Reflective façade ⑨ Green roof ⑨

Awaiting adoption (TRL 9A)
Cool roof ⑨ Vacuum insulated panel ⑨
Double skin facade ⑨

Demonstration (TRL 7-8)
Thermochromic fenestration ⑧ Aerogel insulation ⑧
Dynamic building envelope ⑧
Building integrated (B.I.) heat and moisture exchange panels ⑦
Funicular floor system ⑦ B.I. phase change materials ⑦

Zero-carbon-ready building envelopes

Zero-carbon-ready buildings are still rare, remaining costly and undervalued

Driven primarily by energy efficiency regulations focused on reducing heating demand, several countries and regions – including Canada, the European Union, the United Kingdom and parts of the United States – have made progress in aligning building codes with principles for zero-carbon-ready buildings (ZCRBs) (IEA, 2022a). However, less than 10% of the existing building stock worldwide meets these standards; about 100 countries – down from more than 130 in 2016 – still lack mandatory building energy codes altogether. As a result, many new buildings are still constructed with poor performance envelopes that lock in high energy use, reduced occupant comfort and limited climate resilience for decades to come.

Around half of the global floor area that will be in place in 2050 has yet to be built, with a large share expected in regions with high cooling demand. At the same time, approximately 75% of today's building stock will still be in use, meaning that renovation would be required to reach ZCRB status. The construction sector is one of the world's largest employers. Currently, ZCRB envelopes cost about 15-20% more than non-code compliant building envelopes in cold climates such as North America, and up to 35% more in mixed and warm climates like India and Brazil. While investment decisions often focus on payback periods, these calculations typically span the long lifetime of buildings and do not fully reflect the benefits of high-performance envelopes, including improved indoor air quality, greater resilience to extreme temperatures and enhanced property value. The limited availability of transparent cost and performance data for ZCRB projects remains a major barrier to wider uptake.

Priority policy actions

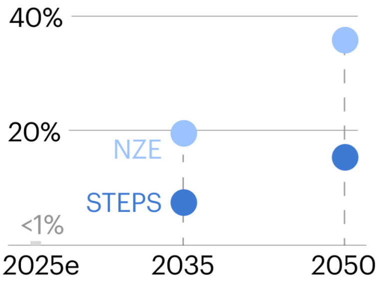
- Incorporate principles of energy efficiency, climate resilience, and whole-life carbon performance in buildings regulation, especially in emerging markets and developing economies (EMDEs).
- Reinforce financial support and simplify building energy renovation procedures, focusing on improving access for low-income households and less-performing buildings.
- Support training of regulators, architects, equipment manufacturers and construction workers.
- Promote robust techno-economic assessments of ZCRB envelopes and ensure clear communication of results to decision-makers and the public.

7 INDUSTRIAL HEAT PUMPS

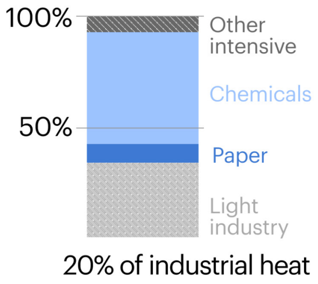
Commercial projects are now operating worldwide across different sectors

Market

Share of heat supplied by HPs in light industry



HP potential per industry



Market status

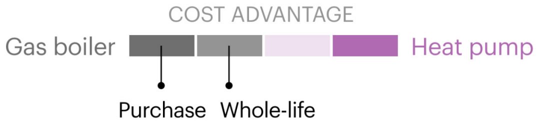
Pre-commercial | Awaiting adoption | **Building momentum** ● | Strong growth | Consolidation

Global market size (USD)

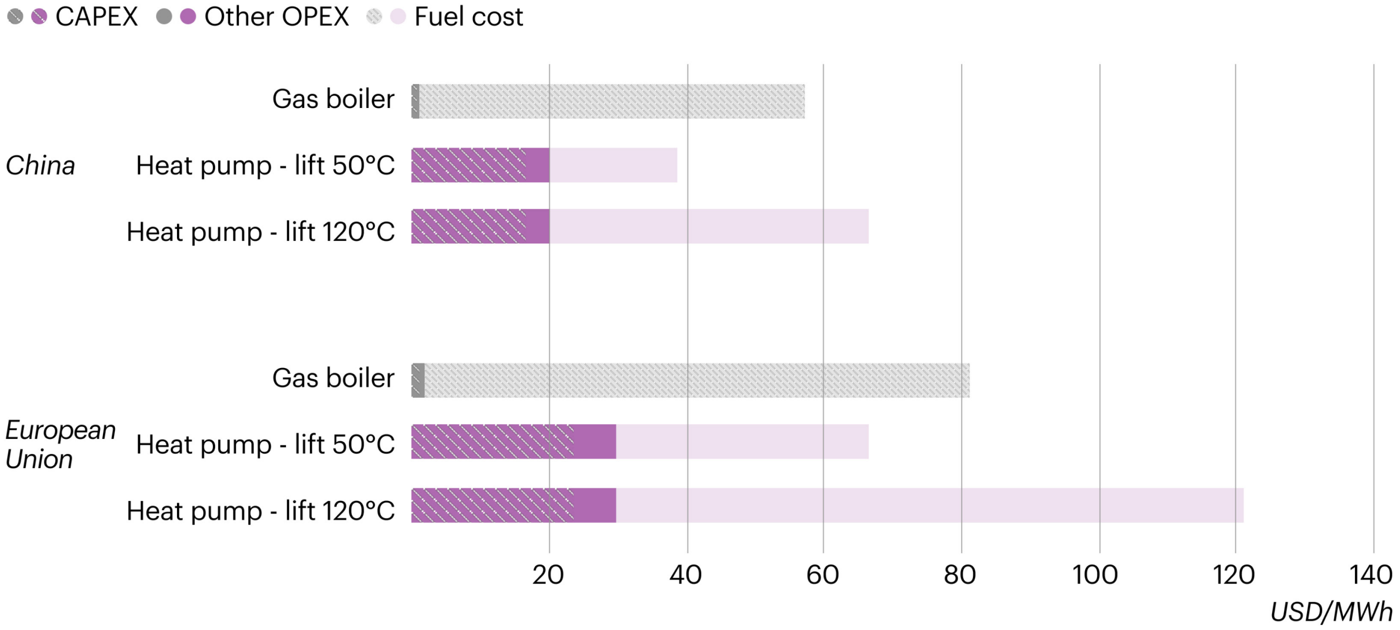
	2025e	2035	2050
NZE		19 bn	25 bn
STEPS	<1 bn	8 bn	6 bn
CPS		<1 bn	<1 bn

Competitiveness

Industrial heat pumps have a high CAPEX, but can have very high efficiency



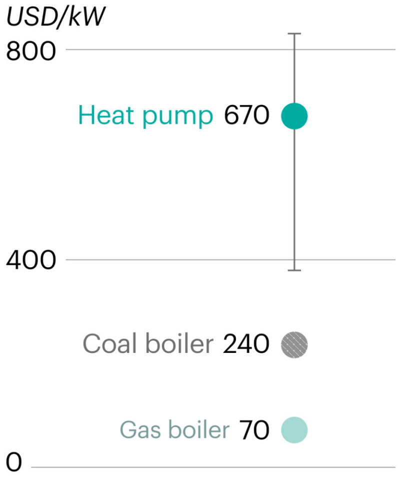
Levelised cost of heating, 2024



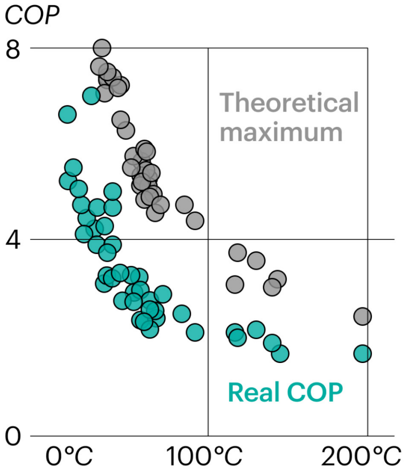
Enabling factors

Electricity affordability and technology improvements can help overcome initial investment

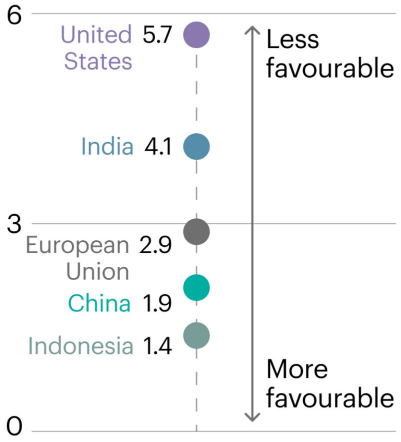
Installation cost, 2024



Efficiency and temperature lift



Electricity to gas price ratio, 2024



Industrial heat pumps

Efficiency advantages enable electrification of industrial heat

Heat pumps are emerging as an effective solution to improve resilience and reduce emissions from low-temperature industrial heat. Electricity currently provides less than 5% of global industrial heat demand, although electricity consumption grew by around 2% per year between 2010 and 2020 and is now accelerating, growing 4% since 2020. A major contributor to this increase is the growing deployment of high-efficiency heat pumps. Their efficiency is highest when providing heat below 100ºC, though systems that integrate waste heat can achieve temperatures above 200°C while maintaining strong performance (HPT TCP, 2023). Heat pumps could now meet a substantial share of industry heating needs cost-effectively: up to 45% in light industry, and around 20% across all industrial sectors, depending on the availability of waste heat.

On average, industrial heat pumps cost around three times more than coal boilers, and up to ten times more than natural gas-fired alternatives. The potential need to expand electricity grid connections can add to upfront costs. This remains a major hurdle to wider adoption, particularly for smaller firms and those in EMDEs. When running costs are also considered, industrial heat pumps can be competitive with natural gas boilers under certain circumstances; the breakeven point is highly dependent on the electricity to gas price ratio.

Higher-efficiency applications can have a narrower cost gap, as can hybrid approaches, such as heat pumps with gas backup or thermal energy storage. These combinations can reduce average electricity costs, lower utility bills and improve energy security, strengthening the overall business case for heat pumps.

Installed heating capacity of industrial heat pumps rises in the STEPS to 80 GWth by 2035 (around 8% of thermal needs in light industries). It sees a more muted trend in the CPS and reaches nearly triple this level in the NZE Scenario.

Priority policy actions

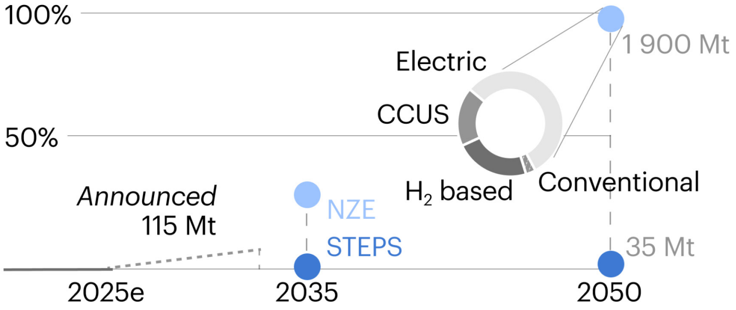
- Adjust energy taxes and levies as well as electricity tariffs (e.g. time-of-use pricing) and support flexible demand.
- Reinforce electricity grids, reduce grid fees, and prioritise grid connections for industrial loads that can provide flexible demand to stabilise power systems.
- Scale up financial support for first adopters of electrified industrial heat, particularly if paired with optimised process integration.
- Promote standardised system designs (including effective communication of best practices across sectors) and expand training to build a skilled workforce.

8 NEAR-ZERO EMISSIONS STEEL

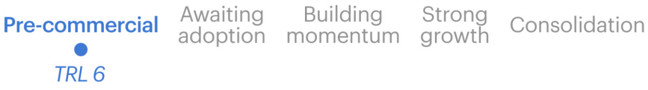
Announcements are promising, but investment is lacking

Market

Global share of near-zero emissions steel production



Market status

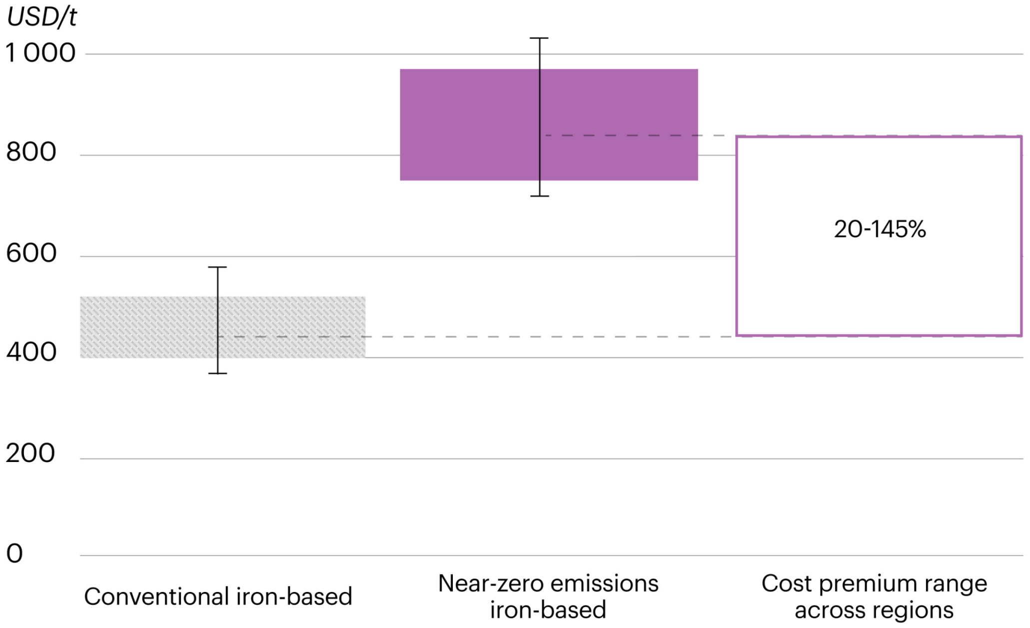


Global market size (USD)

	2025e	2035	2050
NZE		380 bn	1 350 bn
STEPS	1 bn	15 bn	20 bn
CPS		5 bn	5 bn

Competitiveness

Cost premiums for initial projects are significant, but the impact on end products is more manageable



Impact of cost pass-through on final product price

Car

+1-2%

Solar PV

+1-7%

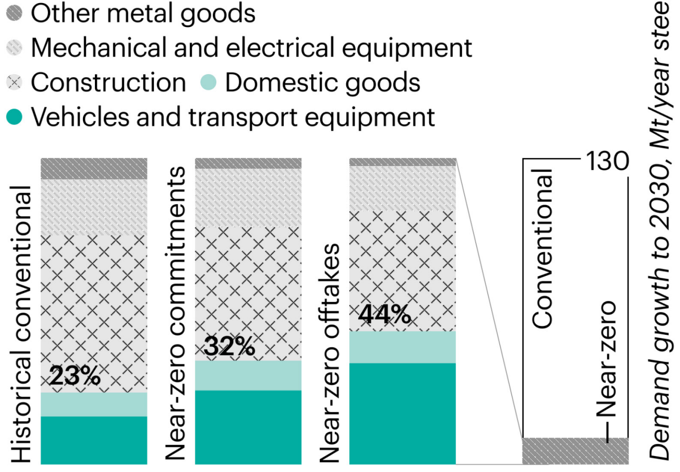
Wind turbine

+1-9%

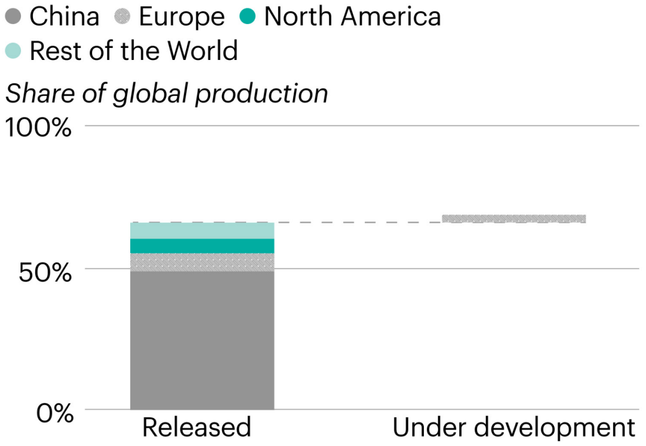
Enabling factors

Demand is driven by consumer-facing markets and use of voluntary labels

Share of steel demand



Potential coverage of voluntary labels for near-zero and low-emissions steel



Near-zero emissions steel

Overcoming cost premiums has been harder than anticipated

Commercial-scale technologies for near-zero emissions steel are starting to emerge, as well as earlier-stage technologies like iron ore electrolysis. The global project pipeline grew rapidly from 2020 to 2023, led mainly by iron-based projects using hydrogen. Despite this, by end-2025, planned capacity was just 115 Mt/year – around 5% of today's steel production and 20% of the deployment needs by 2035 in the NZE Scenario. Much of the planned capacity is still in early development, or is intended to start with natural gas and lacks firm plans to transition to low-emissions hydrogen – less than 10% is fully near-zero emissions. Only 6 Mt (5%) of fully near-zero emissions capacity has reached final investment decision (FID), while over 15 Mt of total planned capacity has been postponed or cancelled since 2024, cutting expected capacity in 2027 by almost one-fifth.

Near-zero emissions steel is more expensive than conventional. This is especially true for iron-based steel, where levelised costs of production in 2035 are expected to be about 20-145% higher (USD 125-600 per tonne of crude steel) in the STEPS, in the absence of targeted policy support or significant scale-up. Rising energy prices, especially in the European Union (30% higher since 2020), have increased costs. Together with tighter fiscal conditions, global excess capacity and lower-than-hoped buyer willingness to pay a premium, this has stalled global progress.

Yet the race continues to launch the first commercial-scale plant, with projects in China, Finland, Namibia, Spain and Sweden at or near FID (IEA, 2025d). These are backed by subsidies and early offtake agreements from buyers willing to pay a premium. So far, offtakes total over 5 Mt, worth almost USD 5 billion, but the potential market is larger; in the NZE Scenario, it reaches USD 380 billion by 2035, 30% of the total steel market. Consumer-facing markets are key for demand creation, making up almost half of publicly announced offtakes for near-zero emissions steel, despite accounting for less than one-quarter of all steel demand.

Priority policy actions

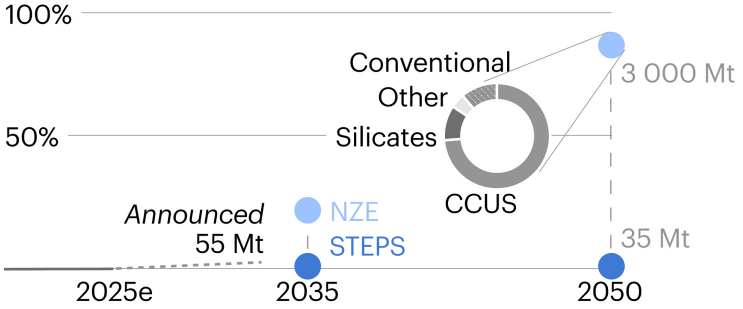
- Adopt interoperable standards for near-zero and low-emissions steel.
- Reinforce and expand near-term supply-side support policies (e.g. direct subsidies, contracts for difference) (IEA, 2025a).
- Stimulate private and public demand for near-zero emissions steel (e.g. public procurement, buyer subsidies/incentives, embodied carbon limits, labelling).
- Consider strategic partnerships with iron ore-rich regions that have access to low-cost renewable energy (see Chapter 7).
- Invest in infrastructure for electricity grids and low-emissions hydrogen.

⑨ NEAR-ZERO EMISSIONS CEMENT

Market growth remains sluggish

Market

Global share of near-zero emissions cement production



Market status

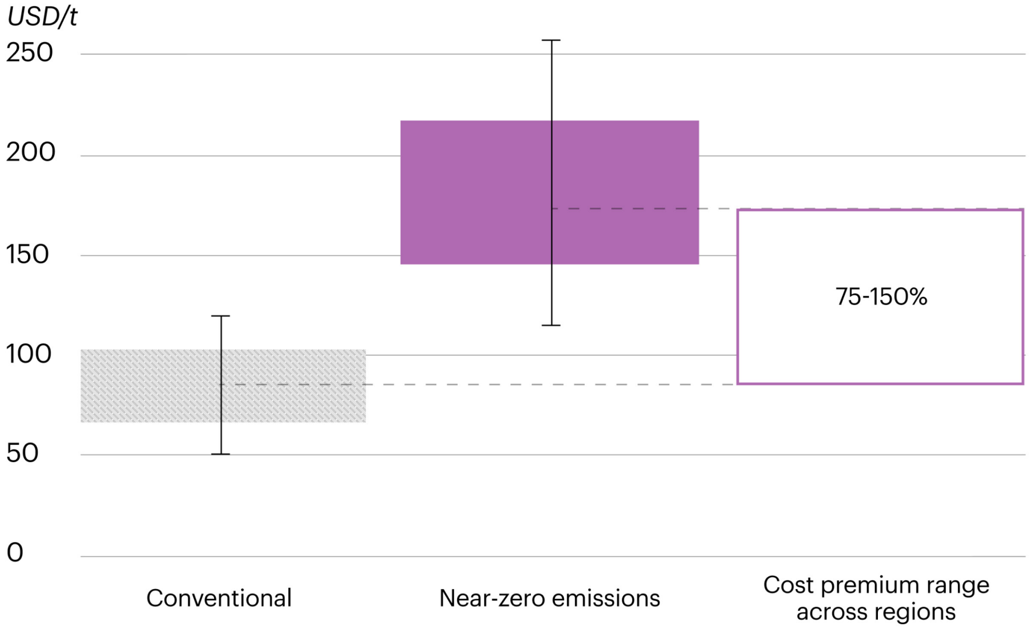
Pre-commercial ● *TRL 7* | Awaiting adoption | Building momentum | Strong growth | Consolidation

Global market size (USD)

2025e		2035	2050
<1 bn	NZE	**70 bn**	**430 bn**
	STEPS	**1 bn**	**3 bn**
	CPS	**<1 bn**	**<1 bn**

Competitiveness

Cost premiums for initial projects are significant, but the impact on end products is more manageable



Impact of cost pass-through on final product price

House

+1-2%

Railway

+1-2%

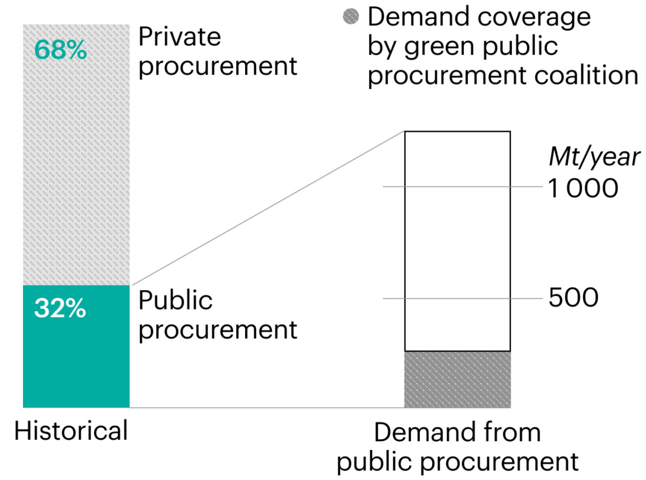
Road

+2-5%

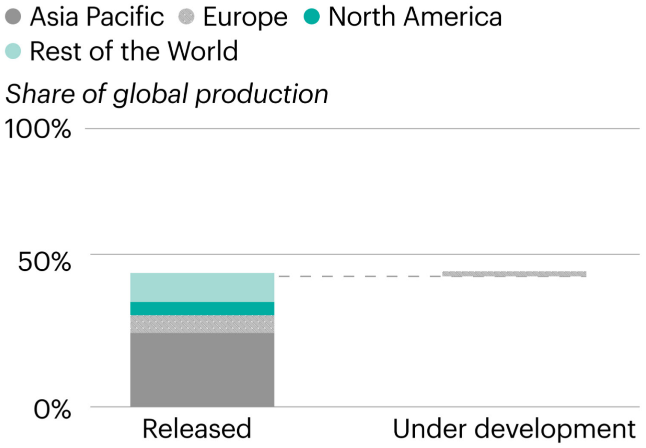
Enabling factors

Public procurement commitments and use of voluntary labels create demand pull

Share of cement demand



Potential coverage of voluntary labels for near-zero and low-emissions cement



Near-zero emissions cement

Willingness to pay cost premiums remains limited

While technologies to reduce emissions from cement production are advancing, progress has been slow. The most advanced near-zero emissions options involve CO_2 capture, while conventional cement made without limestone is a promising earlier-stage option. Since 2020, project announcements have increased sevenfold, but few have reached FID. All announced projects are in advanced economies, though the bulk of projected demand is in EMDEs – posing a major hurdle. Many announcements also plan for only partial CO_2 capture or lack defined storage solutions. Total announced capacity stands at about 55 Mt (with just 20 Mt at an advanced stage) – equivalent to 1% of today's conventional capacity.

A milestone was reached in 2025 when the first large-scale cement plant with carbon capture began operating in Norway, capturing around half of its emissions and with its cement already sold for the year (Buli, 2025). Limited near-zero emissions cement has been sold, but advanced purchase agreements secured 0.1 Mt of silicate-based cement in 2025, at around USD 10 million in value.

Near-zero emissions cement remains significantly more expensive, and in 2035 is still 75-150% more costly (USD 50-175 per tonne) in the STEPS, in the absence of policy support and significant scale-up. Low- or no-clinker alternatives that can reduce emissions with little or no cost premium are emerging, such as those using calcined clay. Of the 15 full-scale calcined clay plants in operation today, eight are in EMDEs. Limestone filler or activated slag can also play a role, though some of these pathways may be constrained by raw material availability and technical limitations to the extent of clinker substitution.

Announced near-zero emissions capacity today is only 10% of the level required in the NZE Scenario in 2035, a gap of roughly 640 Mt. In this scenario, the market value reaches USD 70 billion in 2035, around 20% of the total cement market. Deployment is much lower in the STEPS and CPS, given limited policy support.

Priority policy actions

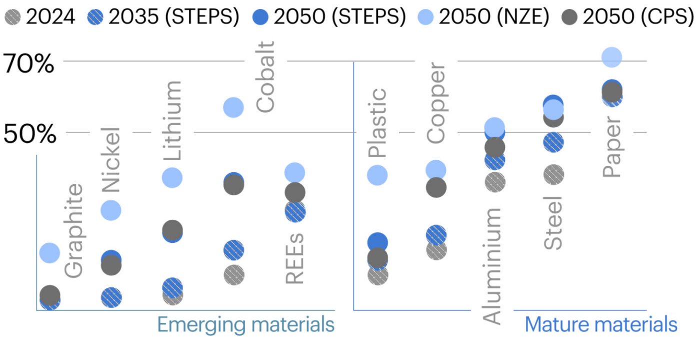
- Adopt interoperable standards for near-zero and low-emissions cement.
- Reinforce and expand near-term supply-side support policies (e.g. direct subsidies, retrofit-ready requirements, contracts for difference) (IEA, 2025a).
- Boost public and private demand for near-zero emissions cement (e.g. through public procurement, embodied carbon limits, novel cement in building codes).
- Accelerate the development of CO_2 transport and storage infrastructure.
- Increase funding for low- and no-clinker cements, as well as recycling and material efficiency innovations.

⑩ RECYCLING

Mature materials drive recycling today; emerging materials are progressing but need time to scale

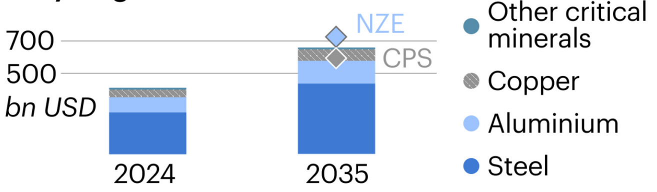
Market

Share of demand met by recycling



Market status

Recycling metal market size STEPS

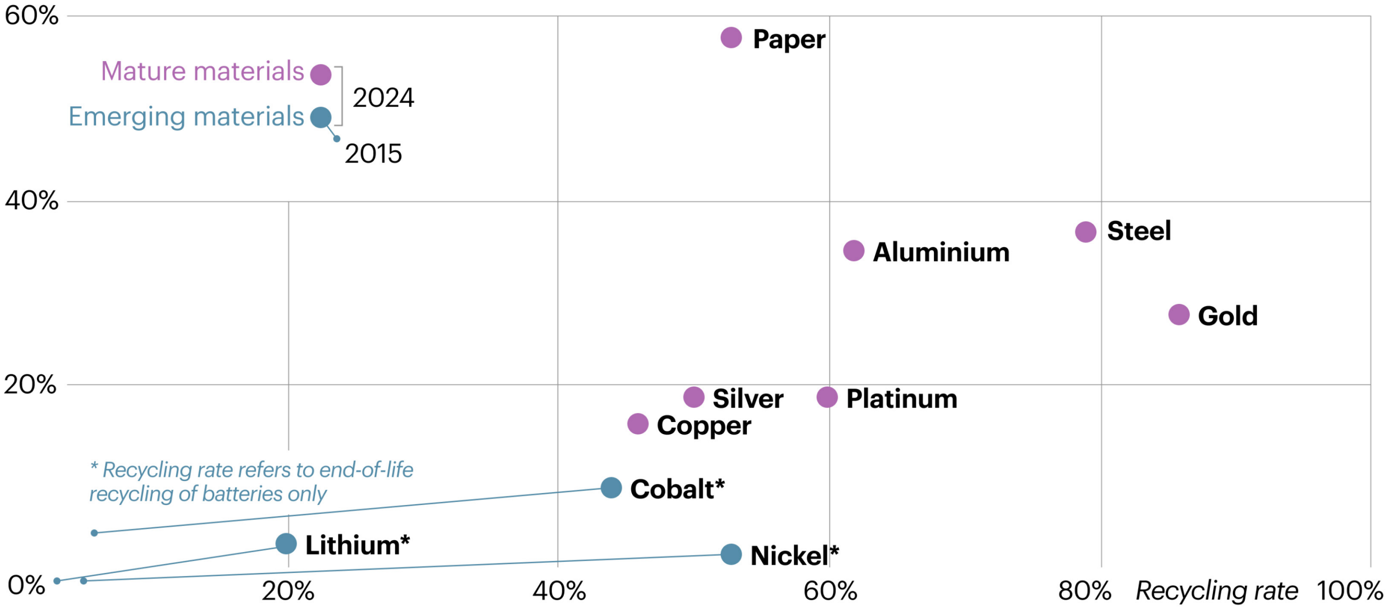


Competitiveness

Recycling of emerging materials expands, but market impact stays low

Recycling share and recycling rate, 2015-2024

Share of demand met by recycling

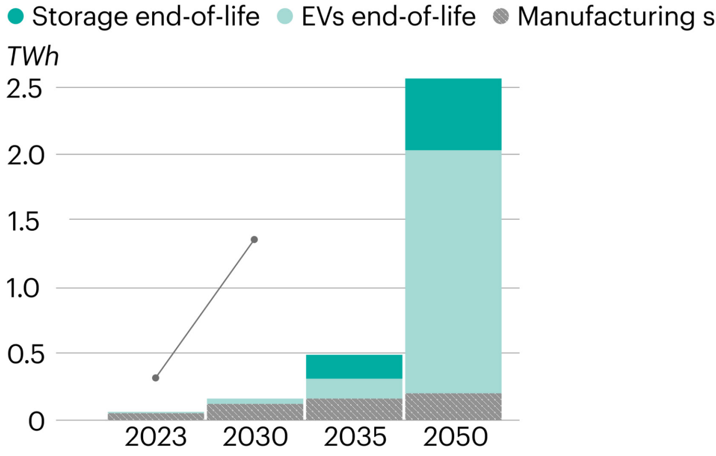


** Recycling rate refers to end-of-life recycling of batteries only*

Enabling factors

Innovation in battery recycling can increase recovery and lower cost, but feedstocks limit growth

Maximum available battery recycling feedstock and recycling capacity in China in the STEPS



Technologies to reduce costs, Technology Readiness Level 2020-2024

Automatic battery separation ③ → ④

Direct battery recycling ③ → ⑤

Technologies to improve recovery, TRL 2020-2024

Battery passport ② → ⑥

Biological metal reclamation ④ → ⑦

Electrochemical recovery ④ → ⑦

Recycling

Progress on recycling is uneven across materials and regions

Recycling trends vary widely, depending on the material. For bulk materials such as aluminium and paper, global average recycling rates have remained stable at high levels or seen modest gains recently. By contrast, the recycling of critical minerals is accelerating quickly. Lithium recycling from batteries, for example, has jumped from just 4% in 2015 to around 20% today. Even so, recycling rates for battery minerals remain well below those for metals produced at higher volumes: between 40% and 80% globally for key metals like steel, aluminium and copper.

There is a wide geographic divide. In Asia and Latin America, electronic waste collection rates remain below 5% and in Africa they are barely at 1%, with little improvement since 2010. In contrast, rates reach 30% in Japan and Korea, and 40-50% across Europe and North America.

The pace of recycling growth hinges on how quickly materials reach end-of-life. For bulk materials like steel and aluminium, ageing infrastructure is expected to boost scrap availability, potentially easing demand for primary production – especially in China – or increasing exports. By contrast, battery mineral recycling remains limited in the short term, mostly due to limitations on available feedstock. By 2035, recycled lithium and nickel are expected to meet only about 5% of demand, as usage far outpaces available end-of-life feedstock. Innovation and shifting technology choices can also limit recycling potential for certain critical minerals. For example, the increasing uptake of lower-cost battery chemistries like lithium iron phosphate (LFP) in mass-market EVs is reducing demand for cobalt and nickel in battery production.

Recycling of all types of material is projected to grow in the STEPS, the CPS and the NZE Scenario, particularly in China and other EMDEs, where decades of accumulated stock are now reaching end-of-life, boosting scrap availability.

Priority policy actions

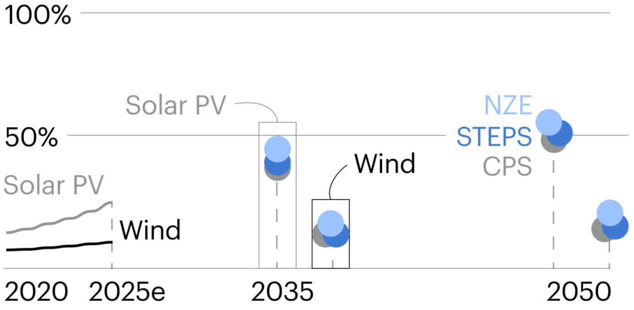
- Develop clear long-term policy roadmaps with targets and intermediate milestones to guide industry efforts and boost investor confidence.
- Promote traceability, standards and certification schemes.
- Set up tolling models to maintain the economic viability of recycling low-value materials or chemistries such as LFP batteries.
- Align and harmonise waste and recycling regulations to facilitate trade.
- Introduce targeted policies to improve material recovery, spur innovation and tap into new sources of recyclable content, including mining waste and tailings.

⑪ SOLAR PV AND WIND

Solar and wind dominate power capacity additions but further integration is needed

Market

Share of global installed capacity



Market status

Pre-commercial | Awaiting adoption | Building momentum | **Strong growth** ● | Consolidation

Solar PV global market size (bn USD)

CPS STEPS NZE

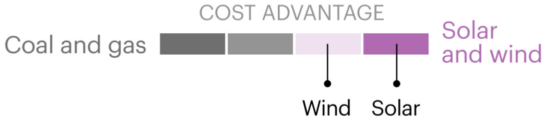
2025e **56** 2035 36 **46** **86** 2050 36 **40** **49**

Wind global market size (bn USD)

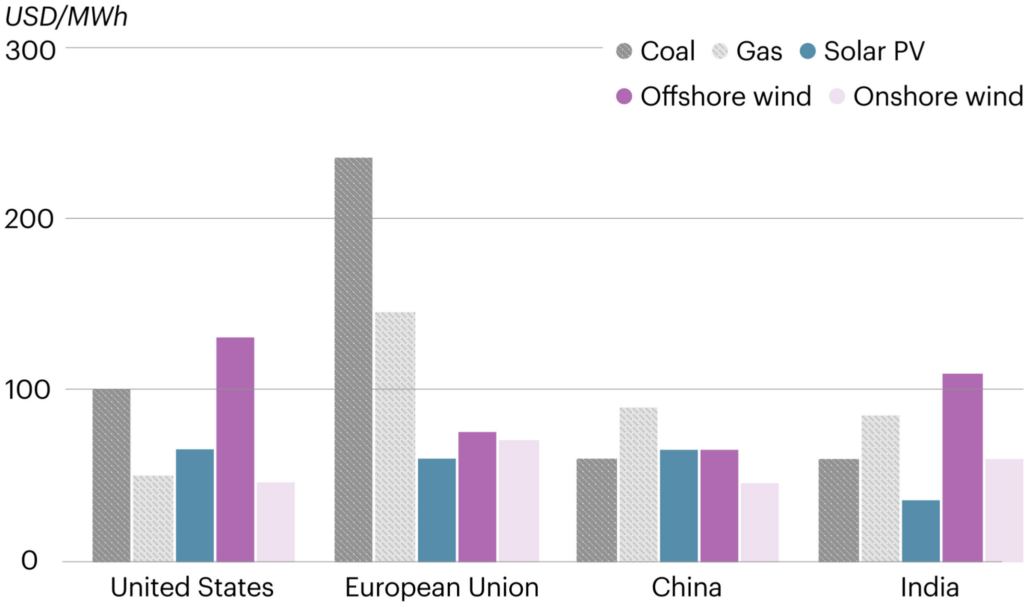
2025e **75** 2035 91 **103** **272** 2050 96 **106** **198**

Competitiveness

Solar and wind are competitive in many markets



Value-adjusted levelised cost of electricity in selected markets, 2024

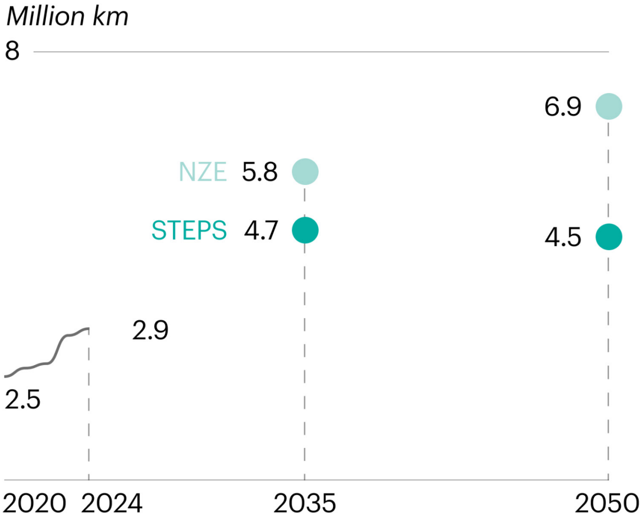


80%

of global wind and solar generation is in countries where average levelised costs for wind and solar are lower than those of fossil generation

Enabling factors

Grid extensions are picking up but still lagging



Grid-level battery storage capacity deployment remains behind

Solar PV and wind power

Manufacturing gains and policy support are driving record capacity additions

The year 2024 was another record-breaker for solar PV and wind deployment. Global solar PV capacity additions surged by nearly 30%, and wind installations slightly outpaced 2023, itself a record year. Together, solar and wind accounted for nearly 80% of total electricity capacity additions and over 95% of new renewables capacity. China led the way with 60% of global additions, driven by strong policy support for utility-scale and distributed systems, and low-cost domestic manufacturing that has made solar and wind generation competitive with coal in many provinces. Capacity additions are estimated to have grown around 10% for both technologies combined in 2025. Rooftop and small-scale installations, while more costly than utility-scale systems in many markets, also saw rapid growth, particularly in China and India (albeit from a lower base in the latter), backed by local incentives and rising demand for self-generation. Offshore wind is gaining momentum too, especially in Europe.

Solar PV continues to dominate renewables deployment globally in all IEA scenarios, accounting for 75% of renewable capacity additions and over 50% of total electricity capacity additions by 2035 in both the STEPS and CPS, of which two-thirds are in China. Installed wind capacity doubles by 2035 in the STEPS and CPS, supported by improvements in auction design, permitting and grid access – particularly in Europe, China and India. In the NZE Scenario, solar and wind capacity grow nearly sixfold and fourfold, respectively, by 2035. However, growing difficulties in integrating new capacity into power systems could impact the viability of solar and wind projects, with curtailment already reaching 16% in some regions (IEA, 2025e). China offers a strong example of progress: average wind curtailment fell from its peak at over 15% in 2016 to less than 5% in 2024, and solar PV curtailment declined to similarly low levels, thanks to grid upgrades, power market reforms and demand-side measures.

Priority policy actions

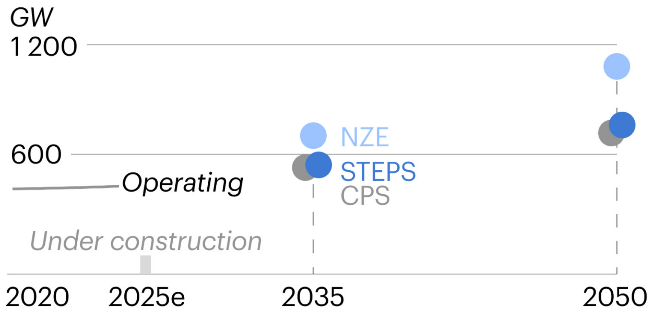
- Support investment in transmission capacity, deploy energy storage and modernise grid operations to reduce curtailment and improve reliability.
- Streamline permitting to facilitate faster deployment and predictable demand.
- Strengthen support for distributed solar PV (e.g. via feed-in tariffs, tax incentives and smart meter rollouts), especially in EMDEs.
- Train workforce for installation, maintenance and offshore operations, including port infrastructure and vessels.

⑫ NUCLEAR

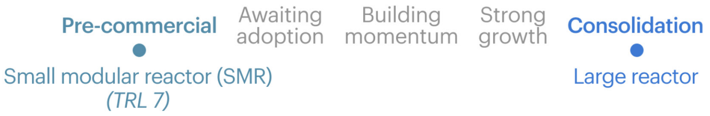
Nuclear energy is making a strong comeback

Market

Installed capacity



Market status

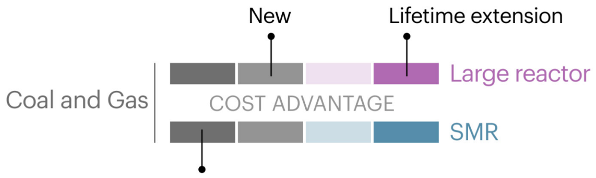


Annual investment spending (USD)

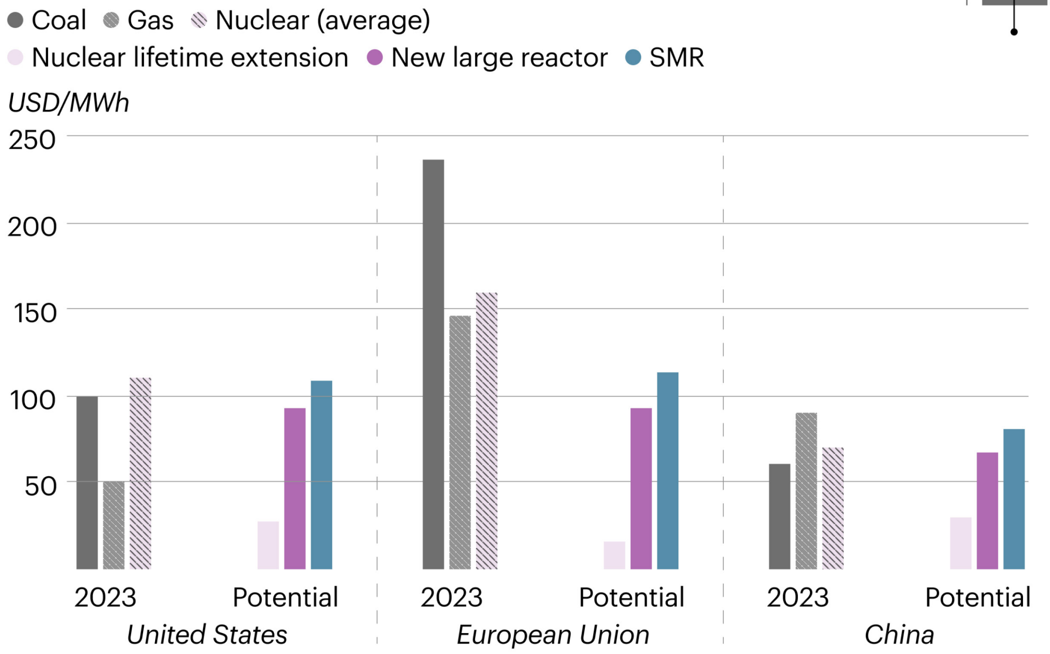
	2024	2035	2050
NZE		**157 bn**	**94 bn**
STEPS	**72 bn**	**102 bn**	**77 bn**
CPS		**93 bn**	**66 bn**

Competitiveness

Nuclear power is a competitive source of electricity in some markets



Value-adjusted levelised cost of electricity



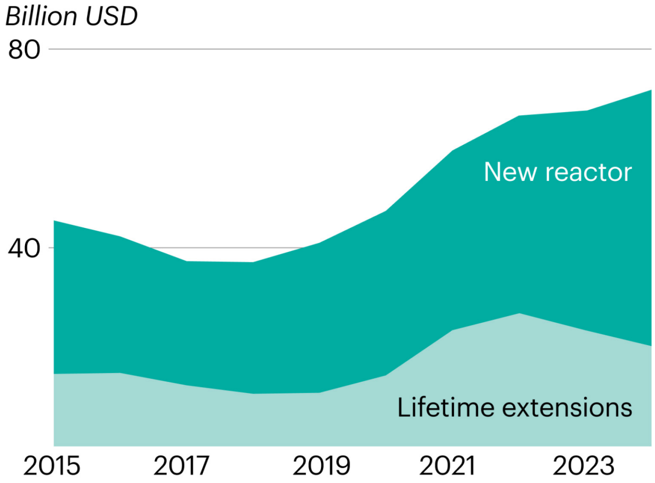
SMRs generation costs could still be

+20%

more than large reactors but shorter construction time and lower CAPEX could make them more attractive to investors.

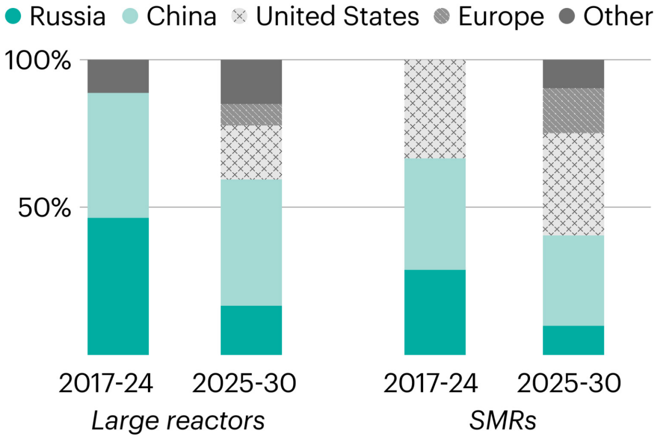
Enabling factors

Global investment in new reactors is increasing



The nuclear technology market could diversify according to announcements

Project construction start by origin of technology



Nuclear

Investment is growing as new technologies develop

Nuclear power's share of global electricity was at 9% in 2024, making it the second-largest source of low-emissions electricity after hydropower. Growth is being driven by rising electricity demand and the ability of nuclear to provide dispatchable low-emissions electricity and heat. Over 40 countries now have policies in place to expand its use. Capacity that had been suspended or was in maintenance is set to restart production in France and Japan, and new reactors are due to begin commercial operations in markets including China, India, Korea and Europe.

Innovation in small modular reactors (SMRs) is also reshaping the technology landscape, with a view to diversify providers, reduce costs, and cut lead times. As of November 2025, there were agreements and expressions of interest for 30 GW of SMR capacity, the majority of which is in the United States, in large part to meet growing demand from data centres. Government support and new business models will be critical in ensuring these reactors become cost-competitive, unlocking a path to wider adoption. However, the market for nuclear technologies remains highly concentrated, with Chinese and Russian technologies being used in 57 of the 61 reactors that have started construction since 2017. A new wave of projects – both SMRs and large-scale reactors – creates the possibility for Europe, Japan and the United States to regain technology leadership. Fusion is still a longer-term prospect although investments are growing (see Chapter 1).

Momentum should be maintained over the longer-term: annual investment in nuclear has increased by 50% since 2020, exceeding USD 70 billion in 2024. Over 70 GW of nuclear capacity is under construction, one of the highest levels since 1990. Almost half of these projects are located in China, where installed capacity is expected to surpass the European Union and the United States by around 2030. Global nuclear capacity grows by around 35% by 2035 in the STEPS and CPS, and 70% in the NZE Scenario. But tripling installed capacity by 2050 would require around 50% higher annual investment in the 2040s than in the NZE Scenario.

Priority policy actions

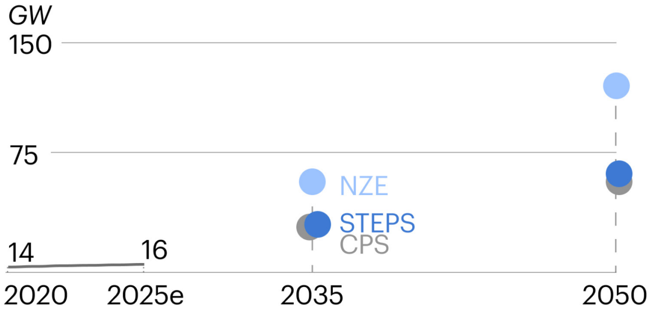
- Build robust, diverse supply chains including for technology design and nuclear supply and enrichment.
- Invest in a skilled workforce and support innovation.
- Support business models through de-risking mechanisms for investment as well as direct financial support.
- Implement effective, transparent nuclear safety regulations, alongside provisions for decommissioning and waste management.

⑬ GEOTHERMAL

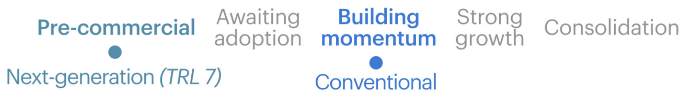
Growth could soar with next-gen breakthrough

Market

Installed capacity



Market status

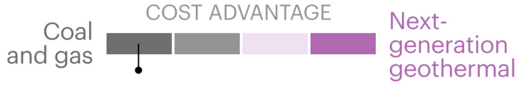


Global market size (USD)

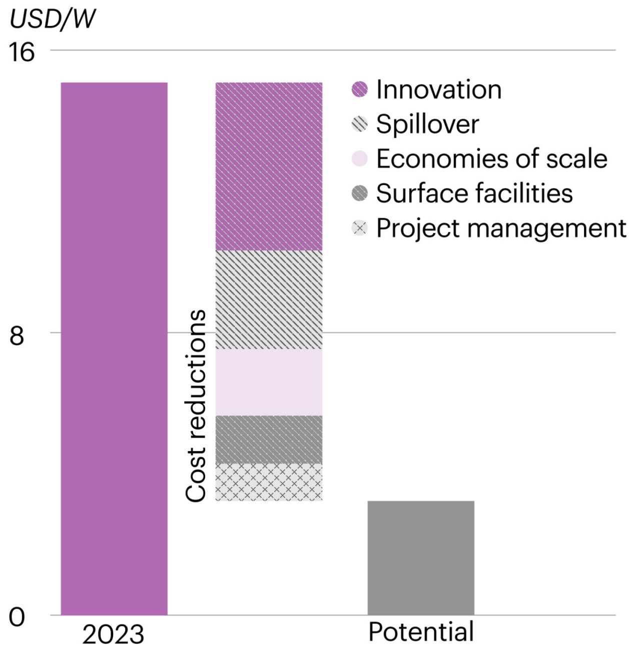
	2025e	2035	2050
NZE		**7 bn**	**6 bn**
STEPS	**1 bn**	**4 bn**	**4 bn**
CPS		**4 bn**	**3 bn**

Competitiveness

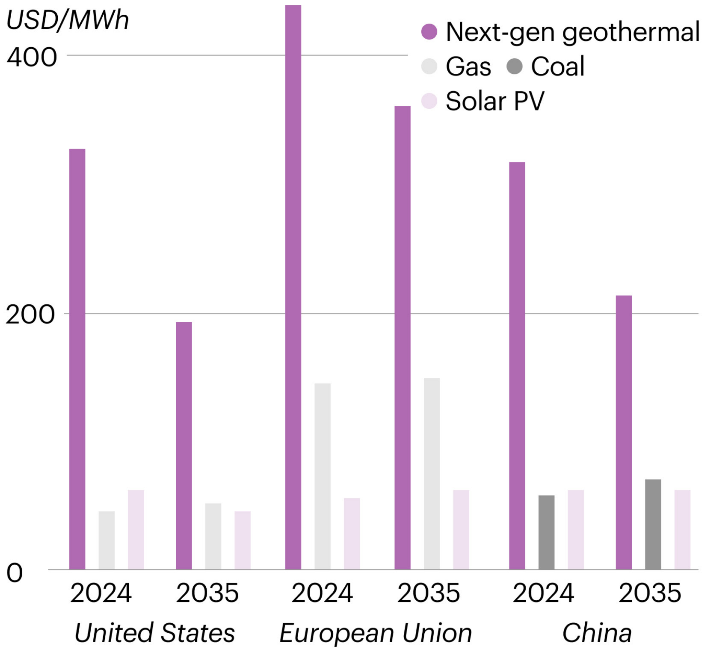
Stronger policy support is needed to exploit potential for deep cost reductions



Potential for cost reduction



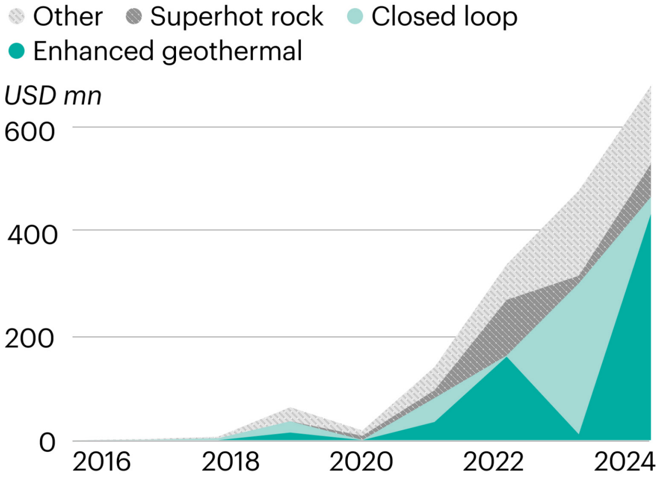
Value-adjusted levelised cost of electricity, STEPS



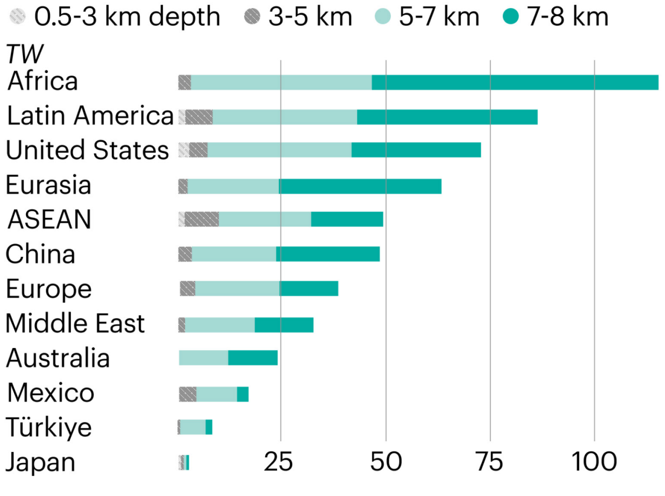
Enabling factors

Surge in venture capital investment to tap into large potential for next-generation geothermal

Venture capital investment



Technical electricity potential



Geothermal

Next-generation geothermal remains expensive and cost reduction is essential

In 2024, electricity generation from geothermal was about 100 TWh (0.3% of the global total) with total installed capacity at over 15 GW across more than 30 countries. In Costa Rica, El Salvador, Iceland, Kenya, New Zealand and Nicaragua, geothermal contributed more than 10% to the annual electricity supply. Net additions in 2025 are estimated to have reached almost 0.5 GW, mostly from conventional projects, and multiple large-scale enhanced geothermal projects will start operations in 2026-27. About 30 countries have supportive policies (IEA, 2025e).

Conventional geothermal (i.e. all capacity deployed today) relies on the location of naturally formed hydrothermal reservoirs. Next-generation geothermal uses directional drilling and hydraulic fracturing to access heat at much larger depth, meaning that generation is not location dependent. Generation cost from conventional geothermal is on average USD 60-80/MWh today (IEA, 2024b). This jumps to around USD 230/MWh for next-generation geothermal but could be reduced by 80% by 2035 through innovation, scale and learnings from the oil and gas industry. Such a cost reduction would make geothermal competitive with other low-emissions alternatives, and would enable tapping into 600 TW of technical potential (almost 2 000 times larger than conventional geothermal) at a depth of less than 8 km, and 42 TW at less than 5 km. As reference, the global power generation capacity was over 11 TW in 2025.

By 2030, 42 countries are expected to have some geothermal capacity, with annual capacity additions tripling 2024 levels, driven by growth in Indonesia, Japan, Kenya, the Philippines, Türkiye and the United States (IEA, 2025e). By 2035, global geothermal capacity more than doubles in the STEPS (32 GW), doubles in the CPS (30 GW) and reaches more than 55 GW in the NZE Scenario.

Priority policy actions

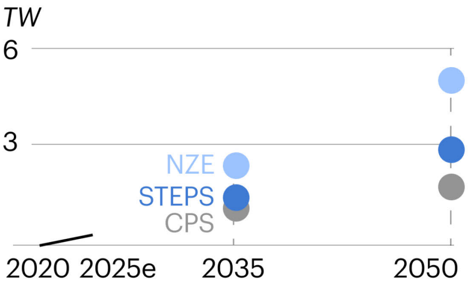
- Improve subsurface data quality and create open data repositories to facilitate geothermal resource assessments.
- Broaden risk mitigation schemes for early-stage projects, including demonstration and testing of emerging technologies, and remuneration schemes that ensure long-term revenue certainty and that value flexibility.
- Consolidate administrative steps involved in permitting for geothermal energy and consider dedicated regimes separate from minerals mining.

⑭ STATIONARY ENERGY STORAGE TECHNOLOGIES

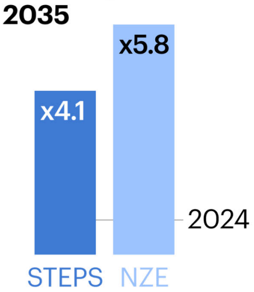
Battery storage is among the fastest growing energy technologies in the electricity sector

Market

Deployment of stationary energy storage systems



Global short-term flexibility needs in 2035



Market status

Pre-commercial | Awaiting adoption | **Building momentum ●** | Strong growth | Consolidation

Global market size (USD)

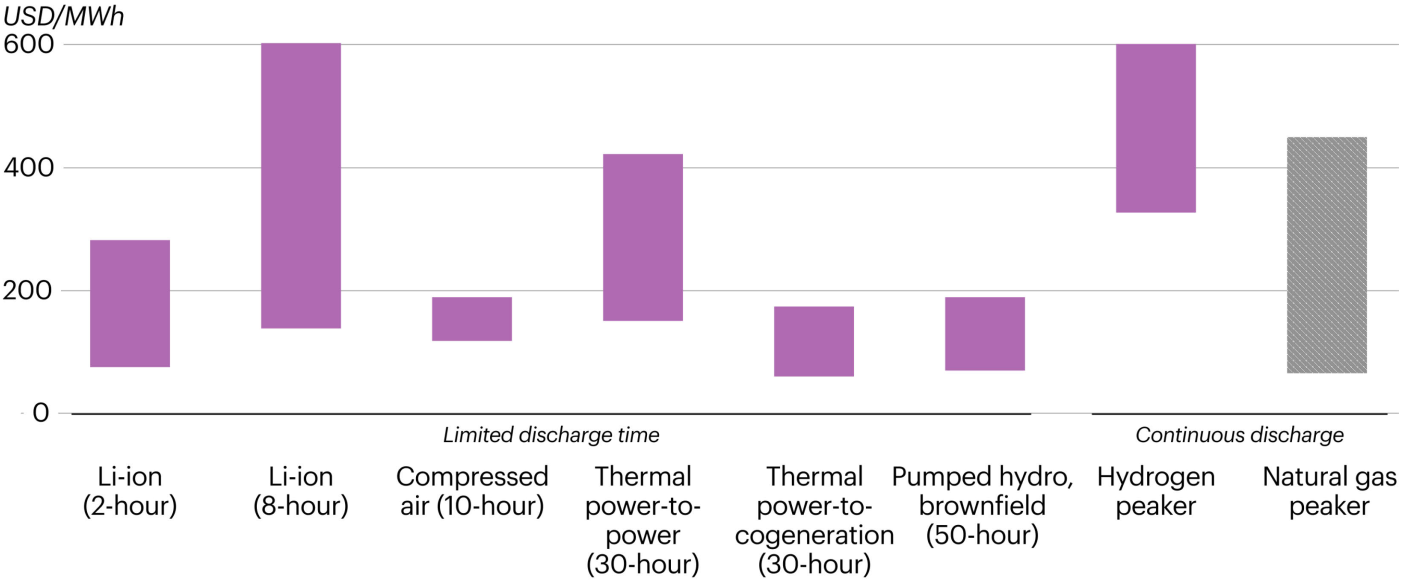
2025e		2035	2050
29 bn	NZE	89 bn	131 bn
	STEPS	51 bn	85 bn
	CPS	41 bn	65 bn

Competitiveness

Some storage technologies can provide cost-competitive flexibility services today

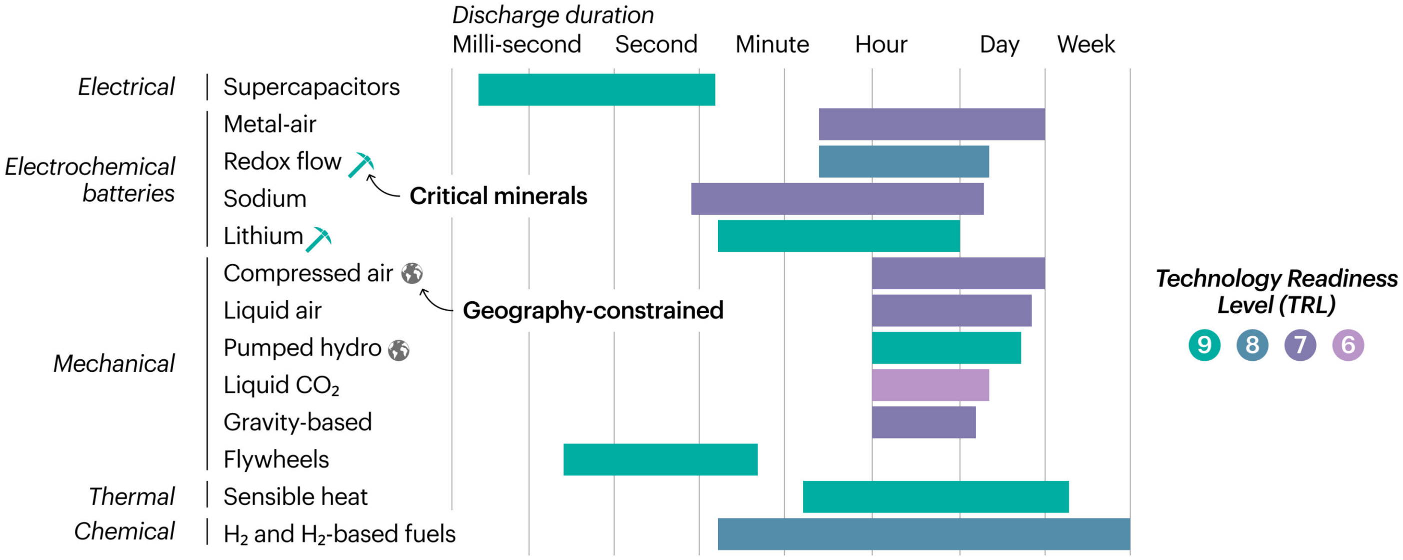
Indicative levelised cost of electricity

The range illustrates different utilisation rates and price ranges for natural gas and low-emissions hydrogen



Enabling factors

Innovation remains key to bring longer duration energy storage technologies to market



Stationary energy storage technologies

Surging battery storage is complementing pumped hydro

Until the early 2020s, nearly all grid-scale storage came from pumped-storage hydropower, with under 200 GW of installed capacity globally (about 8 500 GWh of storage), though it is limited to geologically suitable locations. Over the past 5 years, electrochemical battery storage capacity has surged, growing at an average annual rate of 70%, nearly three times that of solar PV today and faster than solar PV’s peak growth in the early 2010s. Global stationary battery capacity is estimated to have surpassed pumped hydro in power terms by the end of 2025, reaching around 270 GW, though energy storage capacity will still lag at approximately 625 GWh.

This rapid growth has been driven by battery cost reductions of over 75% since 2015, which are largely due to the rise in electric car sales. Falling solar PV costs have also boosted demand for storage to integrate higher shares of renewables, especially in areas with weak transmission networks, as batteries can be deployed more quickly than grid upgrades. Globally, around 4 GW of other long-duration storage technologies are now in operation, including 1 GW of mechanical systems (e.g. compressed air, liquid CO_2 and liquid air energy storage).

Battery storage is set to continue expanding rapidly, though the pace will depend on several factors. In the STEPS, it reaches 1.7 TW/4.9 TWh by 2035, compared with 1.4 TW/4.2 TWh in the CPS and 2.9 TW/8.5 TWh in the NZE Scenario. This gap reflects three drivers in the NZE Scenario: faster electrification of end-uses (electricity accounts for more than 40% of final consumption compared to 30% in the STEPS), a higher share of generation from variable renewables (60% versus 40%), and a sharper decline in fossil-based dispatchable capacity. By 2035, storage provides 30% of dispatchable capacity in the NZE Scenario, almost twice the share in STEPS or more than double that in the CPS. Scale-up will also depend on how much flexibility can be delivered via demand-side response, and how competitive storage technologies – especially long-duration – can become.

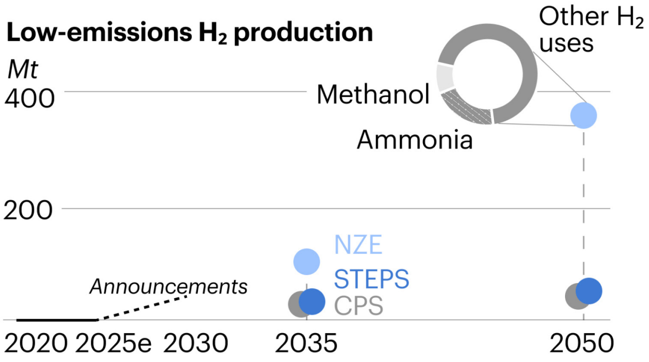
Priority policy actions

- Support demonstration and scale-up of emerging long-duration storage technologies, while maintaining efforts to lower battery costs.
- Provide long-term revenue predictability, including via capacity payments, availability-based remuneration or government-backed guarantees.
- Grant storage providers access to electricity markets, covering energy, capacity and ancillary services, to enable stacking of revenue streams.
- Streamline grid connection procedures through one-stop-shop permitting and efficient pricing mechanisms.

⑮ LOW-EMISSIONS HYDROGEN, AMMONIA & METHANOL

Production is growing, though at a slower pace than anticipated

Market



Market status

Pre-commercial | **Awaiting adoption** ● | Building momentum | Strong growth | Consolidation

Market size: Ammonia (bn USD)

2025e **0.5** 2035 11 **13** 115 2050 24 **27** 243

Methanol (bn USD)

2025e **0.2** 2035 2 **3** 74 2050 5 **5** 114

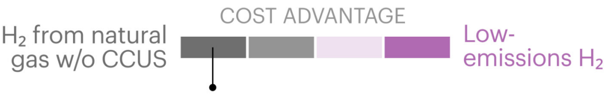
Other H_2 uses (bn USD)

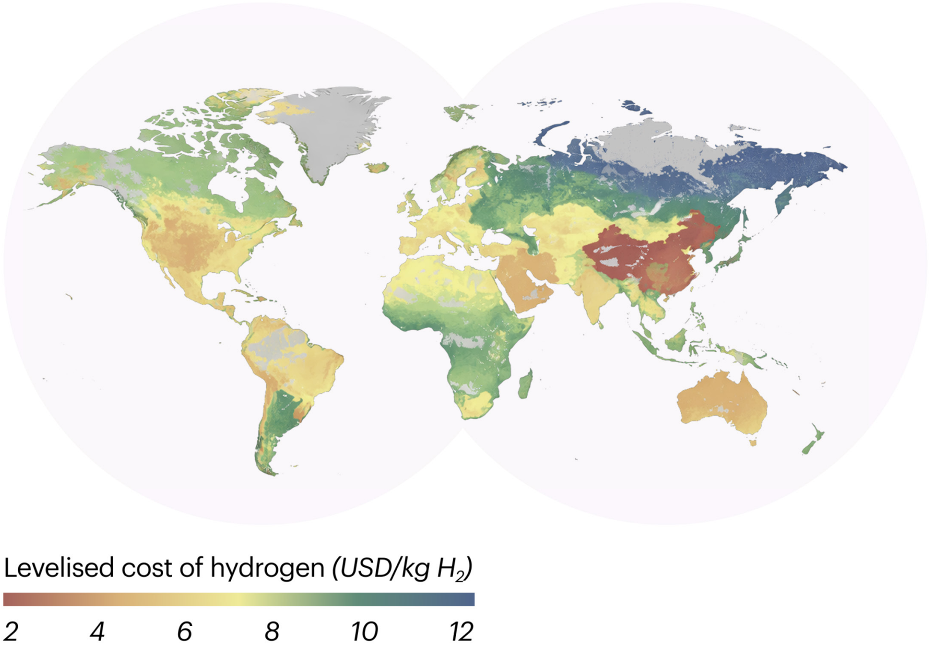
2025e **1.5** 2035 34 **38** 361 2050 131 **145** 1 074

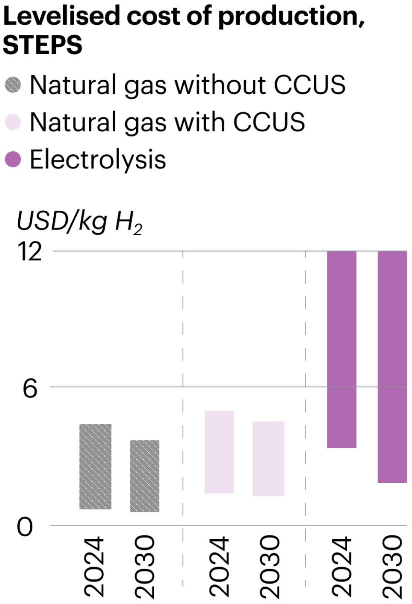
Competitiveness

The cost gap could be closed in some regions this decade

Hydrogen production cost using electrolysis in the STEPS, 2030

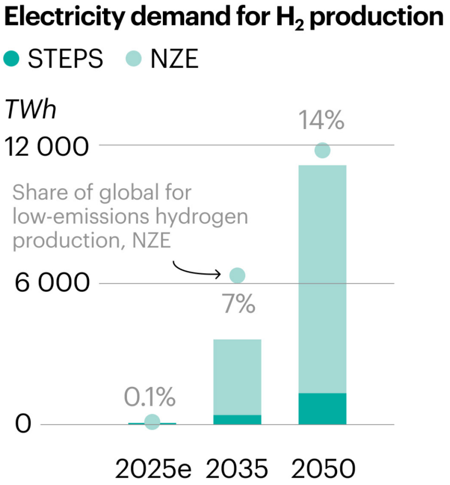


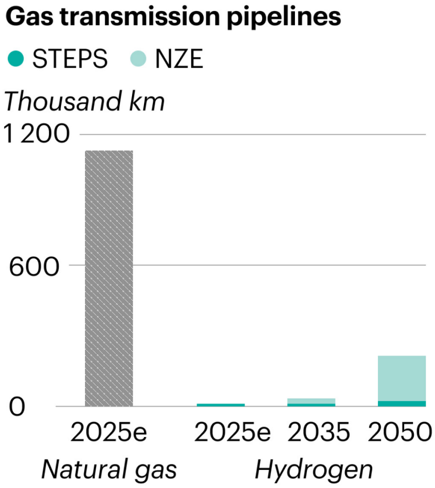


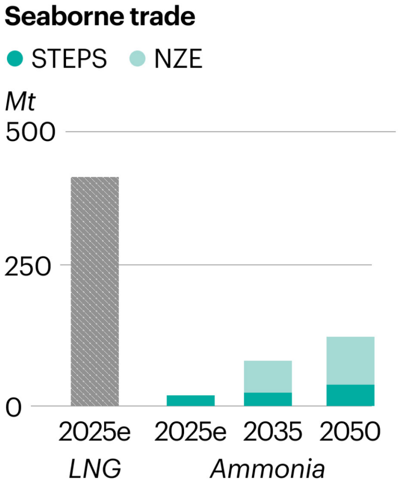


Enabling factors

Low-emissions hydrogen production depends on availability of cheap, low-emissions electricity and rollout of transport infrastructure







Low-emissions hydrogen, ammonia and methanol

Public support and off-takers drive initial growth

Global low-emissions hydrogen production is rising briskly, but at an estimated 1 Mt in 2025, still accounts for less than 1% of total hydrogen production. Production grew by more than 70% since 2020, albeit from a low base. In 2024, almost 85% of supply came from fossil fuels with CCUS; the rest was mainly from electrolysis, with electrolytic production having nearly quintupled since 2020. In 2025, low-emissions hydrogen is estimated have risen by 30%, with 60% of the increase from electrolytic hydrogen, driven by China, and 40% from CCUS. Around 30% of it is used for ammonia and methanol production.

China has commissioned the world's largest electrolytic ammonia plant, supported by low-cost renewables and domestic equipment, and an offtake agreement with Marubeni, a Japanese conglomerate. In Denmark, the largest CO_2-to-methanol plant using electrolytic hydrogen started operating in 2025, backed by public funding and offtake agreements with Lego, Mærsk and Novo Nordisk, and using biogenic CO_2 from biogas. In the United States, CCUS-based hydrogen projects are advancing, spurred by the 45Q tax credit for CO_2 storage.

Projects that are operational or have committed investments in low-emissions hydrogen stand at 4.2 Mt per year, more than four times the estimated production in 2025. If all announced projects go ahead, production could reach 37 Mt by 2030. In the STEPS, low-emissions hydrogen grows to 13 Mt by 2035, compared with 11 Mt in the CPS and more than 120 Mt in the NZE Scenario. In the latter scenario, ammonia and methanol production – used as both chemicals and fuels – consume 32 Mt and 14 Mt of low-emissions hydrogen, over 35% of global demand. Achieving the much faster scale-up envisioned in the NZE Scenario would call for lower production costs and stronger demand signals, including for existing hydrogen uses. The volume of hydrogen covered by offtake agreements is just 7 Mt today, and only a quarter of those are on firm contractual terms.

Priority policy actions

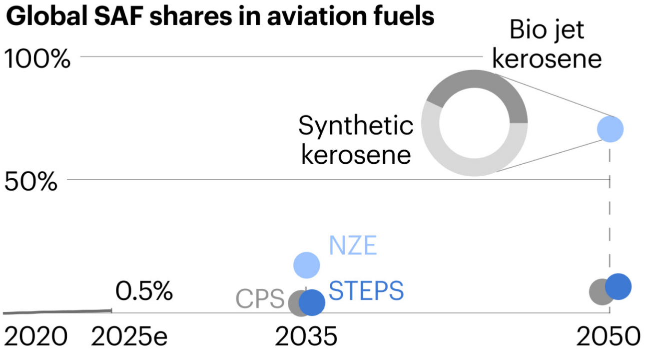
- Develop lead markets through the introduction of quotas, mandates and public procurement to create early demand.
- Close the cost gap with fossil hydrogen with investment incentives, revenue-stabilising tools, such as contracts for difference, and access to cheap finance.
- Support investment in power grids, and hydrogen and CO_2 transport and storage, to avoid infrastructure bottlenecks.
- Adopt clear, pragmatic regulation and certification schemes that ensure environmental integrity and enable cross-border interoperability.

16 SUSTAINABLE AVIATION FUELS

Production is increasing, but more efforts are needed to unlock feedstocks and narrow the cost gap

Market

Global SAF shares in aviation fuels



Market status

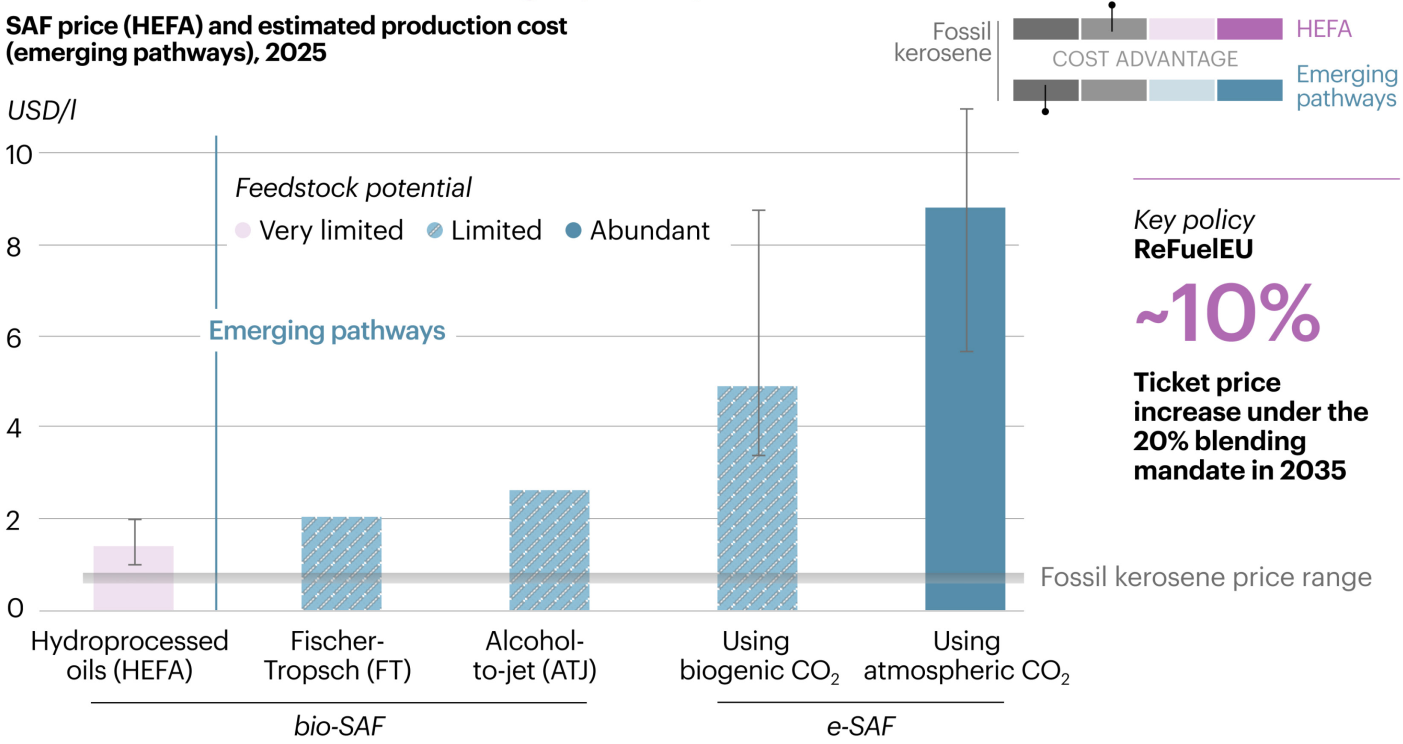
Global market size (USD)

	2025e	2035	2050
NZE		174 bn	650 bn
STEPS	2.4 bn	39 bn	130 bn
CPS		36 bn	120 bn

Competitiveness

SAF at scale comes at a high price premium

SAF price (HEFA) and estimated production cost (emerging pathways), 2025



Key policy
ReFuelEU

~10%

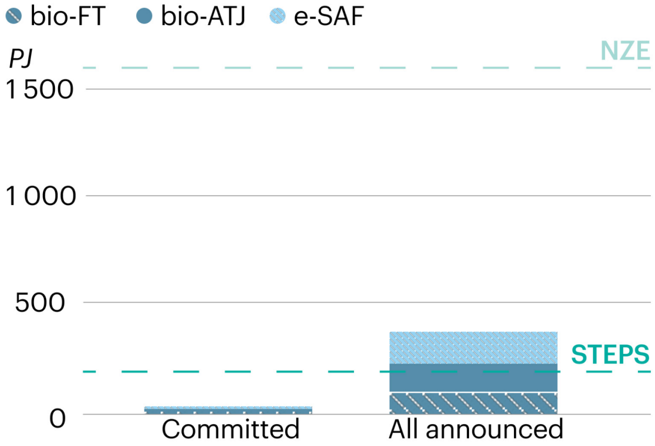
Ticket price increase under the 20% blending mandate in 2035

Enabling factors

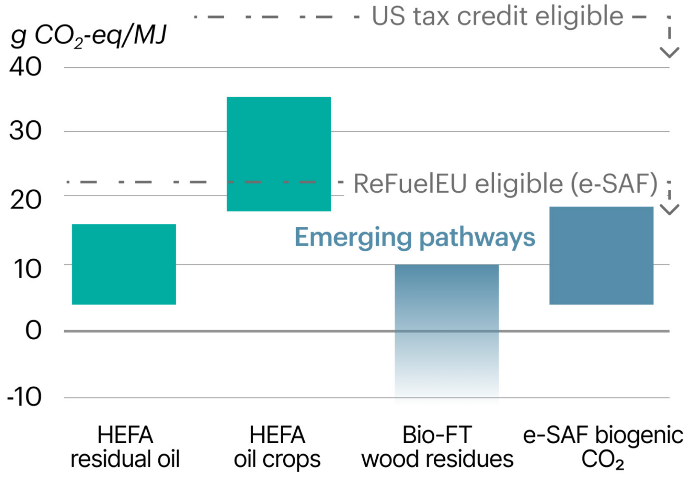
A growing but insufficient project pipeline

SAF projects using emerging pathways

2025-35 capacity additions



Policies can enable the best performing pathways



Sustainable aviation fuels production

SAF output is rising on the back of blending mandates

Global production of sustainable aviation fuel (SAF), derived from biofuels and low-emissions hydrogen, is estimated to double in 2025, but still meet only around 0.5% of total jet fuel demand. Growth is being primarily driven by policy measures, such as the European Union’s ReFuelEU Aviation regulation, which requires a 2% SAF blend from 2025, rising to 20% by 2035. The United Kingdom has set a 10% blending mandate by 2030, and in Brazil, airlines are obliged to reduce their emissions by 1% through SAF in 2027, and by 10% by 2037.

The high production costs of SAF remain an immediate obstacle to wider deployment. SAF produced via the prevailing technology today – hydroprocessed esters and fatty acids (HEFA) – costs two to three times more than fossil jet fuel. Producing synthetic kerosene (still at the demonstration phase) costs over nine times more. But the impact on the consumer is likely to be lower. For example, under the ReFuelEU 20% SAF mandate by 2035 (5% synthetic), average ticket prices would rise by around 10%, as costs decrease for emerging SAF pathways. Waste and residue oils are important bio-SAF feedstocks, and likely the main avenue to 2030, intensifying pressure on their already limited supply (IEA, 2022b). Crop-based feedstocks may compete with food production, whereas for e-SAF, the availability of CO_2 feedstocks is a key constraint. Biogenic CO_2 sources are limited and require nearby facilities such as biorefineries or CO_2 transport infrastructure; capturing CO_2 directly from the air is prohibitively expensive for now.

In the STEPS and the CPS, global SAF output grows tenfold by 2035, reaching 4% of projected jet fuel demand, mainly driven by current mandates. Projected needs in the NZE Scenario are four times higher.

Priority policy actions

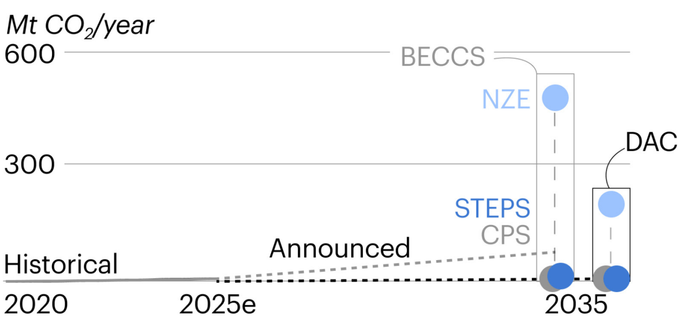
- Accelerate SAF uptake by confirming existing mandates and tax incentives, and creating demand signals in new markets.
- Promote financing mechanisms based on GHG performance to support emerging production routes (e.g. contracts-for-difference, flexible loans).
- Establish clearly defined minimum performance thresholds that are compatible across borders and sectors, ideally under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) framework.
- Encourage strategies to expand production of sustainable biomass feedstocks (e.g. sequential cropping, cultivation on degraded lands).
- Update the ASTM D7566 standard specification and accelerate testing and certification by aircraft manufacturers for full approval of SAF as a drop-in fuel.

⑰ CARBON DIOXIDE REMOVAL

Further growth needs policy support to build demand and boost innovation

Market

Global deployment



Market status

Pre-commercial ● — DAC (TRL 6-7), Other BECCS (TRL 7)

Awaiting adoption ● — Bioethanol/biogas with capture

Building momentum

Strong growth

Consolidation

DAC (bn USD)

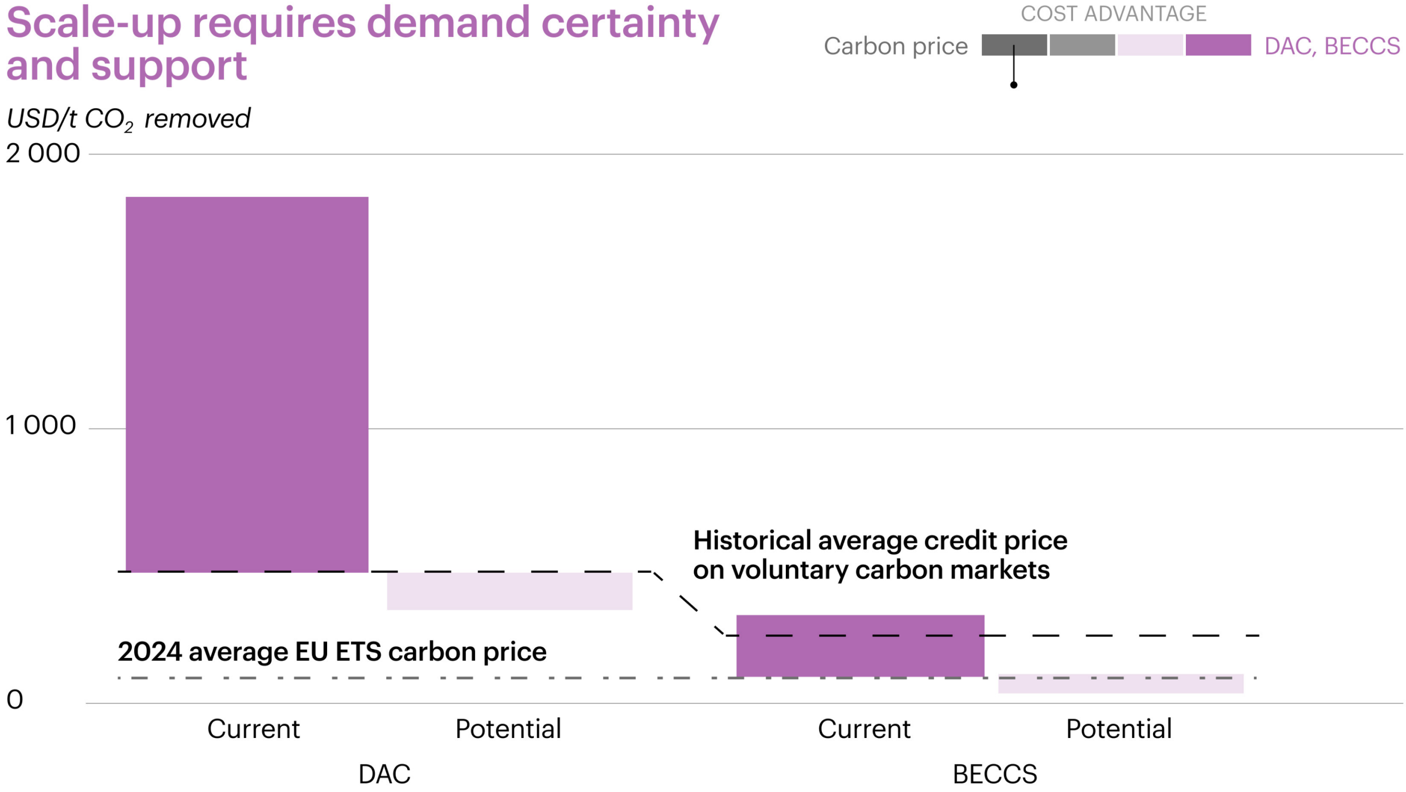
2024 **0.3** 2035 0 **0** 29 2050 0 **0** 238

BECCS (bn USD)

2024 **1.2** 2035 0 **1** 74 2050 0 **1** 235

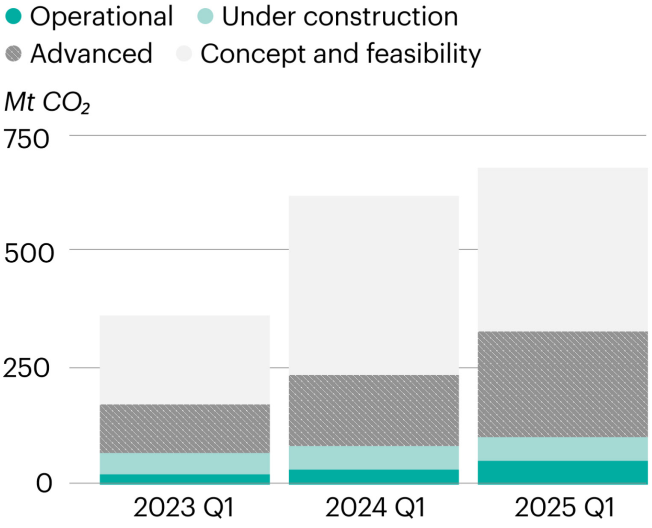
Competitiveness

Scale-up requires demand certainty and support

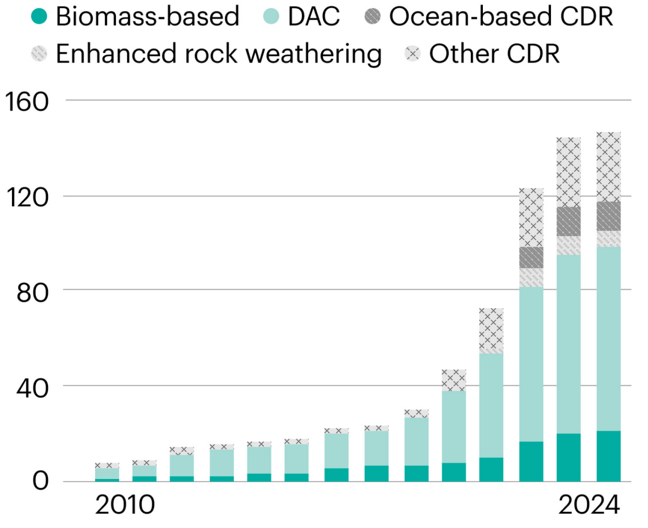


Enabling factors

More CO_2 storage capacity is being built



CDR start-ups are growing and diversifying



Carbon dioxide removal

Public funding and voluntary markets are driving first-of-a-kind projects

Bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) are among the leading carbon dioxide removal (CDR) technologies today in terms of capacity. Their deployment is set for a step change, with several first-of-a-kind projects expected to be commissioned soon in Denmark, Iceland, Sweden and the United States. Projects already under construction alone could more than double current BECCS capacity and expand DAC capacity by a factor of 50 worldwide, albeit from a low base. These efforts are largely backed by public funding, with around USD 5 billion committed over the past 5 years.

Voluntary carbon markets have been critical in enabling projects to reach FID by providing stronger demand signals and revenue certainty. In 2024, developers signed advanced offtake agreements covering nearly 6 Mt of CO_2 removals using these two technologies – almost double the volume seen in 2023. These markets, however, remain highly concentrated: about 65% of purchases of carbon credits from CDR projects in 2024 came from a single buyer, Microsoft (CDR.fyi, 2025a). They cannot provide the long-term, stable demand needed to scale investment.

Stronger policy support is essential to foster innovation, lower costs and ensure removals are durable, measurable and verifiable. DAC, in particular, faces high energy needs and steep first-of-a-kind costs, currently estimated at USD 500-1 900 per tonne of CO_2. However, advances in capture materials and scale effects could bring costs down to around USD 300/t CO_2 in the longer-term.

If all announced projects proceed, CO_2 removal capacity could grow around 80-fold by 2035 from today's level of around 1 Mt CO_2 per year, surpassing by a wide margin the 7 Mt projected in the STEPS or the 5 Mt in the CPS, though far short of the 660 Mt in the NZE Scenario.

Priority policy actions

- Create demand, including through the introduction of legally binding targets, public procurement, integrating CDR in compliance and international carbon markets, and policies such as carbon contracts for difference.
- Increase public RD&D funding, focusing on material performance, energy use and climate adaptability, supported by open-access testbeds.
- Facilitate data-sharing and establish robust, consistent standards for monitoring, reporting and verification across CDR methods.
- Promote early investment in scalable CO_2 transport and storage infrastructure to enable cost-effective deployment of CDR technologies.

Technical notes on the dashboards

General notes

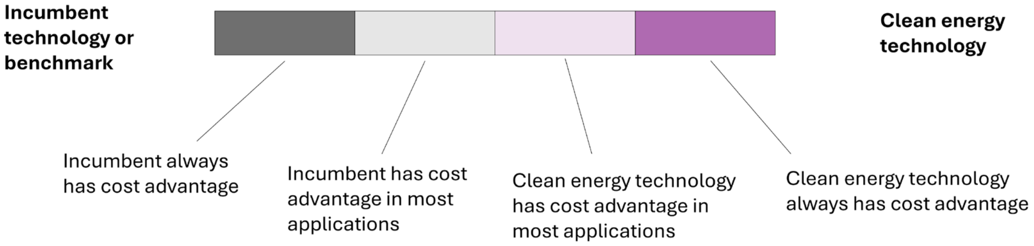
Common abbreviations

STEPS	Stated Policies Scenario
CPS	Current Policies Scenario
NZE	Net Zero Emissions by 2050 Scenario
TRL	Technology readiness level

Definition of market status categories

- Pre-commercial: has not yet reached TRL 9. Includes technologies which can be ordered but are not yet in commercial operation.
- Awaiting adoption: has reached TRL 9 but struggling to be deployed in the market.
- Building momentum: has entered certain markets but not being widely adopted, global impact limited.
- Strong growth: widely adopted, market size/share growing substantially.
- Consolidation: widely adopted, market size/share stabilising or declining.

Qualitative cost advantage indicator



- Costs are assessed on a like-for-like basis (e.g. production costs for similar products, value-adjusted levelised cost of electricity).
- For some technologies, both purchase cost and whole-life costs, i.e. total cost of ownership, are assessed separately.
- Policies influence the competitiveness of technologies; they define the playing field.
- This assessment is for 2025.

Electric cars

- Chargers less than or equal to 22 kW are classified as slow, chargers greater than 22 kW and up to 150 kW as fast, chargers 150 kW and up to 1 MW as ultra-fast, and chargers 1 MW or above as MW-scale.
- Sources: IEA analysis based on country data submissions and data from European Automobile Manufacturers' Association (2025); European Commission (2025b); EV Volumes (2025); Marklines (2025); S&P Global Mobility (2025); and US Department of Energy (2025).

Zero-emissions trucks

- HD = heavy-duty; MD = medium-duty; BEV = battery electric vehicle; TCO = total cost of ownership.
- Medium-duty trucks have a gross vehicle weight of greater than 3.5 tonnes and up to 15 tonnes; heavy-duty trucks have a gross vehicle weight greater than 15 tonnes.
- Assumptions used for the total cost of ownership analysis are described in Annex A of the Global EV Outlook 2025 (IEA, 2025c).
- Sources: IEA analysis based on data from EV Volumes (2025); China EV100 (2025); China Commercial Vehicles Dealers Association (2025); and CALSTART (2025).

Ammonia and methanol propulsion ships

- The total cost of ownership is calculated for a representative containership of capacity 9 400 Twenty-foot Equivalent Units (TEUs), fitted with the energy efficiency technologies expected to be deployed at the time of investment (2035). Fuel costs as per IEA's Global Energy and Climate model results (IEA, 2025f). Operating costs exclude fuel costs.
- Alternative fuel readiness of ports is based on the score defined in the IEA's Global Hydrogen Review 2025 (IEA, 2025g). The score is calculated as follows: Score = 3 × ammonia (NH_3) + 3 × liquefied petroleum gas (LPG) + 3 × methanol (MeOH) + 1 × liquefied natural gas (LNG), where each variable is binary: 1 if the port has storage infrastructure for that carrier (NH_3, LPG, MeOH, or LNG), and 0 otherwise. "High" means a score of 8 to 10, "Medium" means a score of 5 to 7, "Low" means a score of 1 to 4, "Nil" means a score of 0.
- Alternative propulsion ship construction means construction of ships equipped with a methanol or ammonia dual-fuel engine (it does not include LNG-powered ships). Constructed gross tonnage values for 2035 in the different scenarios are averaged over a period of 5 years (2031-2035).

Buildings heat pumps

- In calculating the levelised cost of heat, heat pumps are assumed to have a lifetime of 15–20 years, compared with 17 years for gas boilers. Annualisation of operating expenditures is performed using a 3% discount rate. Annualised CAPEX and operational cost assumptions rely on the IEA Global Energy and Climate Model (IEA, 2025f).
- 2025e data are based on data available as of February 2026, while 2019 - 2024 data are based on data available in 2025 from EHPA (2025); AHRI (2025); JRAIA (2025); and ChinaIOL (2025).

Air conditioning systems

- Efficiency is reported in CSPF = Cooling Seasonal Performance Factor.
- CSPF values have been standardised based on ISO group 1, applying distinct harmonisation models for fixed-speed versus inverter technologies.
- Annualised capital and operational cost parameters follow the assumptions of the IEA Global Energy and Climate Model (IEA, 2025f).
- Shipments from China are categorised under the GB 21455-2019 classification, wherein Class 2 and above represent high efficiency, Classes 3 - 4 represent medium efficiency, Class 5 medium to low, and below Class 5 represent the lowest efficiency.

Zero-carbon-ready building envelopes

- A zero-carbon-ready building is highly energy-efficient and either uses renewable energy directly or an energy supply (e.g. electricity or district heating) that will be fully decarbonised by 2050.
- Building construction costs are evaluated over a 50-year horizon with a 3% discount rate. Assumptions for heating and cooling expenditures and construction costs are aligned with those used in the IEA *Global Energy and Climate Model* (IEA, 2025f).
- Buildings designated as compliant are those governed by applicable energy efficiency standards or regulations; those lacking such requirements are classified as non-compliant.
- Technology readiness levels follow the framework provided in the *ETP Clean Energy Technology Guide* (IEA, 2025b).

Industrial heat pumps

- HP = Heat pump; COP = Coefficient of Performance; this represents the ratio between thermal energy provided by the heat pump and the energy supplied to make it work.

- Due to uncertainty in current stock and sales of industrial heat pumps, data focuses on potential future growth in industrial heat pump installations.
- The temperature lift is the delta between the average temperature of the heat source, and the average temperature of the heat sink.
- In the electricity to gas price ratio figure, average industrial end-user prices for 2024 are used. Those prices include specific taxes and network cost for industrial users associated with those fuels.
- CAPEX includes equipment and installation cost but not grid connection cost. The error bar represents the range of capital costs in between the 20% and 80% percentile, as listed by HPT TCP (2023).
- Heat pump potential per industry considers the heat output potential for those sectors. For the food and tobacco, chemical and paper sectors, the same assumptions as in the article by Marina et al. (2021) are used. Other sectors either use a sector-specific assumption or an assumed deployment potential of 95% of temperatures below 60°C, 50% between 60°C and 100°C, 30% between 100°C and 150°C, 3% between 150°C and 200°C and no deployment potential above 200°C. The total amount of industrial heat demand is estimated using internal IEA data.
- In the levelised cost calculation, a COP of 5 is assumed for the temperature lift of 50°C, and a COP of 2 for the 120°C lift. This is based on the average COP of real heat pumps as listed by HPT TCP (2023).
- The theoretical maximum COP is the Lorenz COP. It is calculated using the ratio between the entropic mean temperature of the sink and the temperature lift.
- Sources: IEA analysis based on Marina, Spoelstra, Zondag, & Wemmers (2021); Taibi, Gielen, & Bazilian (2010); ITP Thermal (2019); Madeddu et al. (2020); HPT TCP (2023); US Energy Information Administration (2021).

Near-zero emissions steel

- “Near-zero emissions” refers to projects that, once operational, will operate at an emissions intensity consistent with near-zero emissions from the start, as defined in the IEA report *Achieving Net Zero Heavy Industry Sectors in G7 Members* (IEA, 2022c).
- “Near-zero emissions capable” refers to capacity that operates using the same core process equipment as near-zero emissions capacity and will achieve a substantial reduction in emissions intensity (compared to current conventional technologies) from the start – but initially fall short of the emissions intensity for near-zero emissions – with plans to reduce emissions further to a level consistent with near-zero emissions at a later date and with technical capabilities such that it could achieve near-zero emissions production without substantial additional capital investments in core process equipment.

- "Announced" is the estimated capacity based on publicly available project announcements for iron-based steel and includes both near-zero emissions and near-zero emissions capable capacity. Based on publicly available information as of November 2025.
- Assumed materials prices for market size estimation are derived using the evolution of levelised cost of production and demand in each scenario.
- Near-zero emissions steel includes both iron-based and scrap-based steel production.
- Levelised cost of production (LCOP) estimates are based on regional averages in 2035 in the STEPS and are reported per tonne of crude steel. Conventional production is represented by production from blast furnace basic oxygen furnace and natural gas direct reduced iron electric arc furnace pathways and near-zero emissions production is represented by hydrogen direct reduced iron electric arc furnace pathways. Costs do not include any explicit policy supports, e.g. carbon pricing or subsidies. The box represents the range of expected typical LCOP values, while the whiskers include the average LCOP in higher- or lower-cost regions. Cost premiums are calculated based on the difference between LCOP for conventional and near-zero emissions production in each region. The global average production cost premium is based on the difference between the median LCOP across regions for conventional and near-zero emissions.
- Cost pass-through of cost premiums to final products are estimated as follows: Prices for technologies are based on 2024 capital costs (including installation costs) of typical products, which are USD 40 000 for an electric car, USD 1 030 per kilowatt (kW) of onshore wind power, and USD 700 per kW of utility solar PV power. The assumed material intensities are global averages and constant over time. Cost increases are derived from the difference in production cost between near-zero emissions and conventional steel, following the methodology described in the previous paragraph. Two value chain stages with a 10% profit margin have been assumed, used as an illustrative average to account for the escalation of initial material costs across the value chain.
- The share of historical conventional steel by final use is calculated using the IEA's model of steel consumption by end use sector (IEA, 2025f) including sources such as (Cullen, Allwood, & Bambach, 2012). Share of near-zero commitments is based on sectoral representation of members within key private sector demand aggregation initiatives for near-zero emissions steel and of companies that have publicly announced commitments, including letters of intent, memoranda of understanding, and offtake agreements. Share of near-zero offtakes is based on estimated quantities of near-zero emissions steel purchases from publicly announced commitments. Based on publicly

available information as of November 2025. Demand growth to 2030 is based on the STEPS and represents the global total.

- Potential coverage of voluntary labels for near-zero and low-emissions steel is based on production volumes based on membership under private organisations or based on jurisdiction of governments that have released or are developing voluntary labels.

Near-zero emissions cement

- "Near-zero emissions" refers to capacity that, once operational, will operate at an emissions intensity consistent with near-zero emissions from the start, as defined in the IEA report *Achieving Net Zero Heavy Industry Sectors in G7 Members* (IEA, 2022c).
- "Near-zero emissions capable" refers to capacity that operates using the same core process equipment as near-zero emissions capacity and will achieve a substantial reduction in emissions intensity (compared to current conventional technologies) from the start – but initially fall short of the emissions intensity for near-zero emissions – with plans to reduce emissions further to a level consistent with near-zero emissions at a later date and with technical capabilities such that it could achieve near-zero emissions production without substantial additional capital investments in core process equipment.
- "Announced" is the estimated capacity based on publicly available project announcements for cement production and includes both near-zero emissions and near-zero emissions capable capacity. Based on publicly available information as of November 2025.
- Assumed materials prices for market size estimation are derived using the evolution of LCOP and demand in each scenario.
- LCOP estimates are based on regional averages in 2035 in the STEPS. Conventional production is represented by production from dry kiln pathways and near-zero emissions production is represented by dry kiln with carbon capture and storage pathways. Costs do not include any explicit policy supports, e.g. carbon pricing or subsidies. The box represents the range of expected typical LCOP values, while the whiskers include the average LCOP in higher- or lower-cost regions. Cost premiums are calculated based on the difference between LCOP for conventional and near-zero emissions production in each region. The global average production cost premium is based on the difference between the median LCOP across regions for conventional and near-zero emissions.
- Cost pass-through of cost premiums to end products are estimated as follows: Prices for infrastructure are based on 2024 capital costs, which are USD 420 000 for the construction of a single-family home, USD 950 000 for construction of a kilometre of paved lane, and USD 2 550 000 for construction

of a kilometre of track. The assumed material intensities are global averages and constant over time. Cost increases are derived from the difference in production cost between near-zero emissions and conventional steel, following the methodology described in the previous paragraph. Two value chain stages with a 10% profit margin have been assumed, used as an illustrative average to account for the escalation of initial material costs across the value chain.

- Green public procurement coalition refers to the Industrial Deep Decarbonisation Initiative (IDDI); membership of IDDI as of November 2025. Current IDDI members are Australia, Brazil, Canada, Germany, India, Japan, Saudi Arabia, the United Arab Emirates, the United Kingdom, and the United States. Share of public procurement is taken as a constant global average for the purposes of the analysis. IEA analysis is based on publicly available estimates on share of public procurement (Global Efficiency Intelligence, 2024a) and (Global Efficiency Intelligence, 2024b).
- Potential coverage of voluntary labels for near-zero and low-emissions cement is based on production volumes based on membership under private organisations or based on jurisdiction of governments that have released or are developing voluntary labels.

Recycling technologies

- EVs = Electric vehicles.
- When not stated otherwise, projected data refers to the STEPS.
- “Recycling rate” is defined as the efficiency of the entire recycling supply chain (collection, separation, metallurgy), while “share of demand met by recycling” is defined as the share of total material demand met by recycled inputs.
- Other critical minerals include nickel, manganese, cobalt, graphite, lithium, neodymium, praseodymium, terbium and dysprosium.
- Global available feedstock shows maximum possible feedstock volumes for recycling before any collection rates or recycling process yield losses. Projected capacity is based on announced projects. 85% maximum utilisation rate for production capacity is assumed. Recycling capacity refers to material recovery capacity. Available feedstock excludes batteries from portable electronics and e-bikes.
- Sources: IEA (2024a); Bloomberg (2025); Food and Agriculture Organization of the United Nations (2025); US Geological Survey (2025); IEA (2021); World Gold Council (2024); and Silver Institute (2025).

Solar PV and wind

- Detailed levelised cost of electricity and value-adjusted levelised cost of electricity are available from (IEA, 2025h) (annex B).

Nuclear

- CAPEX = capital expenditure; SMR = small modular reactor.
- Annual investment spending is presented as a 5-year average.
- 2024 Value-adjusted levelised cost of electricity (VALCOE) represents an average for coal, gas, and nuclear power generation, and is available from (IEA, 2025h) (annex B). Potential reflects potential cost reductions associated with a deployment trajectory consistent with the Announced Pledges Scenario by 2040 (see analysis in IEA [2025i]).

Geothermal

- Market sizing is based on the share of the annual investment that is associated with equipment manufacturing (i.e. excluding items such as permitting costs, exploration, drilling). See page 26 of (IEA, 2024b).
- Potential cost reduction is based on a high level of transfer and productivity gains from the oil and gas industry and correspond to next-generation geothermal. See pages 68 and 69 of (IEA, 2024b).
- VALCOE is based on the STEPS from IEA (2025h). In case full cost reduction potential is reaped, next-generation geothermal could reach parity with fossil-based generation (IEA, 2024b).
- Technical potential for next-generation geothermal from IEA (2024b).
- Venture capital data from Group,C. (2025), Crunchbase (2025).

Stationary energy storage technologies

- In IEA's *Global Energy and Climate* (GEC) *Model* (IEA, 2025f), lithium-ion batteries serve as a proxy for stationary energy storage technologies. This reflects their commercial maturity and modelling constraints. Consequently, the model represents stationary storage using utility-scale lithium-ion battery systems with different storage duration ranges, and the corresponding global market size is estimated based on their costs. These results should not imply that all future deployment of stationary storage would be met exclusively by lithium-ion batteries. Instead, they serve as an economically representative benchmark for current technologies. Other storage technologies, such as redox-flow batteries, compressed air, or thermal storage, may ultimately deliver the required flexibility and duration ranges, particularly as their costs decline or they become better suited to specific system needs. For example, batteries are less suited for long-duration storage (>10 hours), creating opportunities for alternative technologies to meet this need.

- Short-term flexibility addresses hour-to-hour variations in demand and supply. Today, typical requirements for short-term flexibility are equivalent to around 10% of average demand. In the GEC model, by 2035, short-term flexibility needs are handled by a combination of batteries, demand response, hydropower, thermal power and curtailment (IEA, 2025h).
- The levelised cost of electricity delivered from each energy storage technology includes CAPEX, fixed and variable operating costs (OPEX), and the cost of input energy, namely electricity for charging, or hydrogen production for hydrogen turbines or natural gas for single-cycle gas turbines, which serve as a benchmark for today's dispatchable generation technologies. Typical conversion efficiencies and energy losses are considered. The uncertainty range reflects different annual full-load hours, with the lower bound corresponding to 2 000 hours and the upper bound to 250 hours. For hydrogen and natural gas peaker plants, the uncertainty range also reflects variability in fuel prices. For hydrogen, the assumed range of low-emissions prices is from USD 3.4/kg H_2, corresponding to the minimum levelised cost of renewable hydrogen production achievable with current technologies in China, to USD 8.0/kg H_2. Higher low-emissions hydrogen prices are possible but would make the technology uncompetitive for providing dispatchable capacity. For natural gas, prices are assumed to range from USD 3 per million British thermal units (MMBtu) to USD 15/MMBtu. A constant electricity price of USD 40/MWh is assumed in all cases.
- The maximum storage duration range presented reflects economically feasible potential rather than technical limits. While it is technically possible to extend the storage duration of certain technologies, such as using electrochemical batteries for longer discharge periods, doing so would generally result in lower capacity factors and substantially higher levelised costs of energy storage. Therefore, the storage duration ranges are based on economic considerations and current and near-term prospects rather than on technological capabilities.

Low-emissions H_2, ammonia and methanol

- Low-emissions hydrogen includes hydrogen which is produced through water electrolysis with electricity generated from low-emissions sources, such as renewables like solar and wind turbines, and nuclear. Hydrogen produced from biomass or from fossil fuels with CCUS technology is also counted as low-emissions hydrogen. However, production from fossil fuels with CCUS is only included if upstream emissions are sufficiently low, capture is applied at high rates to all CO_2 streams associated with the production route, and all CO_2 is permanently stored to prevent its release into the atmosphere. The same principles apply to low-emissions feedstocks and hydrogen-based fuels, such as methanol, produced using low-emissions hydrogen and a sustainable carbon source, i.e. this must be of biogenic origin or directly captured from the atmosphere, but not from fossil fuels or fossil-derived process emissions.

- The market size is estimated based on the weighted average cost of low-emissions hydrogen and its main derivatives in the region of consumption, including low-emissions ammonia, low-emissions synthetic methanol (using CO_2 as a feedstock, not syngas), synthetic methane, and synthetic kerosene. In the dashboard, ammonia's market size includes its use both as a fuel and as a feedstock for fertilisers, explosives, and other industrial applications. Similarly, the market size of methanol covers both fuel and feedstock uses. The market size under "Other H_2 uses" includes pure hydrogen applications (such as direct combustion, iron ore reduction and inputs to biorefineries), as well as synthetic methane and synthetic kerosene. It also includes hydrogen used as a feedstock to produce high value-added chemicals, accounted for based on the value of the hydrogen input, rather than that of the final chemical product.
- The map of hydrogen production from electrolysis reflects the production from the least-cost configuration of renewable energy supply and storage. It considers an optimised combination of solar PV, onshore and offshore wind and battery storage, operating off-grid with the electrolyser, to minimise the levelised cost of electrolytic hydrogen. The electrolyser capacity factor is optimised accordingly. Water costs are not included. A larger version of the map can be consulted at IEA's Hydrogen Tracker (IEA, 2025j).
- The range in the levelised cost of hydrogen production reflects regional differences in fossil fuel prices, renewable costs, technology CAPEX and OPEX as well as cost of capital. Electrolyser CAPEX includes the electrolyser system, balance of plant, engineering, procurement and construction, and contingencies; electrolyser capacity factor is assumed to be the same as the renewable power plant. Figure is capped at USD 12/kg H_2, although some production routes reach higher values. Water cost is not included. Detailed techno-economic data can be found in the Annex of IEA's *Global Hydrogen Review 2025* (IEA, 2025g).
- Hydrogen pipeline capacity is represented as a weighted average of 6.9 GW, reflecting a typical mix of pipeline diameters rather than a single one. The assumed mix includes 48-inch (~1 200 mm, 12.7 GW), 36-inch (~900 mm, 3.6 GW) and 20-inch (~500 mm, 0.9 GW) pipelines operating at 75% of their design capacity for 5 000 full-load hours (IEA, 2023). Seaborne trade of ammonia includes shipping of both fossil-based ammonia and low-emissions ammonia.

Sustainable aviation fuels production

- Sustainable aviation fuels include biojet kerosene and synthetic kerosene.
- Prices for HEFA biojet and fossil kerosene are taken as January-September 2025 averages across major regions (Europe, North America, China, Singapore) and IEA analysis based on Argus (2025). Ranges for HEFA biojet prices are given as error bars. For emerging pathways, no market prices exist yet and thus average estimated production costs are provided based on IEA analysis with error bars giving the range of estimated costs for e-SAF, based on the cost of renewable electricity supply and regional differences.
- The ticket price increase under ReFuelEU was calculated as the extra airline cost due to the mandated use of SAF compared to using 100% fossil kerosene in 2035. It was assumed that fuel accounts for 26% of total airline operating cost and that airlines have a profit margin of 4% (IATA, 2025). ReFuelEU mandates the use of 20% SAF with a sub-mandate of 5% for e-SAF. Following IEA cost projections, bio-SAF was assumed to be 2.2 times more expensive as fossil kerosene in 2035, and e-SAF 6.2 times.
- The pipeline of SAF production projects using emerging pathways is based on IEA analysis based on IEA (2025e).
- GHG intensities for the bio-SAF pathways are taken from R&D GREET 2024 Rev1, where direct land use change is included, but indirect is excluded. Carbon capture and storage (CCS) assumptions and e-SAF pathways are based on IEA analysis.

Carbon dioxide removal: BECCS and DAC

- BECCS = bioenergy with carbon capture and storage; DAC = direct air capture.
- Historical deployment of BECCS, DAC and CO_2 storage is based on the IEA CCUS Projects Database (IEA, 2025k).
- 2024 market size was based on volumes of BECCS and DAC credits and average credit prices in 2024 (CDR.fyi, 2025b; S&P, 2025). 2035-2050 markets are based on volumes of CO_2 removed via BECCS and DAC in each scenario multiplied by assumed carbon price (see Annex B of IEA (2025h) for selected carbon prices in the CPS, STEPS, and NZE Scenario).
- 2024 cost was estimated based on available capital and operating cost information from existing projects:
- Bioethanol plants: CAPEX: USD 58-285 million; fixed OPEX: 5%; electricity input: 0.66 GJ per tonne CO_2; CO_2 captured: 0.16-0.50 Mt CO_2 per year; electricity price: USD 80/MWh; CO_2 transport and storage fee: USD 0 per tonne CO_2 (integrated); carbon removal efficiency: 87%; WACC: 8%; project lifetime: 25 years.

- Combined heat and power: CAPEX: USD 1 230 million; fixed OPEX: 4%; heat input: -2.4 GJ/tonne CO_2 (recovery); electricity input: 2 GJ per tonne CO_2; CO_2 captured: 0.87 Mt CO_2 per year; heat price: USD 121/MWh; electricity price: USD 36/MWh; CO_2 transport and storage fee: USD 70-105 per tonne CO_2; carbon removal efficiency: 90%; WACC: 8%; project lifetime: 15 years.
- Solid-DAC: CAPEX: USD 11-17 million; fixed OPEX: 18%; heat input: 7.2 GJ/tonne CO_2; electricity input: 2.3 GJ per tonne CO_2; CO_2 captured: 0.0036 Mt CO_2 per year; heat price: USD 5/MWh; electricity price: USD 57/MWh; CO_2 transport and storage fee: USD 30 per tonne CO_2; carbon removal efficiency: 90%; WACC: 8%; project lifetime: 10 years.
- Liquid-DAC: CAPEX: USD 2 600 million; fixed OPEX: 5%; gas input: 5.3 GJ/tonne CO_2; electricity input: 1.3 GJ per tonne CO_2; CO_2 captured: 0.98 tonnes CO_2 per year; gas price: USD 8/MWh; electricity price: USD 64/MWh; CO_2 transport and storage fee: USD 30 per tonne CO_2; carbon removal efficiency: 90%; WACC: 8%; project lifetime: 25 years.
- Potential reflects levelised costs that could be reached without the cost premiums that are typically associated with first-of-a-kind plants: BECCS based on IEAGHG (2021a); Schmitt, et al. (2022); and NETL (2022); DAC based on IEAGHG (2021b); McQueen, et al. (2021); and Keith, et al. (2018).
- Historical average prices on voluntary carbon markets estimated from disclosed deals between 2021 and 2025 (CDR.fyi, 2025b; S&P, 2025).

References

AHRI. (2025). *the Air-Conditioning, Heating and Refrigeration Institute*. Retrieved from https://www.ahrinet.org/

HPT TCP. (2023). *High-Temperature Heat Pumps - Task 1 - Technologies*. Retrieved from https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2023/09/annex-58-task-1-technologies-task-report.pdf

Argus. (2025). *Argus Direct*. Retrieved from https://www.argusmedia.com/en/solutions/how-we-deliver/client-portal/argus-direct-workspaces

Bloomberg. (2025). *Precious and Industrial Metals*. Retrieved from https://www.bloomberg.com/markets/commodities/futures/metals

Boston Consulting Group. (2025). The $10 Billion Opportunity in Green Shipping. *Boston Consulting Group*. Retrieved from https://www.bcg.com/publications/2025/the-10-billion-opportunity-in-green-shipping

Buli, N. (2025). Heidelberg sells out of net-zero cement from Norway plant, CEO says. *Reuters*. Retrieved from https://www.reuters.com/sustainability/climate-energy/heidelberg-sells-out-net-zero-cement-norway-plant-ceo-says-2025-06-18/

CALSTART. (2025). *Drive to Zero's Zero-emission Technology Inventory (ZETI) Tool Version 9.0*. Retrieved from https://globaldrivetozero.org/tools/zeti/

CDR.fyi. (2025a). *2024 Year in Review*. Retrieved from CDR.fyi: https://www.cdr.fyi/blog/2024-year-in-review

CDR.fyi. (2025b). *Key Metrics*. Retrieved from https://www.cdr.fyi/

China Commercial Vehicles Dealers Association. (2025). Retrieved from https://www.ccvda.cn/

China EV100. (2025). Retrieved from https://www.chinaev100.com/

ChinaIOL. (2025). *ChinaIOL*. Retrieved from http://www.chinaiol.com/

Crunchbase. (2025). Retrieved from https://data.crunchbase.com/docs/using-the-api

Cullen, J., Allwood, J., & Bambach, M. (2012). Mapping the global flow of steel: from steelmaking to end-use goods. *Environ. Sci. Technol.* Retrieved from https://doi.org/10.1021/es302433p

EHPA. (2025). *European Heat Pump Association*. Retrieved from https://ehpa.org/

European Automobile Manufacturers' Association. (2025). *ACEA*. Retrieved from ACEA: https://www.acea.auto/

European Commission. (2025a). *Decarbonising maritime transport – FuelEU Maritime.* Retrieved from https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

European Commission. (2025b). Retrieved from European Alternative Fuels Observatory: https://alternative-fuels-observatory.ec.europa.eu/

EV Volumes. (2025). Retrieved from EV Volumes: https://ev-volumes.com/

Food and Agriculture Organization of the United Nations. (2025). *FAO Stat*. Retrieved from https://www.fao.org/faostat/en/#home

Global Efficiency Intelligence. (2024a). *The Scale and Impact of Green Public Procurement of Steel and Cement in Canada, Germany, the UK, and the US*. Retrieved from https://www.globalefficiencyintel.com/scale-and-impact-of-green-public-procurement-of-steel-and-cement-in-canada-germany-uk-us

Global Efficiency Intelligence. (2024b). *Advancing Green Public Procurement of Steel and Cement in China*. Retrieved from https://www.globalefficiencyintel.com/green-public-procurement-of-steel-and-cement-in-china

Group, C. (2025). Retrieved from https://i3connect.com/

IATA. (2025). *Airline Profitability to Strengthen Slightly in 2025 Despite Headwinds*. Retrieved from https://www.iata.org/en/pressroom/2025-releases/2025-06-02-01

IEA. (2021). *The Role of Critical Minerals in Clean Energy Transitions*. Retrieved from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IEA. (2022a). *Technology and Innovation Pathways for Zero-carbon-ready Buildings by 2030*. Retrieved from https://www.iea.org/reports/technology-and-innovation-pathways-for-zero-carbon-ready-buildings-by-2030/introduction

IEA. (2022b). *Is the biofuel industry approaching a feedstock crunch?* Retrieved from https://www.iea.org/reports/is-the-biofuel-industry-approaching-a-feedstock-crunch

IEA. (2022c). *Achieving Net Zero Heavy Industry Sectors in G7 Members*. Retrieved from https://www.iea.org/reports/achieving-net-zero-heavy-industry-sectors-in-g7-members

IEA. (2023). *Energy Technology Perspectives 2023*. Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2023

IEA. (2024a). *Recycling of Critical Minerals*. Retrieved from https://www.iea.org/reports/recycling-of-critical-minerals

IEA. (2024b). *The Future of Geothermal Energy*. Retrieved from https://www.iea.org/reports/the-future-of-geothermal-energy

IEA. (2025a). *Demand and Supply Measures for the Steel and Cement Transition*. Retrieved from https://www.iea.org/reports/demand-and-supply-measures-for-the-steel-and-cement-transition

IEA. (2025b). *ETP Clean Energy Technology Guide*. Retrieved from https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

IEA. (2025c). *Global EV Outlook 2025*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2025

IEA. (2025d). *Races to First in Energy Innovation*. Retrieved from https://www.iea.org/data-and-statistics/data-tools/races-to-first-in-energy-innovation

IEA. (2025e). *Renewables 2025*. Retrieved from https://www.iea.org/reports/renewables-2025

IEA. (2025f). *Global Energy and Climate Model*. Retrieved from https://www.iea.org/reports/global-energy-and-climate-model

IEA. (2025g). *Global Hydrogen Review 2025.* Retrieved from https://www.iea.org/reports/global-hydrogen-review-2025

IEA. (2025h). *World Energy Outlook 2025*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2025

IEA. (2025i). *The path to a new era for nuclear energy.* Retrieved from https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy

IEA. (2025j). *Hydrogen Tracker*. Retrieved from https://www.iea.org/data-and-statistics/data-tools/hydrogen-tracker

IEA. (2025k). *CCUS Projects Database*. Retrieved from https://www.iea.org/data-and-statistics/data-product/ccus-projects-database

IEAGHG. (2021a). *Biorefineries with CCS*. Retrieved from https://ieaghg.org/publications/biorefineries-with-ccs/

IEAGHG. (2021b). *IEAGHG Technical Report 2021-05*. Retrieved from https://publications.ieaghg.org/technicalreports/2021-05%20Global%20Assessment%20of%20Direct%20Air%20Capture%20Costs.pdf

IMO. (2025a). *New sulphur emission limits enter into effect in the Mediterranean.* Retrieved from International Maritime Organization: https://www.imo.org/en/mediacentre/pages/whatsnew-2254.aspx

IMO. (2025b). *IMO approves net-zero regulations for global shipping.* Retrieved from International Maritime Organization: https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-approves-netzero-regulations.aspx

ITP Thermal. (2019). *Renewable Energy Options for Industrial Process Heat*. Retrieved from https://arena.gov.au/assets/2019/11/renewable-energy-options-for-industrial-process-heat.pdf

JRAIA. (2025). *Japan Refrigeration and Air Conditioning Industry Association*. Retrieved from https://www.jraia.or.jp/

Keith, et al. (2018). A Process for Capturing CO_2 from the Atmosphere. Retrieved from https://www.sciencedirect.com/science/article/pii/S2542435118302253

Madeddu et al. (2020). The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research*. Retrieved from https://iopscience.iop.org/article/10.1088/1748-9326/abbd02/pdf

Marina, A., Spoelstra, S., Zondag, H., & Wemmers, A. (2021). An estimation of the European industrial heat pump market potential. *Renewable and Sustainable Energy Reviews*. Retrieved from https://www.sciencedirect.com/science/article/pii/S1364032120308297

Marklines. (2025). *Information Platform*. Retrieved from https://www.marklines.com/en/

McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. (2021). A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Retrieved from https://iopscience.iop.org/article/10.1088/2516-1083/abf1ce

NETL. (2022). *Cost of Capturing CO_2 from Industrial Sources*. Retrieved from https://www.netl.doe.gov/energy-analysis/details?id=865aaad2-9252-44d9-a48a-95599b3072b4

S&P. (2025). *Engineered carbon dioxide removal purchases tracker*.

S&P Global Mobility. (2025). *Global New Vehicle Registrations*. Retrieved from https://www.marketplace.spglobal.com/en/datasets/global-new-vehicle-registrations-(248)

Schmitt, T., Leptinsky, S., Turner, M., Zoelle, A., White, C. W., Hughes, S., James III, R. E. (2022). Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Retrieved from https://www.osti.gov/biblio/1893822

Silver Institute. (2025). *Silver Supply and Demand*. Retrieved from https://silverinstitute.org/silver-supply-demand/

Taibi, E., Gielen, D., & Bazilian, M. (2010). Renewable Energy in Industrial Applications - An assessment of the 2050 potential. *United Nations Industrial Development Organization*. Retrieved from https://www.researchgate.net/publication/339948715_Renewable_Energy_in_Industrial_Applications_-_An_assessment_of_the_2050_potential

United Nations Statistics Division. (2025). *UN Global Platform - Ship Register*. Retrieved from https://unstats.un.org/bigdata/task-teams/ais/index.cshtml

US Department of Energy. (2025). *Alternative Fuels Data Center*. Retrieved from https://afdc.energy.gov/

US Energy Information Administration. (2021). *Manufacturing Energy Consumption Survey*. Retrieved from https://www.eia.gov/consumption/manufacturing/data/2018/

US Geological Survey. (2025). *Commodity Statistics and Information*. Retrieved from https://www.usgs.gov/centers/national-minerals-information-center/commodity-statistics-and-information

World Gold Council. (2024). *Gold Demand Trends Q1 2024*. Retrieved from https://www.gold.org/goldhub/research/gold-demand-trends/gold-demand-trends-q1-2024/supply

WSJ. (2024). Maersk Orders LNG Ships and Takes a Detour on Its Green Goals. *Wall Street Journal*. Retrieved from https://www.wsj.com/business/earnings/maersk-reports-lower-net-profit-despite-strong-container-shipping-demand-b88540a8

Part B

Clean energy technology manufacturing and trade

While the present wave of investment in clean energy technology manufacturing is now falling back, the future trajectory of investment will, in large part, be shaped by efforts to diversify supply chains. Several governments are adopting an increasingly defensive posture on clean energy technology trade, seeking to shield domestic industries from foreign competition and alleged unfair practices. Nevertheless, trade continues to play a central role in the outlook for manufacturing key clean energy technologies.

Part B of this publication includes an in-depth examination of recent developments in clean energy technology manufacturing and trade (Chapter 4), focusing on the policy changes, project announcements and other developments related to key mass-manufactured clean energy technologies that have taken place since *ETP-2024*. This forms the foundation for an updated scenario outlook (Chapter 5) for these mass-manufactured technologies, including manufacturing investment, production, capacity and trade flows.

Chapter 4. Recent trends

Highlights

- Global investment in manufacturing capacity for six clean energy technologies – solar photovoltaic (PV), wind, batteries, electric vehicles (EVs), electrolysers and heat pumps – dropped below USD 200 billion in 2024, down from nearly USD 220 billion in 2023. This downwards trend is estimated to have continued in 2025, mainly due to weaker solar PV and wind manufacturing investment in China. The United States and the European Union are estimated to have accounted for around 30% of global manufacturing investment combined in 2025, up from 15% in 2023, marginally increasing global supply chain diversification.
- After dipping in 2024, global trade in clean energy technologies recovered in 2025, with gross imports for relevant product categories reaching an all-time high in the second quarter. This is despite prices for several technologies falling; solar PV module prices have fallen around 50% since 2023 with those for battery packs falling by 30%. China maintains an out-sized role in global trade in clean energy technologies, with its gross exports exceeding USD 165 billion in 2025 (50% of the global total excluding intra-EU trade). This is equivalent to around 15% of its trade surplus across all goods, which was approaching USD 1.2 trillion in 2025.
- Higher tariffs and duties on clean energy technologies in the United States have contributed to significant increases in domestic production as a share of demand: 40 and 25 percentage points during 2023-2025 for solar PV modules and battery cells respectively. Production tax credits still in place in 2025 and shifting trade patterns offset around half of the estimated increase in average costs across imports and domestic production. In other major importing regions, average costs of batteries are estimated to have fallen due to lower global commodity prices.
- The manufacturing project pipeline has contracted across most clean energy technologies since 2024. The capacity of announced projects that have been completed or cancelled since the last review exceeds that of newly announced projects. This reflects well-supplied markets for several clean energy technologies, notably for solar PV and batteries, and uncertainty about the pace of future deployment.
- Industry margins have tightened across the board. Solar PV manufacturers have seen margins collapse under intense price competition, notably in China, with the top ten firms posting USD 4.5 billion in losses in 2024. Western wind producers, which incurred losses in 2022-23, are beginning to recover, while profits at Chinese wind firms are being squeezed by falling prices. Chinese battery makers remain profitable on average thanks to a small number of high performers, but those outside China are struggling to maintain positive margins.

Global investment and trade

Overall manufacturing investment and trade

Global investment in manufacturing has experienced substantial growth in recent years and is estimated to have stood at around USD 7.5 trillion per year in 2025.[1] It has more than doubled over the past two decades and, by 2024, was 20% higher than in 2019 and 4% up on 2023. This growth has been led primarily by the People's Republic of China (hereafter, "China"), driven by investment in electrical machinery, electronic engineering and high-tech goods, and India, where investment in consumer durables has almost doubled. Between 2019 and 2024, manufacturing investment increased by 50% in China. The United States also saw strong growth, with investment rising by around 15% over the same period, led by electronics (including investment in chip manufacturing facilities, but not data centres, as these are not manufacturing investments) and agricultural machinery. In contrast, Japan recorded a modest contraction while the European Union saw a 30% decrease.

Following a sharp contraction in 2020, the value of global trade in goods and services rebounded strongly, reaching nearly 7% above pre-pandemic levels by 2024. The recovery was more pronounced in services trade, which stood at more than 8% above 2019 levels in 2024, while goods trade was closer to 6% higher. While the physical volumes of goods trade increased between 2023 and 2024, falling prices in some categories such as fuel reduced the value of trade. Goods trade volume growth has been stronger than expected in 2025, due to surges in imports ahead of the imposition of new tariffs and duties in some advanced economies, supportive fiscal policies and strong growth in emerging markets.

In 2025, a series of new tariffs has raised the cost of imported goods for several countries, particularly the United States. Accounting for tariff announcements across all goods imports, the volume-weighted announced tariff rate in the United States rose to around 18% – up from around 3% at the end of 2024. Tariffs on imports from certain trading partners, notably China and India, are considerably higher.

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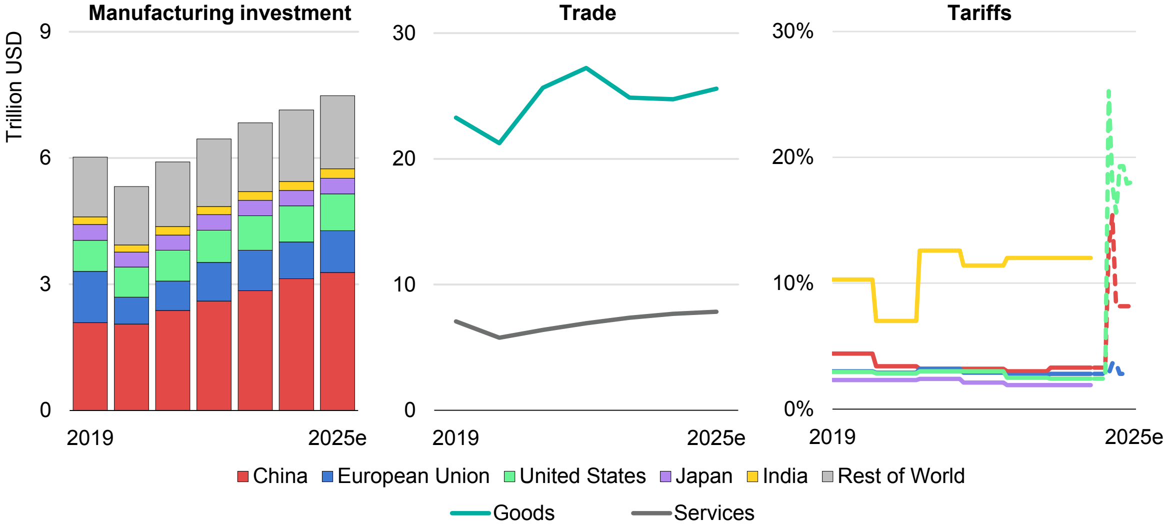
[1] Unless stated otherwise, USD figures are real 2024 dollars in market exchange rate terms throughout this report.

Figure 4.1 Global manufacturing investment, trade and tariffs, 2019-2025e



IEA. CC BY 4.0.

Notes: e = estimated. Manufacturing investment refers to manufacturing industries within ISIC Rev. 4 Divisions 10-33. Tariff rate values are averages across all goods and trading partners; values for 2025 shown as dashed lines are monthly estimates of the long-run effective rate based on announced policies up to 1 November 2025 for the United States, the European Union and China, not accounting for consumption shifts; data prior to 2025 are annual averages.

Sources: IEA analysis based on UN Trade & Development (2025); Oxford Economics Limited (2025); World Bank (2025); and The Budget Lab (2025).

Global goods trade and manufacturing investment rebounded strongly after the Covid-19 pandemic, but growth has since slowed due to geopolitical and trade policy uncertainties.

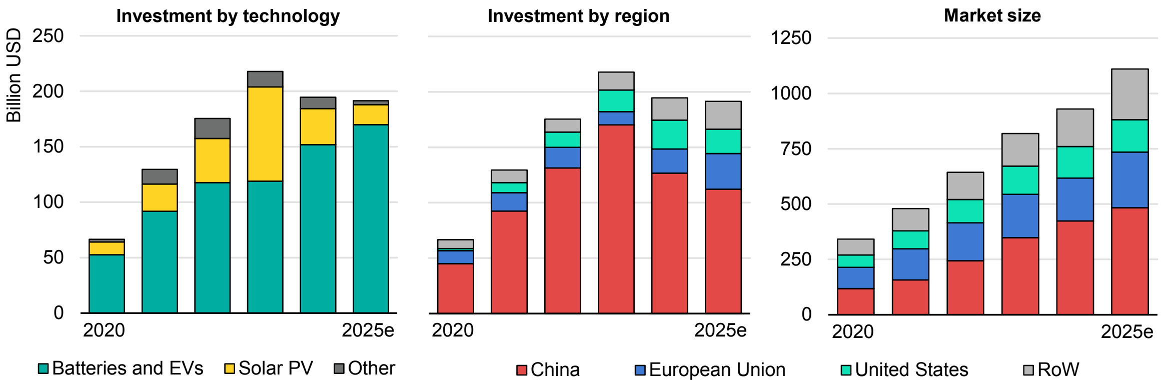
Based on announcements as of 1 November 2025, goods imported from China faced an average tariff of around 48%, down from a mid-April peak of approximately 135% (which was threatened but never fully imposed). This was based on a bilateral agreement between the United States and China, which removed broader tariffs while leaving targeted tariffs, such as Section 232 and 301 tariffs, in place. China responded throughout 2025 with reciprocal tariff increases on US imports. However, because US goods account for a smaller share of Chinese imports than vice versa, the average rate across all Chinese imports remained much lower, at around 8% in November 2025. Other major US trading partners have launched public consultations on possible countermeasures but have not yet announced formal actions.

Clean energy technology manufacturing investment

Global investment in facilities to manufacture clean energy technologies has fallen back recently, following several years of rapid growth in response to surging deployment. In 2023, investment in plants making six mass-manufactured clean energy technologies – solar PV, wind turbines, EVs and batteries, heat pumps and electrolysers (the focus of Part B)[2] – reached nearly USD 220 billion, before declining by 6% to less than USD 200 billion in 2024 (Figure 4.2). For comparison, global investment in oil production the same year was around USD 450 billion. An assessment of plants built and under construction in 2025 points to clean energy technology manufacturing investment continuing a gentle downward trend.

These investments in manufacturing capacity are being made in order to gain access to the market for key clean energy technologies, which continues to grow strongly. The size of this market increased by almost 15% globally in 2024, and is expected to have surpassed USD 1.1 trillion in value in 2025, which is roughly equivalent in size to the global market for coal. EVs make up over 75% of the market by value. China remains the largest market globally and has seen average annual growth of around 40% since 2020, owing to consistently strong clean energy technology deployment. Outside of China, developing economies are expected to have seen some of the strongest growth rates in 2025, at around 35% on average, in part owing to low-cost imports from China.

Figure 4.2 Global investment in selected clean energy technology manufacturing and global market size by technology and country/region, 2020-2025e



IEA. CC BY 4.0.

Notes: EVs = electric vehicles; RoW = Rest of World. Batteries and EVs includes anode and cathode active materials, battery cells and electric cars. Solar PV includes polysilicon, wafers, cells and modules. “Other” includes electrolysers, heat pumps and wind turbines, blades and nacelles.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

The first wave of clean energy technology manufacturing spending has faded; the combined market for these technologies is estimated to have surpassed USD 1.1 trillion in 2025.

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[2] This group of technologies and subsets thereof are referred to as ‘key clean energy technologies’ throughout Part B (Chapters 4 and 5).

In 2024, factories producing batteries and electric cars accounted for more than 75% of total clean energy manufacturing investment, with an increase by approximately USD 20 billion and USD 10 billion that year, respectively. This reflects sustained demand: Global sales of electric cars continued to grow strongly, exceeding 17 million in 2024, and are estimated to have reached 21 million in 2025. In contrast, investment in the solar PV supply chain fell by 50% in 2024. This decline was driven by intense price competition and a large overhang of manufacturing capacity, which for modules had increased by 70% in 2023. Wind energy manufacturing investment also saw a downturn, falling from USD 12 billion in 2023 to less than USD 10 billion in 2024. This was largely the result of a difficult market environment in recent years, marked by supply chain disruptions, profitability pressures and auction rounds for offshore wind farms that in some cases failed to attract any bids.

China continues to attract the majority of global investment in clean energy manufacturing, accounting for around 70% of cumulative spending since 2020. It is also associated with a significant share of the manufacturing investment occurring in other countries. While a full asset-level dataset for these investments is not available to this study, the scale of these outward financial flows can be inferred from studies tracking foreign direct investment (FDI). One recent analysis highlights a sharp increase in outbound investment across a range of clean energy technologies, materials and infrastructure (Xue & Larsen, 2025).[3] It estimates that China's cumulative outbound FDI in these areas reached nearly USD 200 billion between 2022 and the first half of 2025 – roughly six times the total over the preceding 9 years.

Despite China's outsized role in these areas of investment, recent shifts in regional dynamics indicate that the manufacturing base may be broadening. In the **European Union**, investment almost doubled from 2023 to 2024, driven by industrial policy initiatives such as the Net-Zero Industry Act (NZIA) and the Clean Industrial Deal. These and other measures have boosted domestic demand and expanded the size of the internal market. Despite this momentum, EU manufacturers are struggling to compete – particularly for batteries and EVs – with Asian firms, which benefit from lower production costs and greater economies of scale (see Chapter 7). These pressures, along with difficulties in scaling up production, have led to the cancellation or failure of several EU battery projects (see below). Nonetheless, battery production in the European Union, which is currently dominated by Korean and Chinese companies operating within the region, is expected to have grown in 2025, supported by committed projects and rising EV demand (IEA, 2025c).

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[3] This estimate does not fully align with the scope of the technologies in this chapter.

A recent slump in EU heat pump demand has led at least one EU manufacturer to postpone or cancel manufacturing capacity expansions that were announced during the post-2022 market boom (CoolingPost, 2025). However, others have continued to invest. Panasonic, for example, is expanding its European manufacturing activities (Panasonic Group, 2025), while Midea – another overseas company – is pursuing acquisition and integration initiatives (Midea, 2025).

In the **United States**, the One Big Beautiful Bill Act was passed into law in July 2025, eliminating several tax credits that support the deployment of clean energy technologies, including the 30D and 45W EV tax credits. The 45X manufacturing tax credits remain largely in place, with the exception of those for wind, which are scheduled to expire after 2027. However, uncertainty persists around how strengthened local content requirements and rules around foreign influence will be administered. These uncertainties, together with expectations of weaker domestic demand for EVs following the withdrawal of the 45W credits, have led some manufacturers to cancel projects and others to pause investment plans (Clean Investment Monitor, 2025). As a result, US manufacturing investments, which rose from over USD 19 billion in 2023 to more than USD 25 billion in 2024, are estimated to have declined by around 15% in 2025. Investment in the EV and battery supply chain – which accounts for the vast majority of total clean energy manufacturing investment in the United States – is expected to have declined even more sharply.

Several other regions have also seen strong growth in clean energy manufacturing investment. In **Korea**, investment in battery and EV manufacturing (including upstream components) grew by 25% in 2024, reflecting a renewed focus on industry. Meanwhile, **India**'s total clean energy investment, spanning all major technologies, increased by more than 65% in 2024.

Clean energy technology trade

International trade statistics for product categories that broadly align with the six technologies covered in this chapter indicate a modest decline of around 6% in the global value of trade in 2024 (Figure 4.3).[4] Estimates for 2025 based on data for the first three quarters of the year point to a rebound of around 10%. Physical volumes are continuing to rise with falling unit prices (see below) and rapidly growing deployment. In 2024, demand increased by 30% for batteries and 15% for both solar PV and wind turbines (see Chapter 2).

International trade remains vital to meeting global demand for clean energy technologies. With the exception of China, most countries rely heavily on imports

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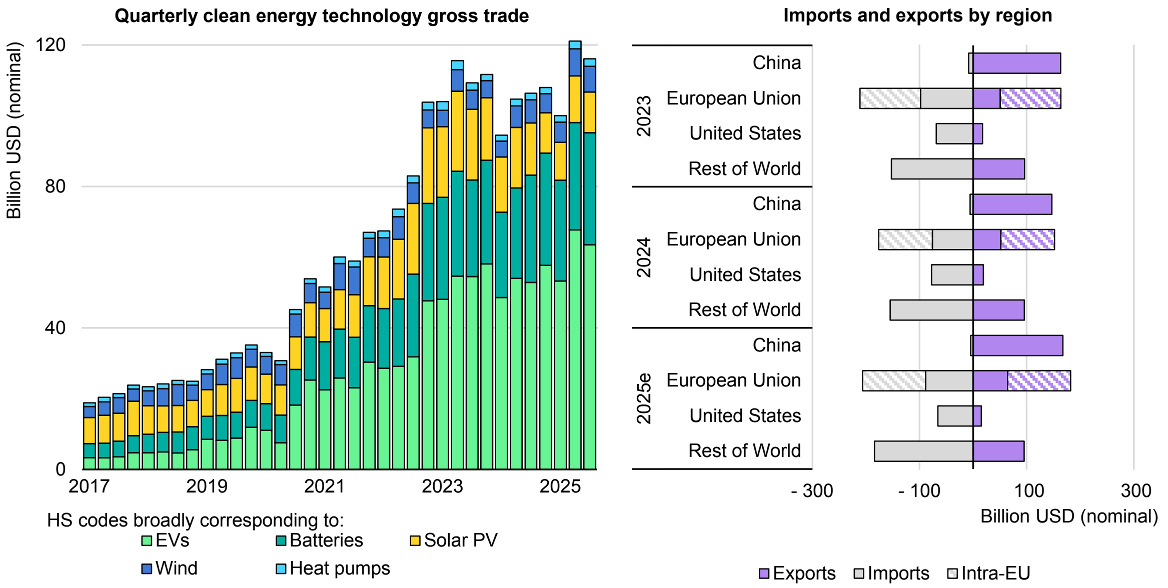
[4] Gross values of trade in monetary units in this publication broadly correspond to those reported in trade statistics.

of technologies, components and materials to meet their rising demand. In 2025, the United States is estimated to have accounted for 15% of global gross imports (20% excluding intra-EU trade), the European Union for 45% (60% excluding intra-EU trade), and India for 2% (also around 2% excluding intra-EU trade). Many countries that are net importers of a given technology also export significant volumes of another, or of their components. The United States and European Union were the largest gross importers across these product categories, though the United States' exports amounted to roughly 25% of its imports in value terms, while they were closer to 70% for the European Union (excluding intra-EU trade).

Figure 4.3 Gross trade for key clean energy technology product categories, 2017-2025, and imports and exports by region, 2023-2025e



Notes: HS = Harmonised System; EVs = electric vehicles. Values are compiled based on statistical data on the value of trade collected by customs authorities for product categories that best correspond to the six key clean energy technologies examined in Part B of this publication. No data are available for electrolyser trade. Values are stated in gross terms, with no aggregation of individual country data. See IEA (2026) for details of the HS codes used.

Source: IEA analysis based on Sinoimex (2025).

The value of trade in clean energy technologies fell by 6% in 2024, with dependence on imports from China remaining high in all major regions.

EVs saw the second-largest fall in traded value among clean energy technologies in 2024. Nonetheless, taking into account recent US market and policy shifts, they are estimated to have accounted for more than 50% of total clean energy technology trade in 2025. Meanwhile, the traded value of solar PV modules saw the largest decline, despite trade volumes remaining stable at around 145 GW in 2023 and 2024. This divergence is largely due to a steep drop in prices, which fell by around 40% over the same period. This trend is expected to continue through 2025, with further price reductions contributing to a decline in the value of trade.

By virtue of its position as the dominant manufacturer, China is by far the largest single exporter of clean energy technologies. Its gross exports were worth about USD 150 billion in 2024 (around 40% of the global total; 50% excluding intra-EU trade), though this was the lowest level since 2022. In 2025, China's exports are estimated to have increased to more than USD 160 billion. This is equivalent to around 15% of its trade surplus across all goods, which reached almost USD 1.2 trillion in 2025. China's reliance on imports is negligible, as domestic manufacturing capacity is more than sufficient to meet internal demand. Indeed, domestic capacity far outstrips internal demand, by roughly four times for cathodes and cells, and three times for solar PV modules.

Most other regions are large net importers of clean energy technologies. In the European Union, a strategic push to expand domestic manufacturing has recently reduced reliance on imports. Excluding intra-EU trade, the import-to-export ratio fell from 1.6 in 2023 to an estimated 1.4 in 2025, driven largely by a surge in EV exports to other European countries (including the United Kingdom, Norway, Switzerland and Türkiye) and the United States. Over the same period, the EU solar industry shifted from heavy import dependence to becoming a net exporter in some countries and parts of the value chain. In the United States, import and export values are estimated to have decreased by 15-20% in 2025. Although domestic manufacturing capacity is expanding for key components such as cathodes, solar cells, and wafers, it has not kept pace with growing demand. Lower prices have also partially offset rising import volumes.

Low prices, a rapidly evolving trade policy landscape and significant excess capacity relative to demand globally for some technologies, are among the factors contributing to growing inventories. Consistent data on inventories are not available to this study, but estimates can be made for some technologies:

- Global production of **solar PV modules** was around 40% higher than demand in 2023 and around 30% higher in 2024. This has resulted in inventory build-up, especially in Europe and North America, to levels roughly double those of annual installations. This is around eightfold the typical levels that might be expected. The gap between demand and production appears to have narrowed in 2025, due to low prices and mounting financial losses for many producers, which has led to lower shipments. However, given their starting point, inventory levels are expected to have remained elevated in 2025 and continue to remain so thereafter.
- In 2023, global sales of Chinese-made **electric cars** outside China were around 275 000 cars lower than the exports reported by Chinese customs. This led to clogged ports, particularly in Europe and Brazil, and limited the capacity for additional imports in 2024 until excess inventory was cleared. In the first three quarters of 2025, exports outstripped overseas sales by around 350 000 units, which is roughly two months' worth of China's average EV exports. Some Chinese EV manufacturers are reporting inventory levels

exceeding 3 months' worth of sales, compared with a typical industry average of less than 6 weeks (Reuters, 2025a). Global inventories of **batteries** have also built up to an estimated 20–30% of annual demand during 2024.

The policy landscape

Government industrial and trade policies play a critical role in driving manufacturing investment, with far-reaching implications for export potential, import dependence, trade balances and surplus manufacturing capacity. They can shape cost structures and help improve overall competitiveness. While factors intrinsic to a location, such as access to affordable energy, specialised workforce and finance, remain important, industrial and trade policies, along with broader deployment-oriented measures, can significantly influence costs and capital flows, both directly and indirectly. For instance, policies that promote harmonisation of technical standards, streamline permitting processes and strengthen R&D are vital to the long-term competitiveness and resilience of supply chains.

Trade policy measures

Since the release of *ETP-2024*, there has been a marked increase in the use of trade policy measures across a broad range of goods, notably by the United States and China. This follows decades of tariff liberalisation under multilateral and bilateral agreements, and is closely tied to wider policy goals, including national security, industrial competitiveness and climate objectives. This recent increase in the use of trade policy measures has resulted in a higher trade-weighted average tariff and duty rates on clean energy technologies (Figure 4.4).

While rising tariffs and duties can reduce overall trade flows, the trade-weighted approach reflects the rates actually applied to products that enter the country. This indicates that, despite some degree of trade diversion to avoid higher tariffs and duties, imported clean energy technologies are now facing higher rates on average. Tariff escalation is more pronounced in the United States, where average rates surged across all technologies. Solar PV faced the steepest increase, with the announced ad valorem[5] trade-weighted tariff and duty rate averaging 169% in 2025 across all US trade partners and peaking at 315% for imports from China. EVs also became a major target: US tariffs climbed from zero in 2023 to an average of 34% across all trading partners, and up to 148% for China, the highest levied partner. Following the US-China trade and economic agreement of October 2025, China retained a broad 10% tariff on US goods while suspending its earlier retaliatory duties of 34% (Financial Times, 2025b). Tariff

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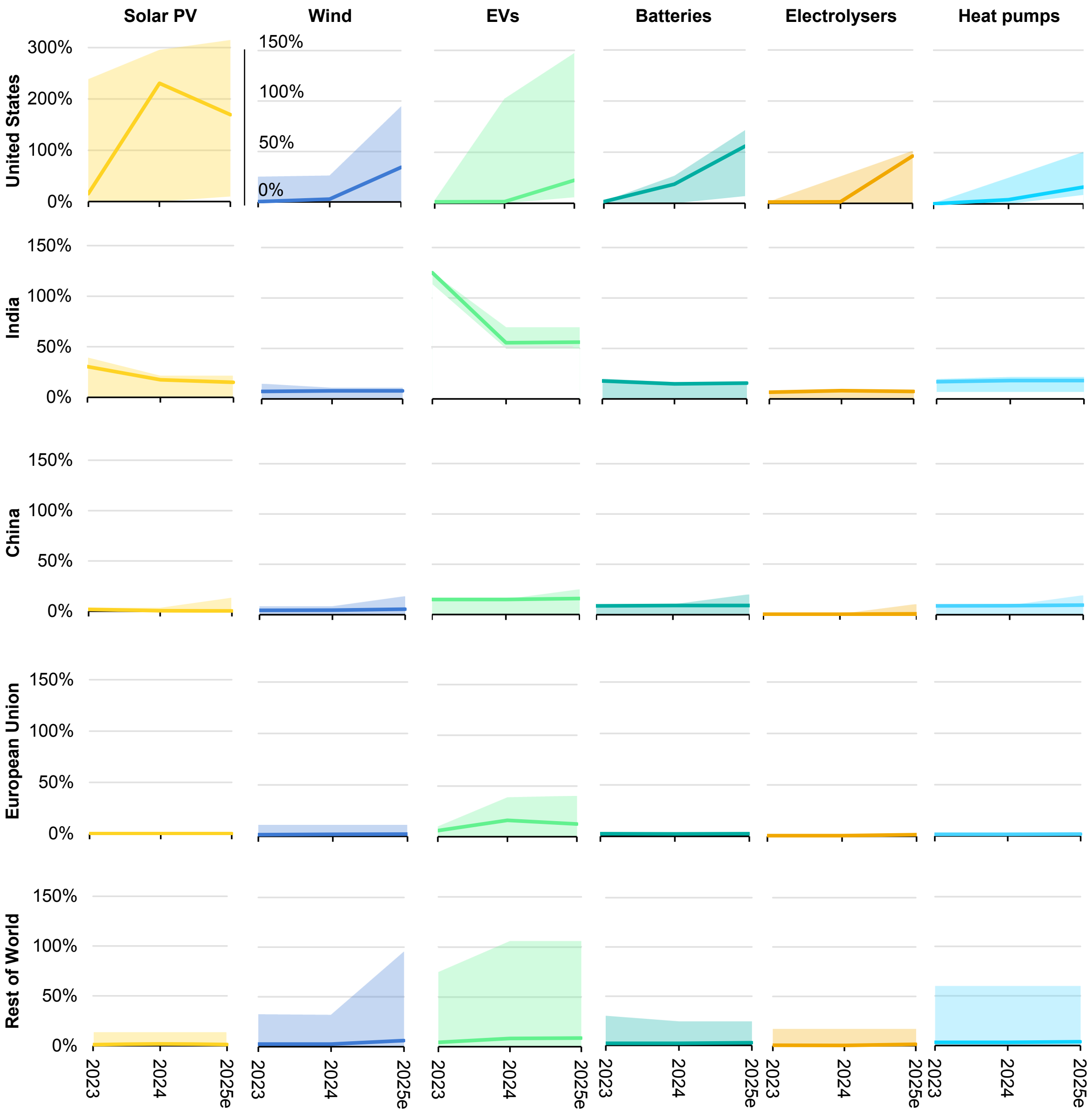
[5] Ad valorem tariffs are duties charged as a percentage of the value of imported goods.

adjustments elsewhere were narrower in scope and mainly concentrated on specific components rather than broad, sector-wide measures.

Figure 4.4 Announced estimated trade-weighted average tariffs and duties on selected clean energy technology imports in key countries and regions, 2023-2025e



IEA. CC BY 4.0.

Notes: EVs = electric vehicles. 2025e = estimated based on trade data for the first three quarters and the tariffs and duties announced as of 1 November 2025. The bold lines show the trade-weighted average tariff and duty rate applied across all trading partners and all components of a product category (e.g. solar PV includes a trade-weighted average of polysilicon, wafers, cells and modules). The shaded area refers to the range of rates applied across trading partners. See (IEA, 2026) for details of the HS codes used.

Sources: IEA analysis based on World Trade Organization (2025); US National Archives (2025); International Trade Administration (2025b); Office of the United States Trade Representatives (2025); China, Ministry of Finance (2025); European Commission (2025b); Diário Oficial da União [Official Diary of the Union] (2025); Sitharaman (2025); Brown, (2025); Financial Times (2025a); and The White House (2025c).

The weighted-average rate of tariffs and duties applied to clean energy technologies surged in the United States during 2023-2025; rates in other major regions remained relatively flat.

The United States, the European Union and Canada have introduced anti-dumping duties (ADDs) and countervailing duties (CVDs) on imports of solar panels, wind turbines and EVs. These measures, sometimes directed at specific companies, aim at addressing alleged distortions in trade competition, such as foreign production subsidies and selling below cost. China is the principal target of these actions. These duties, which can be very high, generally function in the same way as regular tariffs, and can significantly impact trade patterns.

A notable example is the United States, which in April 2025 concluded an investigation into alleged non-market practices in the PV cells and module supply chain from Cambodia, Malaysia, Thailand and Viet Nam, and has imposed CVDs exceeding 3 000% on certain firms and countries. These duties are expected to effectively halt imports from the targeted entities altogether. The European Union has also imposed firm-specific CVDs on battery electric car imports from China (excluding plug-in hybrids), ranging from 17% to 35%, coming into effect on 30 October 2024 for a period of 5 years (European Commission, 2024).

Industrial strategies

As in *ETP-2024*, this report's analysis of manufacturing and trade in clean energy technologies incorporates the latest developments in national industrial strategies and trade policies. Key policies, including the production tax credits for clean energy technology manufacturing under the US Inflation Reduction Act (IRA), domestic production targets outlined in the European Union's Net-Zero Industry Act (NZIA) and India's Production Linked Incentives scheme, remain in place. However, some of these measures have been significantly modified, and others have been complemented by new policy initiatives.

For example, NITI Aayog, a policy think tank of the Government of India, recommended moving toward 60% local sourcing in the wind sector in 2024 (Sharma, 2024), a move later reinforced by the Minister of New & Renewable Energy in October 2025, urging the raising of local content levels from around 64% to 85% by 2030, aligning with the government's broader strategy for clean energy self-reliance (Energy World, 2025). Additionally, Japan aims to achieve a domestic procurement ratio of 65% or more by 2040, based on its Offshore Wind Industry Vision 2.0 formulated in August 2025 (Japan, Ministry of Economy, Trade and Industry, 2025). These developments are part of a wider trend towards reinforcing domestic supply chains in the clean energy sector. Meanwhile, the United States has reallocated subsidies under the IRA, notably through the One Big Beautiful Bill, which amends the Advanced Manufacturing Production Tax Credit (45X). The provision immediately terminates 45X credits for wind energy components sold after 31 December 2027, while maintaining a phased reduction for solar, batteries, inverters, and critical minerals through 2032–2033 (US Congress, 2025).

Table 4.1 Selected industrial and trade policy developments since *ETP-2024*

Category	Policies
Industrial policies	**India**, wind: >60% local sourcing requirements for key components (JMK, 2025) + reduction of Goods and Services Tax (GST) on renewable energy equipment from 12% to 5% (Government of India, 2025). **United States**, solar, wind and batteries: One Big Beautiful Bill Act including early rollback of the 45X advanced production manufacturing credits under the IRA (US Congress, 2025). **Japan**, wind: The Japanese offshore wind industry has set a voluntary target to achieve a 65% domestic procurement ratio by 2040 (Chiba, 2025). **European Union**'s NZIA has moved to the implementation phase, with secondary legislation being adopted for 'net-zero strategic project' status and mandatory public procurement rules (European Commission, 2025c) . **Korea**'s Industrial Supply Chain 3050 Strategy (Herh, 2023). **Australia**'s Battery Strategy (Australian Renewable Energy Agency, 2025) and the Solar Sunshot programme (Australian Government, 2025).
Trade policies: non-tariff measures	**Viet Nam** ADD on wind components from China. **United States** ADDs and CVDs on solar components from Chinese origins with manufacturing facilities in Viet Nam, Malaysia, Thailand and Cambodia.
Trade policies: general tariff measures	**United States** Section 232 tariffs on car and car parts (The White House, 2025a), and aluminium and steel (The White House, 2025e) from all countries*. **United States** Section 232 tariffs on medium- and heavy-duty vehicles and parts (The White House, 2025f) **Türkiye** tariffs on EVs and motor cars from non-EU/non-domestic origins (Electrive, 2025a). **Russia**'s increase of recycling fees on Chinese imported passenger cars (Financial Times, 2025a). **Brazil**'s revised import tariffs on EVs (Electrive, 2025b). **United States** International Emergency Economic Powers Act (IEEPA) tariffs on products from Canada and Mexico (excluding United States-Mexico-Canada Agreement [USMCA]-compliant goods) and from China (The White House, 2025d)**. **United States** policy on 'Regulating Imports with a Reciprocal Tariff to Rectify Trade Practices that Contribute to Large and Persistent Annual US Goods Trade Deficits' with broad import coverage and exemptions for qualifying goods under USMCA and other free-trade agreements (FTAs) (The White House, 2025g)). **China** retaliatory tariff on all US products (China, Ministry of Finance, 2025). **Canada** retaliatory tariffs on selected US products (Government of Canada, 2025). **Japan and United States** Framework Agreement (The White House, 2025h). **European Union and United States** Framework Agreement on Reciprocal, Fair and Balanced Trade (European Commission, 2025a). **Korea and United States** Strategic Trade and Investment Deal (The White House, 2025i). **United Kingdom and United States** Economic Prosperity Deal (United Kingdom, Department for Business and Trade, 2025).

Note: *The Section 232 car tariffs apply to USMCA non-compliant and non-US value of the content only. **IEEPA tariffs only apply to USMCA non-compliant products from Canada and Mexico.

Export controls

In addition to the increase in tariff and non-tariff measures, there is a growing number of export restrictions, particularly on critical minerals essential to manufacturing clean energy technologies. Within the battery supply chain, for example, China accounts for upwards of 60% – and in some cases more than 95% – of manufacturing capacity at each step, from mineral refining to battery production. Several energy-related minerals face some form of export control today, and the restrictions are expanding, not just to raw and refined materials but also to processing technologies, such as those used for lithium and rare earth refining (IEA, 2025b). China also accounts for about 90% of rare earth element refining, and nearly 95% of global permanent magnet production.

Outside of China, in 2025 the Democratic Republic of Congo introduced export restrictions on cobalt, shifting from a ban to quota-controlled exports. In China, the expansion of export controls in 2025 created uncertainty about supply chains for critical materials and clean energy technologies, notably lithium-ion batteries and permanent magnets used in electric motors for EVs and wind turbine generators. A series of policy changes has increased the country’s leverage over these highly concentrated supply chains:

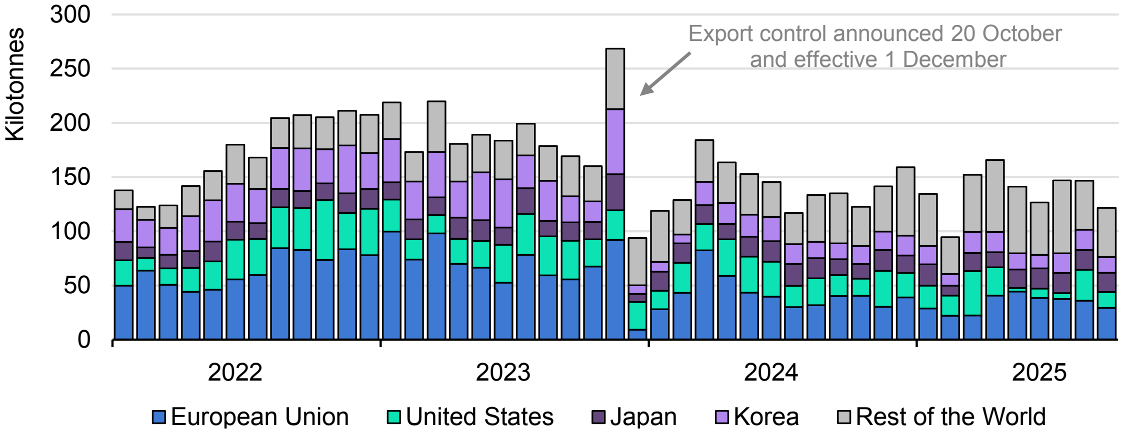
- **Graphite:** In October 2023, China imposed export controls on high-purity synthetic and natural graphite, tightening them further in December 2024, particularly for exports to the United States (China, Ministry of Commerce, 2023) (China, Ministry of Commerce, 2024). With China producing over 90% of anode active material, these measures pose an acute threat to the stability of other countries’ supply. Graphite-based anodes are indispensable to lithium-ion batteries, with limited technological alternative today; a shortage of graphite anodes would effectively halt battery production.
- **Rare earth elements:** In April 2025, China announced export controls on seven key rare earth elements and all related compounds, metals and magnets (China, Ministry of Commerce, 2025a). This led to a sharp decline in export volumes in April and May, with many carmakers in the United States, Europe and elsewhere reporting difficulties in sourcing permanent magnets, forcing some to cut production or suspend operations (Reuters, 2025b). Trade volumes began to recover from June, soon reaching pre-export control levels.
- **Advanced lithium iron phosphate (LFP) technologies and lithium processing:** In July 2025, China updated its “Catalogue of Technologies Prohibited or Restricted from Export”, adding fourth-generation LFP battery and lithium processing technologies (China, Ministry of Commerce and Ministry of Science and Technology, 2025). Virtually all LFP battery production is located in China and only a handful of Chinese companies can produce the latest generation of LFP materials that deliver lower costs, longer driving ranges and support ultra-fast charging. As interest in LFP batteries grows among automakers outside China seeking to reduce EV production costs, several battery manufacturers, led by Korean companies, are investing to

develop LFP production outside of China. However, export restrictions on LFP-related materials, manufacturing equipment and expertise may hinder or delay these efforts.

- **Broader battery and rare earth element controls:** In October 2025, China announced new export controls on rare earth elements and a wide range of battery materials, technologies and equipment (China, Ministry of Commerce, 2025b). They include cathode precursors, broader coverage of LFP materials, nickel-based cathode active materials and advanced technologies under development, such as batteries exceeding 300 Wh/kg and lithium-rich manganese-based cathode materials. These controls also apply to several categories of manufacturing equipment, including technologies previously subject to export restrictions. These measures have been suspended for one year following recent negotiations between China and the United States (The White House, 2025b).

How strictly the latter controls could be enforced remains uncertain. For example, following the announcement of graphite export restrictions in late 2023, exports surged in November ahead of their implementation in December and then fell back to pre-2022 levels as companies obtained export licences (Figure 4.5). Recent export restrictions can create uncertainty, particularly where licensing requires firms to disclose commercially sensitive information and navigate lengthy approval processes. However, negotiation processes and the granting of export licences or case-by-case exemptions enable trade resumption after initial hurdles. As such, these measures tend to reshape trade flows and incur compliance costs rather than resulting in a complete or sustained interruption of supply, although the risk of such disruptions in the future cannot be ruled out.

Figure 4.5 Monthly gross graphite exports from China, 2022-2025



Notes: Graphite includes natural, spherical, and artificial graphite. See (IEA, 2026) for details of the HS codes used. Not all of the exports of these products are destined for lithium-ion battery applications, but batteries account for a significant share of their use. 2025 data is for January to September.

Source: IEA analysis based on data from Sinoimex (2025).

The announcement of graphite export restrictions in late 2023 led to a surge in exports ahead of their implementation and then fell back to pre-2022 levels.

Impact of higher tariffs on costs and trade patterns

Increases in tariffs generally raise the final cost of clean energy technologies, either directly, through duties on importing the technologies, or indirectly, by increasing the cost of intermediate inputs to domestic production, such as raw materials and components. Assessing these effects is difficult because, unlike market prices, data on manufacturing costs are rarely disclosed for commercial reasons. Moreover, many other factors besides tariff changes can influence manufacturing costs, especially in the short term when inventories of imported technologies and components can offset the impact of tariff increases. The longer-term impact of tariff increases on costs, disregarding the impact of inventories, is estimated using a decomposition analysis (see Figure 4.6).[6]

In the **United States**, rising import costs coincided with increases in the share of domestic production for both solar PV modules and batteries. IRA production tax credits for manufacturing initiated in 2023 – and maintained through 2025 – have been crucial to closing cost gaps between domestic production and imports, and dampening the cost increases that may otherwise be passed onto consumers:

- US tariffs and duties on **solar PV modules** increased over the period 2023-2025 for all the major exporters to the United States, during which time the share of supply met by domestic production increased from around 15% to around half. Tariffs and duties would have increased the average delivered costs (i.e. the weighted average cost across domestic production and imports after tariffs have been imposed) by nearly 200%, around half of which was offset by shifts in trade patterns. The most important shift was the increase in domestic production, where the IRA production tax credits make the US production cost among the lowest in the world). A shift in the role played by different trading partners also dampened the impact of the tariff increases on delivered costs. Countries in Southeast Asia that were subject to CVDs and ADDs are estimated to have seen a reduction in their combined share in total US imports from more than four-fifths in 2023 to about half in 2025. The main sources of supply to fill the gap were Indonesia, primarily, and then India.

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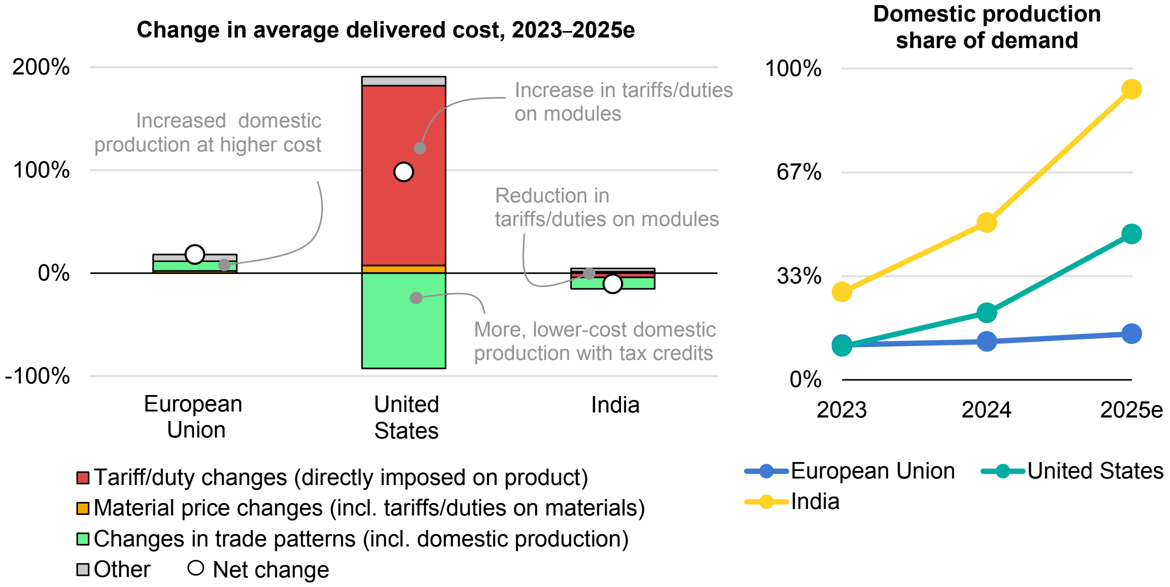
[6] A decomposition analysis was performed using the IEA MaT model to illustrate the contribution and interaction of three key categories of cost factors: First, changes in the prices of input materials and components (including the indirect impact of tariffs on imports thereof) that impact the cost of both imports and domestic production. Second, changes in trade patterns, including substitution between imports and domestic production, which impact the average delivered cost by changing the source of imports (i.e. changes in trading partners) and the share of imports vs. domestic production. Third, changes in tariffs and duties (including ADDs and CVDs) that impact the cost of importing the technology. Tariffs are imposed on costs as opposed to prices, which is an approximation. Two selected periods that saw rapid tariff increases across two key technologies are used – 2023-25 for solar PV modules and 2024-25 for lithium-ion batteries – to examine the impact across three key importing countries/regions: the United States, the European Union and India. The analysis disregards inventories of technologies and components that were imported before tariffs came into effect, which would likely dampen the immediate impact on cost increases.

- The average delivered cost of **battery cells** in the United States during 2024-25 was also subject to counteracting forces: on the one hand, tariffs and duties pushed up producer costs, and on the other, an increase in the share of demand being met by domestic production that was eligible for financial support (increasing from almost 60% to 70%) pushed them down. The additional factor that had a non-negligible impact for battery cells was changes in material and component prices: whereas prices for critical minerals, cathodes and anodes declined globally during this period, increases in tariffs and duties on these inputs in the United States raised their costs. The increase in the average rate of tariffs and duties on lithium-ion batteries – from nearly 25% in 2024 to almost 70% for imports from China in 2025 – has the larger impact, contributing to an estimated rise of more than 15% in the average delivered cost. The net impact of the input price changes, shifts in trade patterns and tariff and duty increases was an almost 10% increase in the delivered cost.

Figure 4.6 Estimated changes in average delivered costs and domestic production as a share of demand for solar PV modules in selected importing countries and regions, 2023–2025e



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Notes: 2025e = estimated based on trade data for the first three quarters. The average cost in 2025 reflects the full impact of tariffs and duties announced as of 1 November 2025, without accounting for use of stockpiles of earlier imports. Delivered costs refer to the weighted average unit cost of supply, including both domestic production and imports, with the latter including tariff and transport costs. Costs presented are inclusive of explicit financial support mechanisms in industrial strategies, such as the production tax credits in the US Inflation Reduction Act. The increase in component costs due to tariffs and duties is included in "Material price changes".

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

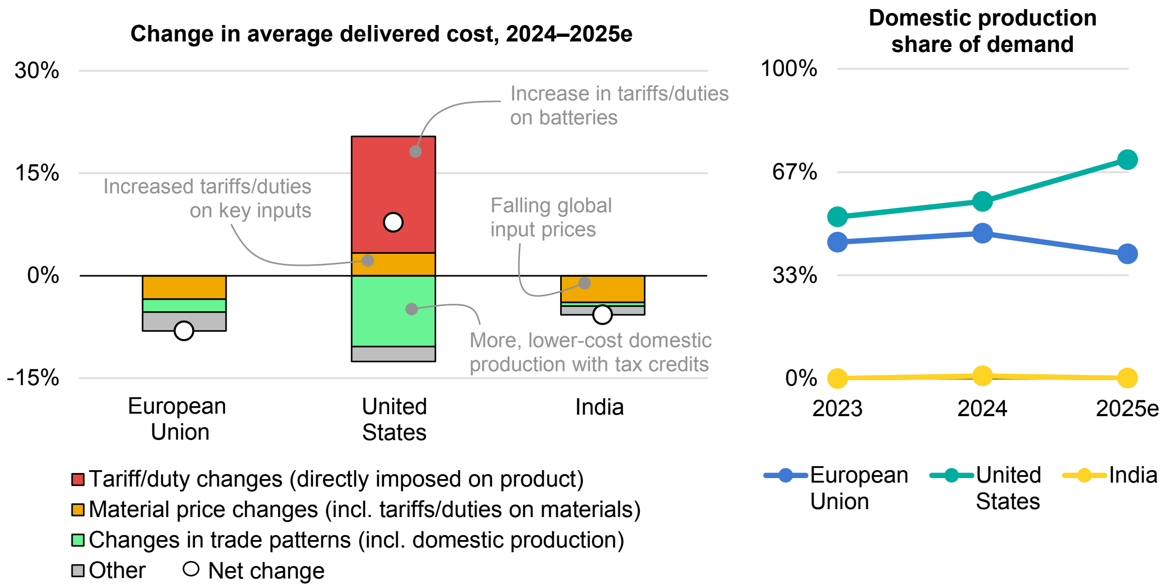
The impact of US tariffs and duties on costs for imported solar PV module and components has contributed to driving up domestic production and average delivered costs.

The **European Union** maintains relatively low levels of tariffs and duties on most goods, including clean energy technologies, of which it is the largest importer globally. The region has benefited from falling global prices for most technologies, materials and components in recent years. Domestic demand for clean energy technologies remains strong, drawing on some domestic production. However, a lack of any systematic financial support mechanisms, together with high energy and labour costs, mean that the region remains among the most expensive for manufacturing most clean energy technologies:

- Average delivered costs of **solar PV modules** in the European Union are estimated to have increased by around 20% during the period 2023-25. This is partly due to slight increases in global prices for key input materials (e.g. aluminium, silver), but mostly because of a slight increase in the share of its domestic production, of around 4 percentage points between 2023 and 2025. There is not an obvious cost incentive underpinning this small increase, but consumer preferences and project-level domestic procurement requirements are thought to explain the shift.
- Global prices for input materials and components for **battery cell** production have fallen sharply during the period 2023-25, after reaching historic highs in 2022. For example, lithium prices at the start of 2024 were about 80% lower than at the beginning of 2023. In early 2025, prices declined by a further 35% compared with early 2024, reaching similar prices to those at the end of 2015, despite global demand having expanded six-fold between 2015 and 2024 and seeing continued growth in 2025. Material price declines contribute nearly half of the nearly 10% decline in average delivered cost of battery cells estimated for the European Union during 2025. The remaining cost decline is mostly attributable to minor shifts in sourcing across trading partners, with a slight increase in the proportion sourced from China (the lowest-cost producer globally). The European Union's domestic production is also becoming more cost-effective over time as its manufacturing efficiency increases (see Chapter 7).

India's average delivered costs for solar PV modules and battery cells have followed a similar trajectory to those of the European Union during the recent period of global tariff and duty increases: the cost of the former is estimated to have decreased by 10% during 2023–25 and the latter by almost 6% during 2024-25e. India's goods imports were already subject to relatively high tariffs and duties before 2023, and various rates (e.g. including the most favoured nation or "MFN" rate) for certain groups of products have continued their gradual downwards trajectory in recent years. Tariffs and duties on solar PV modules decreased on average by 17 percentage points, which is estimated to have contributed a nearly 4% decline in average delivered costs, whereas the rest of the decrease stems from increased domestic production, which is cheaper when tariffs and duties are taken into account.

Figure 4.7 Estimated changes in average delivered costs and domestic production as a share of demand for battery cells in selected importing countries and regions, 2023-2025e



IEA. CC BY 4.0.

Notes: 2025e = estimated based on trade data for the first three quarters. The average cost in 2025 reflects the full impact of tariffs and duties announced as of 1 November 2025, without accounting for use of stockpiles of earlier imports. Delivered costs refer to the weighted average unit cost of supply, including both domestic production and imports, with the latter including tariff and transport costs. Costs presented are inclusive of explicit financial support mechanisms in industrial strategies, such as the production tax credits in the US Inflation Reduction Act. The increase in component costs due to tariffs and duties is included in "Material price changes".

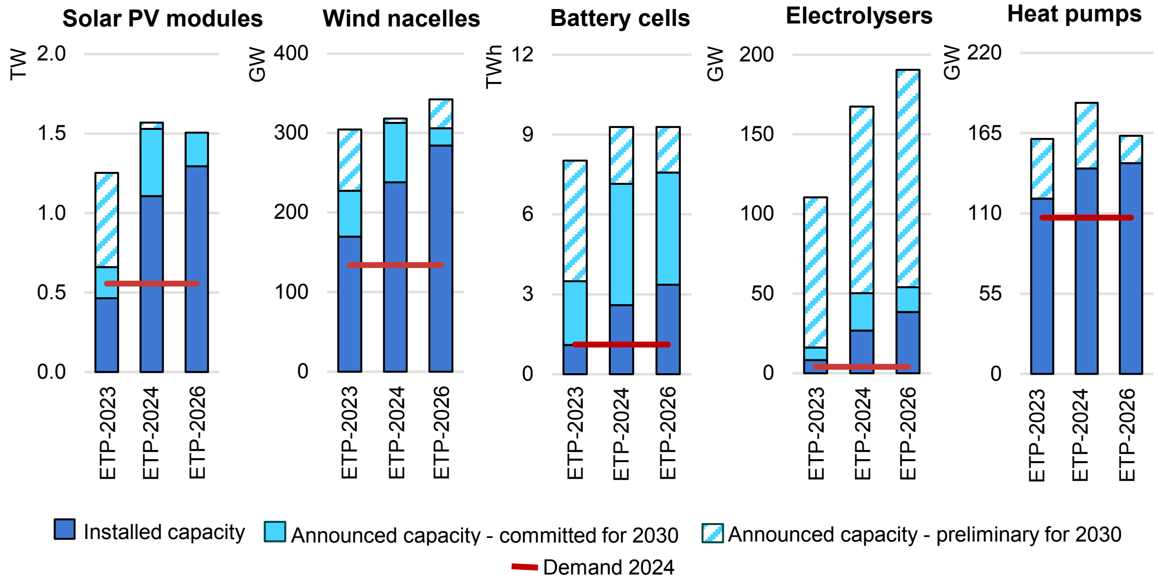
Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Lower prices for battery materials and components globally and production efficiency gains drove costs down, except in the United States, where tariffs and duties increased costs.

Manufacturing project pipelines

The global pipeline of announced projects for manufacturing key clean energy technologies provides a useful indicator of shifts in investor sentiment and progress in expanding manufacturing capacity. The latest data compiled for *ETP-2026* show that the project pipeline has contracted since the assessment conducted for *ETP-2024* (Figure 4.8). For most technologies, the capacity of previously announced projects that have either been completed or cancelled since the last review exceeds that of newly announced projects (Table 4.2). This trend reflects a comfortable level of capacity relative to current demand, as well as uncertainty about the pace of future technology deployment (see Chapter 5).

Figure 4.8 Global manufacturing project pipelines in 2030 for selected clean energy technologies by edition of *Energy Technology Perspectives*



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Notes: ETP = Energy Technology Perspectives. Capacities are annual. Announced capacity to 2030 refers to all announcements, both committed and preliminary. *ETP-2023* was published in January 2023 featuring assessed announced projects as of November 2022. The cutoff point for *ETP-2024* was June 2024 and, for *ETP-2026*, it is November 2025. Battery deployment includes all EV types and stationary storage. The results for wind manufacturing are not directly comparable across editions due to methodological changes in underlying data sources.

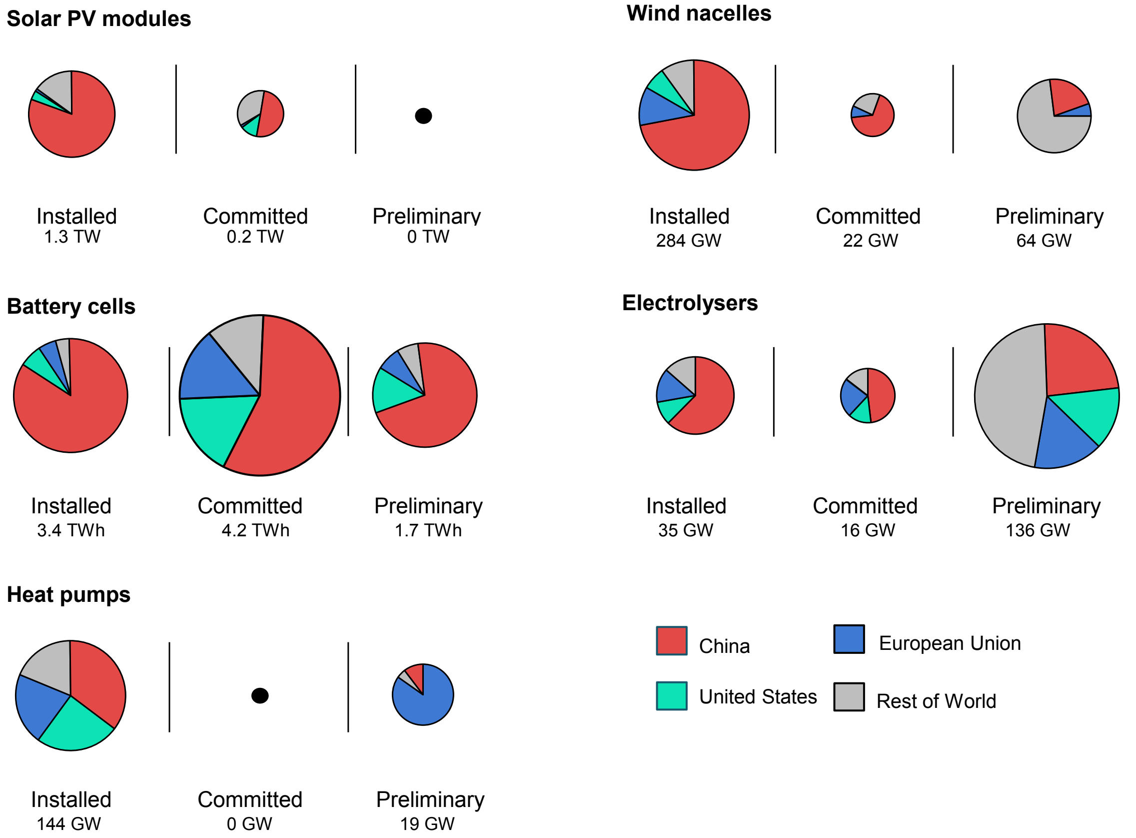
Sources: IEA analysis based on data from Benchmark Mineral Intelligence (2024); BNEF (2025); EV Volumes (2025); InfoLink (2025); S&P Global (2025); UN Comtrade (2025) and announcements by manufacturers and personal communications.

Existing manufacturing capacity remains comfortably above current demand for all key clean energy technologies but planned capacity expansions are slowing.

Solar PV

Planned additions to solar PV module manufacturing capacity declined sharply in 2025. Many planned projects have already come online, while manufacturers scaled back expansion plans slightly in response to low utilisation rates at existing plants and weaker earnings prospects. The capacity additions that remain in the pipeline mostly relate to the replacement of Passivated Emitter Rear Contact (PERC) module production with more efficient Tunnel Oxide Passivated Contact (TOPCon) modules. Planned capacity for other designs, such as Heterojunction Technology (HJT) or Back Contact (BC) cells, has held steady or increased marginally.

Figure 4.9 Clean energy manufacturing installed capacity and project pipelines to 2030 by technology, stage and country and region



Notes: Committed = projects that have reached a final investment decision (FID) or are under construction. Preliminary = projects that have not yet reached an FID. The areas of the pie charts are proportional to the capacity level.

Sources: IEA analysis based on data from UN Comtrade (2025): S&P Global (2025); BNEF (2025); Wood Mackenzie (2025); InfoLink (2025); Benchmark Mineral Intelligence (2024); EV Volumes (2025) as well as announcements by manufacturers and personal communications, gathered by the IEA.

China dominates the clean technology manufacturing project pipelines for 2030 across all technologies apart from heat pumps.

Rapid capacity growth in recent years has contributed to steep declines in module prices, intensifying financial pressure on manufacturers. Current utilisation rates at module factories stand at 57%; they could produce up to 1.1 TW per year if utilisation increased to 85% – about double the 540 GW of solar PV capacity additions in 2024. In parallel, the scale of individual projects has increased enormously: Jinko Solar's new PV module plant in Shanxi, with a planned capacity of 56 GW could alone almost meet the annual demand of the European Union (Shaw & Thompson, 2024).

In China, which accounts for 80% of global solar PV module production, intensifying price competition is further dampening industry expectations. In July 2025, for instance, Zhejiang Bangjie Holding Group Co. cancelled its planned 16 GW cell factory in the Jiangshan Economic Development Zone, citing changing market conditions. LONGi has also suspended plans for a 15 GW module plant in

Wuhu for 18 months due to income uncertainty. As a result, around half of planned capacity additions to 2030 are now located outside of China, mainly in India and the United States, though they are small relative to current capacity in China.

Across the sector, firms are under growing pressure to scale up or innovate in order to remain competitive in a well-supplied market. Governments are also increasingly aware of the global capacity overhang. In July 2025, Chinese authorities announced plans to address overcapacity in the solar PV sector, aiming to curb price wars and rebalance the market. This mirrors announcements made by the Chinese authorities during the same month, cautioning the Chinese EV industry against unsustainably low pricing strategies and inventory-clearing practices, which are seen as contributing to unhealthy levels of competition within the sector and raising concerns about long-term market stability (China, Ministry of Industry and Information Technology, 2025).

Table 4.2 Notable clean energy technology manufacturing project cancellations, delays and shutdowns since June 2024

Company	Location	Description
Solar PV		
Zhejiang Bangjie Holding Group Co.	Zhejiang, China	Plans announced in July 2025 to scrap a 16 GW n-type cell factory and subsequent 16 GW wafer factory, due to changing market conditions (Shaw & Thompson, 2024) (Shaw, 2025).
LONGi	Wuhu, China	18-month delay to LONGi's 15 GW PV module factory reported in December 2024, citing income uncertainty (Bloomberg, 2024).
3Sun	Inola, United States	3 GW PV modules plant placed on hold in October 2024 due to financial uncertainties regarding the IRA (Alliance News, 2024).
Risen	China	Decision to delay a 10 GW module factory announced in August 2024, citing supply chain disruption (Bhambhani, 2024).
Risen	China	Decision to delay 5 GW HJT PV cells factory in August 2024, citing supply chain disruption (Bhambhani, 2024).
Meyer Burger	Goodyear, United States	Closure of solar cell plant with 1.4 GW capacity in May 2025 due to financing problems (Meyer Burger, 2025).
Wind		
LM Wind Power, (GE Vernova)	Suape, Brazil	Closure of a blade factory in Suape (employing 1 000 people) announced in February 2025, due to weak demand in the Latin American market (Chetwynd, 2025).
Siemens Gamesa	Esbjerg, Denmark	Plans for new offshore nacelle factory put on hold in October 2025, citing market conditions (Ivanova, 2025).
Vestas	Szczecin, Poland	Plans for a new blade factory suspended in October 2025 due to weaker than expected demand in Europe (Vachkova, 2025).

Company	Location	Description
Batteries		
Northvolt	Skellefteå, Sweden	In November 2024 and March 2025, Northvolt filed for restructuring in the United States (Northvolt, 2024) and Sweden (Northvolt, 2025).
Svolt	Überherrn, Germany	Factory with 24 GWh capacity cancelled in October 2024 due to weak EV demand in Europe (Randall, 2024).
Freyr	Georgia, United States	34 GWh factory cancelled in February 2025 due to unfavourable market conditions and strategic realignment (Maisch, 2025).
Kore Power	Buckeye, United States	12 GWh battery manufacturing plant cancelled in February 2025 (Colthorpe, 2025).
Stellantis	Belvidere, United States	Plan for 34 GWh battery plant cancelled in June 2025 (Avila, 2025).
Electrolysers		
Green Hydrogen Systems	Skive, Denmark	Key assets being acquired by Nucera as of June 2025, following failure to restructure or find a buyer (Markosyan, 2025).
Nel	Herøya, Norway	Production at 1 GW alkaline electrolyser plant suspended in January 2025 due to sluggish market (Collins, 2025).
Heat Pumps		
Bosch	Dobromierz, Poland	Planned EUR 280 million facility that would have created 500 jobs by 2027 suspended in September 2025 due to weak sales and policy uncertainties (CoolingPost, 2025).

Wind turbines

The already modest project pipeline for wind component manufacturing has contracted in several producing regions. Investments for new wind turbine factories are typically announced only when a final investment decision (FID) is very close, so the pipeline is much smaller than for solar PV, though it tends to be more stable. Global installed manufacturing capacity stood at around 285 GW at end-2024, compared with 130 GW of deployment during that year.

In several regions, political and policy-related uncertainty is also weighing on the outlook for demand. For example, LM, part of GE Vernova, closed its blade manufacturing plant in Suape, Brazil, in early 2025, citing weak regional demand. In the United States, political opposition to wind power, along with a prolonged pause in offshore wind permitting, has added to market uncertainty (see Chapter 2). However, given the limited number of wind manufacturing investment announcements in the United States in recent years, changes to the manufacturing pipeline are expected to be more modest than changes in demand. The European Union saw two cancellations related due to lower-than-expected demand for offshore wind energy.

Batteries

The battery manufacturing project pipeline has contracted slightly since the last assessment in *ETP-2024* due to uncertain demand prospects and low utilisation of installed capacity. Yet the combined total of existing and announced capacity is almost 20% higher than the levels assessed in *ETP-2023*, with installed capacity more than tripling over that period. Over 800 GWh of manufacturing capacity was commissioned in 2024, and about 1.3 TWh is estimated to have been added in 2025. If all announced projects were to proceed, total global capacity would increase more than 2.5 times, reaching over 9.5 TWh. For comparison, battery deployment in 2024 – including for EV sales and stationary storage installations – was about 1.1 TWh.

How much of this announced capacity will materialise is uncertain, as projects may be shelved amid intensifying competition. In China, battery demand remains strong, but fierce domestic competition, significant surplus capacity and the increasing use of international trade restrictions are compressing margins and putting pressure on smaller, less efficient producers (Reid, 2025).

In the European Union, battery manufacturing is going through a defining moment (IEA, 2025d). While the pipeline of battery manufacturing projects remains robust, albeit mostly led by Asian companies, cost pressures and a rising preference for LFP batteries, which are currently produced solely by Chinese firms, is putting increasing pressure on domestic and Korean-owned facilities operating in the region. The bankruptcy of Sweden’s Northvolt – Europe’s largest investment in a domestic battery manufacturer – underscores the difficulties faced by new entrants (Northvolt, 2025).

In the United States, declining battery demand linked to reduced EV sales – driven in part by the phase-out of the USD 7 500 consumer 30D tax credit available under the IRA – raises the risk that factories may operate below the levels required for profitability. Quarterly data on US investments shows a marked decline of battery manufacturing investment in the first three quarters of 2025 (Clean Investment Monitor, 2025).

Electrolysers

Electrolyser project announcements remain substantial, but their viability is increasingly uncertain. If all projects were realised, global manufacturing capacity would total nearly 190 GW in 2030. However, most of these projects have not reached FID. For around 65 GW of planned capacity, the target date for completion has not been confirmed and could be pushed back as market conditions evolve.

Existing manufacturers are already encountering difficulties, as demand for electrolytic hydrogen remains weaker than anticipated at the beginning of this decade (IEA, 2025e). In early 2025, for instance, Norwegian electrolyser manufacturer Nel suspended production of alkaline electrolysers at its facility, citing unfavourable market conditions (Collins, 2025). As of June 2025, the Danish electrolyser manufacturer Green Hydrogen Systems had filed for bankruptcy, and its intellectual property and test site were acquired by Thyssenkrupp Nucera (Markosyan, 2025). Persistently low utilisation rates across existing electrolyser manufacturing facilities – averaging around 10% globally – risk pushing up capital costs. At such low utilisation rates, CAPEX costs could be six to eight times higher than if capacity were utilised at 80%, which is thought to be close to the upper end of what is feasible (see Chapter 7).

Heat pumps

The project pipeline for heat pumps has declined since 2024. Most of the previously announced expansion plans focused on increasing manufacturing capacity in Europe, where demand saw an unprecedented surge from 21 GW in 2021 to 32 GW in 2022. However, following a sharp downturn in 2023 and 2024 – during which European heat pump sales fell by 25% – many manufacturers chose to pause or postpone their expansion plans.

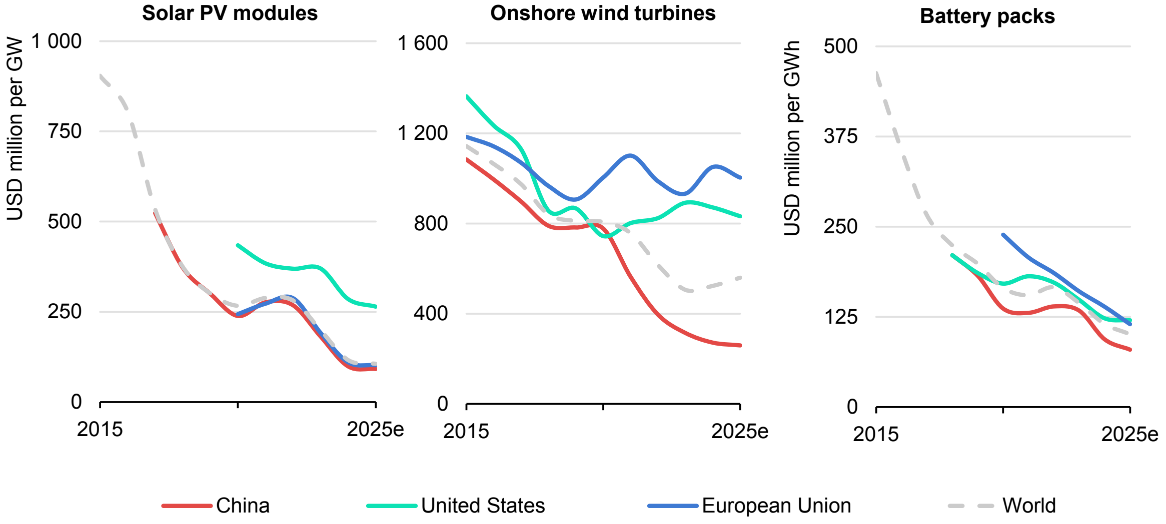
This trend should be interpreted with caution. Outside Europe, most manufacturers do not typically announce capacity increases. This is partly because expanding heat pump manufacturing is generally less complex than for many other clean energy technologies. As a result, such projects are often not announced far ahead of time, especially by original equipment manufacturers (OEMs) for whom heat pumps constitute only a small part of a broader product portfolio. In most cases, manufacturers can adjust and scale up their production lines in response to rising demand without the need for extensive forward planning.

Prices and profitability

Profitability is critical to sustaining investment in new manufacturing capacity. Beyond enabling capital returns to shareholders, healthy profit margins are vital for funding ongoing R&D, process innovation and capacity expansion – activities that drive efficiency improvements and reduce system costs. They are also important for downstream industries, such as grid equipment manufacturers, who must balance investment in long-lived, capital-intensive assets with shorter-term market fluctuations, and can bolster the resilience of supply chains against geopolitical risks and price shocks.

In recent years, profitability in clean energy technology manufacturing has been volatile, largely due to sharp fluctuations in both market prices and the costs associated with building, operating and maintaining production facilities. Over the past 10 years, global average prices for solar PV modules, battery packs and wind turbines have declined steeply – by approximately 90%, 80% and 50%, respectively (Figure 4.10). Prices for these technologies are heavily influenced by three key factors: supply-demand dynamics (including the impact of overcapacity), trade policy measures such as tariffs (which contribute to regional price variations) and production cost reductions driven by technological innovation, process improvements, economies of scale and changes in input costs, particularly for critical minerals.

Figure 4.10 Average prices for solar PV modules, onshore wind turbines and battery packs in selected countries and regions, 2015-2025e



Note: Data for 2025 is estimated.
Source: IEA analysis based on data from BNEF (2025).

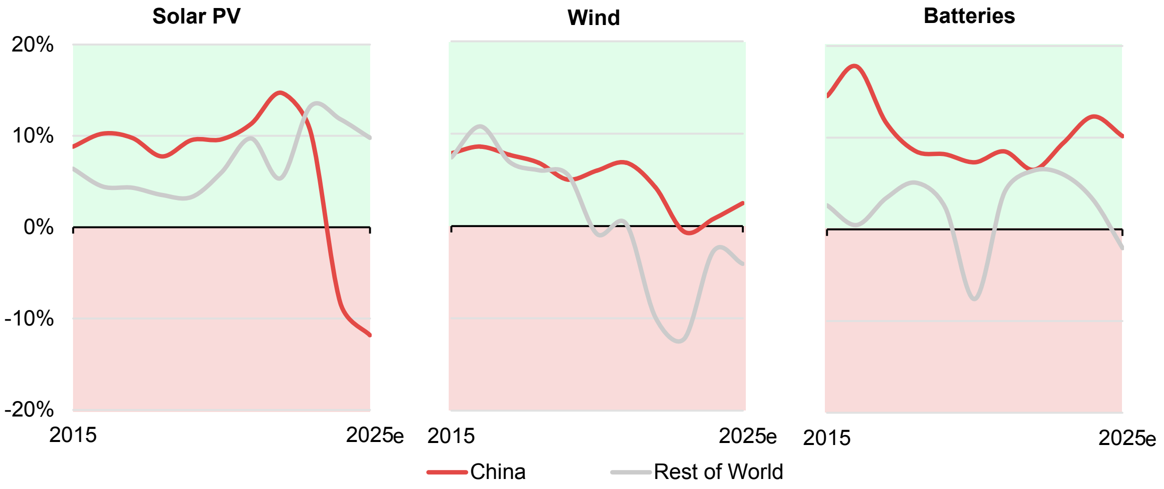
Solar PV and battery costs have dropped sharply due to innovation, scale and competition, while onshore wind costs have fallen in China but stagnated elsewhere, widening price gaps.

Solar PV

Solar PV has experienced the most dramatic price declines among clean energy technologies in recent years. In China, the European Union and Japan, the current price of a solar PV module is now around one-tenth of what it was in 2015. US prices remain higher than in other major markets, largely due to trade measures, including tariffs on imported solar modules and cells, and ADDs and CVDs on imports from China and Southeast Asia. Economies of scale, innovation and commoditisation have significantly reduced manufacturing costs. One clear example is the sharp drop in material intensity: the amount of polysilicon required per watt of module capacity has fallen by 87% since 2004. However, falling prices resulting from excess capacity have reduced profitability, triggering cyclical investment behaviour, with periods of over-expansion being followed by market consolidation.

Solar PV manufacturers have historically maintained profitability, as evidenced by EBIT margins, which measure operating profit as a share of revenue. From 2015 to 2023, the largest publicly listed solar companies maintained an average EBIT margin of around 10% – a similar margin to those recorded by the world's top 500 publicly traded manufacturing companies over the same period.[7] However, solar margins took a sharp downward turn in 2024. Sectoral performance is heavily influenced by Chinese firms, which account for seven of the ten largest companies by revenue. In response to oversupply, many of these firms adopted aggressive pricing strategies, contributing to a steep decline in market prices. In contrast, North American firms, which make up a much smaller share of global production, were somewhat shielded from these pressures due to a more protected domestic market.

Figure 4.11 Profit margins of companies producing selected clean energy technologies by country of company headquarters, 2015-2025e



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Notes: Based on earnings before interest and tax (EBIT) margins, which measure operating profit as a share of revenue. Margins are weighted by revenue in each region to calculate the average for the rest of the world. Companies are categorised according to their regional headquarters. Solar PV includes polysilicon, wafer, cell and module production. Covers publicly listed companies only. Includes companies representing 65% of the global market for solar PV, 80% for wind and 65% for batteries. Data for 2025 is up to June 2025.

Source: IEA analysis based on S&P Global (2025).

Historically, Chinese clean energy technology manufacturers have been the most profitable, owing to low-cost inputs, economies of scale and public financial support.

Historically, vertically integrated companies have generally outperformed component-specific firms, as their ability to offset losses in one segment of the value chain with profits in another has supported more stable margins (IEA, 2022).

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[7] Defined as companies falling under the Nomenclature of Economic Activities (NACE) code C - Manufacturing, with revenue and EBIT data available.

This model helped some Chinese manufacturers weather earlier price declines. However, by 2024, even this approach was not enough to combat falling prices, with the top ten Chinese solar PV manufacturers collectively reporting more than USD 4.5 billion in EBIT losses.

Wind turbines

Wind turbine prices show the widest regional variation among the leading clean energy technologies, reflecting a mix of structural and market factors. Chinese manufacturers benefit from a mature domestic supply chain, a large and expanding home market with many competing firms, and substantial economies of scale. Low-cost upstream inputs such as steel and magnets based on rare earth elements are available domestically, thanks to large government subsidies and persistent excess manufacturing capacity. By contrast, the European Union and the United States face higher costs, with inflationary pressures and a smaller pool of manufacturers contributing to higher prices and less competition. In addition, the size and weight of wind turbine components, particularly blades and towers, means that shipping accounts for a large share of delivered costs, further increasing the price of imported equipment.

The wind industry has experienced significant volatility in recent years, particularly in North America and the European Union. Supply chain disruptions and delivery delays have created major operational difficulties in those regions, undermining profitability. The rising cost of components and raw materials, exacerbated by high inflation, has further eroded profitability. While 2022 was the worst year in recent history for most western companies, the poor performance of other manufacturers in 2023 further reduced the global weighted average margin. Collectively, companies outside of China for which data is available recorded EBIT losses totalling over USD 5 billion in 2023.

In Europe, persistent inflation in the wake of the Covid-19 pandemic has pushed up material costs and caused delays in both manufacturing and installation. The failure to index turbine prices to inflation has further compressed margins, resulting in operating losses in both 2022 and 2023. However, manufacturers in the European Union have shown signs of recovery over the past 2 years, with 2024 marking a turning point, driven by higher selling prices and improved margins. At the same time, companies in North America are struggling to turn a profit, most recently due to delays in completing offshore wind projects.

In contrast, Chinese manufacturers secured their largest set of orders in 2023, totalling more than 100 GW (WoodMackenzie, 2024), yet the top five Chinese manufacturers by revenue reported EBIT profits of only USD 200 million. Margins were squeezed as domestic turbine prices fell more rapidly than production costs amid intense competition and provincial efforts to meet their renewable energy targets by end-2025 (Climate Cooperation China, 2022). Following this period of rapid price declines, Chinese manufacturers agreed to halt further price cuts, a move that appears to have supported a modest recovery in profitability (Energy Watch, 2024).

Batteries

Prices of battery packs continue to decline. Lithium-ion (Li-ion) batteries remain the dominant technology, thanks to consistent cost reductions along the supply chain and steady performance improvements. Within the Li-ion category, LFP batteries have gained significant market share in both mobility and stationary storage applications, largely due to their lower costs and rapid adoption in China. LFP batteries now power half of all global EV sales and account for over 90% of new stationary storage installations, driven primarily by rapid deployment in China, but with increasing uptake in advanced economies and other emerging markets and developing economies (IEA, 2025c).

Technological advancements have also shifted the cost structure of batteries, increasing the proportion of raw material costs in the total cost. As a result, battery prices have become more sensitive to fluctuations in the prices of critical minerals. Since 2023, expansions in supply, particularly from China, Indonesia and the Democratic Republic of the Congo, have helped bring down the prices of key battery metals, easing some of the pressure on overall battery costs (IEA, 2025a).

Battery companies have faced intense competition over the past decade, but the largest players have managed to maintain profitability. In 2024, China's largest battery producer, CATL, reported its highest-ever EBIT profits, exceeding USD 8.5 billion – over ten times the combined profits of the next three Chinese battery firms. Other Asian battery producers remain profitable, though at a considerably lower level than China's CATL. The largest firms based in Japan and Korea posted a combined EBIT profit of just over USD 1 billion in 2024, with margins similar to most Chinese manufacturers.

Non-Chinese manufacturers – particularly those in Europe and the United States, where many Korean and Japanese firms operate – typically have lower economies of scale and higher production costs. In Europe, costs are estimated to be around 50% higher than in China, significantly hampering their competitiveness, while manufacturers in the United States can compete only thanks to IRA tax credits. Upstream in the battery supply chain, margins for battery component producers – primarily Chinese and Korean – are also under considerable pressure. The revenue-weighted average EBIT margins for the largest anode and cathode active material producers have fallen from their respective peaks – from over 15% in 2021 to 7% in 2024 for anodes and from over 15% in 2017 to less than 3% in 2025 for cathodes.

Research and development

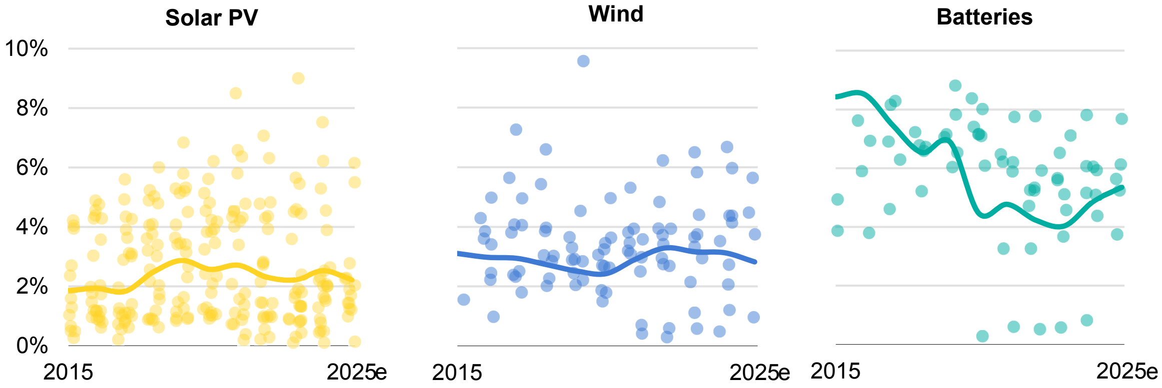
As the market for clean energy technologies continues to expand rapidly and price competition becomes more intense, manufacturers and governments have a bigger incentive to innovate to improve their competitiveness. R&D is a critical driver of innovation, with the potential to generate returns many times greater than the initial investment. Sustained investment in R&D today is essential to driving productivity gains in the future. Such innovation can take many forms, from improving manufacturing efficiency and optimising material use, to developing new technologies or chemistries that lead to better-performing products. However, R&D spending must be carefully balanced against a company's cash flow, as the returns often take years to materialise. Both public and corporate energy R&D spending has risen in recent years, by around 6% per year in real terms over 2015-23 (IEA, 2025f).

Manufacturers often prioritise two broad categories of innovation: cost leadership and product differentiation. Focusing on product differentiation often involves greater risk and higher costs than achieving gains through incremental improvements in manufacturing processes. For example, in 2024 the largest pharmaceutical firms by revenue had R&D-to-revenue ratios of around 20%, while in the automotive industry this was closer to 4%. This reflects the pharmaceutical sector's reliance on a steady pipeline of new products to replace expiring patents, in contrast to automotive firms, which primarily compete through incremental efficiency and production improvements.

Across clean energy technologies, batteries exhibit the highest weighted average R&D-to-revenue ratio, at around 6% between 2015 and 2025, compared with roughly 3% for both solar PV and wind. This likely stems from different innovation strategies, with battery firms pursuing product differentiation by investing in LFP and nickel manganese cobalt (NMC) cathodes, as well as the development of new battery designs, such as solid-state and sodium-ion batteries. Over the past five years, Chinese firms have maintained consistently higher R&D ratios than their Korean peers.

By contrast, solar PV manufacturers have primarily focused on incremental improvements to existing silicon-based cell technologies – such as shifting from PERC to TOPCon and HJT – rather than a fundamental shift in cell chemistry, though development of perovskite, thin-film and other emerging technologies is continuing. In the wind industry, turbine sizes have increased steadily, with average onshore wind turbine rotor diameters growing by around 70% and average power capacity almost tripling over the last decade. Yet the underlying components remain broadly similar, with innovation being driven more by advances in materials and manufacturing logistics than by radical technological breakthroughs.

Figure 4.12 R&D spending to revenue ratio for selected clean energy technologies, 2015-2025e



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Notes: Covers publicly listed companies only. Average line is weighted by revenue. Solar PV includes polysilicon, wafer, cell and module production. The companies included in this analysis represent 65% of the global market for solar PV, 65% for wind and 60% for batteries. 2025 values are estimates based on data up to June 2025.

Source: IEA analysis based on S&P Global (2025).

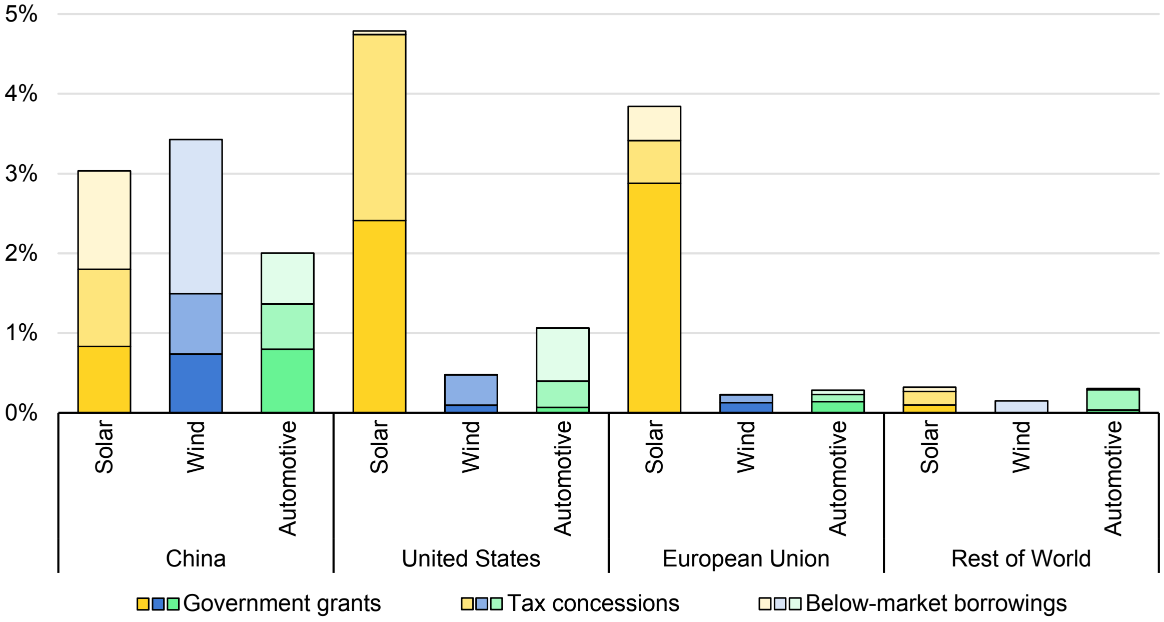
Battery manufacturers spend proportionately more on R&D than solar PV and wind firms.

Government financial incentives

Government subsidies can play an important role in reducing production costs and improving profitability, but measuring their impact is inherently complex, largely due to the difficulty of quantifying the benefits associated with different policy instruments. Grants are relatively straightforward to assess when disclosed, but tax incentives and below-market financing require building counterfactual scenarios to estimate the actual cost differential. The OECD undertakes this work: its Manufacturing Groups and Industrial Corporation (MAGIC) (OECD, 2025) database provides key inputs to the IEA's MaT model used for the supply chains analysis in this and previous editions of the *ETP.*

Assessing support is further complicated by the diversity of support mechanisms used across regions and technologies. China employs a combination of tax concessions, grants and concessional financing across the solar PV, wind and automotive sectors, with concessional finance particularly prevalent in wind, and grants more prominent in automobiles. By contrast, the United States has leaned heavily on tax incentives, especially for solar PV and wind manufacturing, primarily under the 2022 IRA. Although the IRA was revised in 2025 under the One Big Beautiful Bill Act, the overall scale and distribution of support for the manufacturing of many clean energy technologies has remained largely unchanged. However, tax credits for EVs ended in September 2025 and wind and solar manufacturing incentives are due to expire after 2027. This change is already having tangible effects, with several polysilicon, wafer and cell projects cancelled following the introduction of the bill. In comparison, the European Union has provided less support for wind and automotive, while support for solar PV – particularly through grants – has fallen since the early 2010s, in line with the decline of its domestic industry.

Figure 4.13 Average rate of financial support as a share of corporate revenue for selected clean energy technology manufacturing industries by country or region, 2005-2024



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Notes: In the United States, high levels of below-market loans to the automotive sector are a result of lending during and following the 2008-09 financial crisis. Tax concessions received under the US Inflation Reduction Act are recorded as financial grants by some companies in their financial statements and are categorised as such for all companies here.

Source: OECD (2025).

China provides the most financial support in absolute terms, but US and EU support for solar PV manufacturers is at a similar level to China's in proportion to revenue.

In aggregate across all three sectors, China has consistently provided the highest levels of government support to clean energy technologies (Figure 4.13). At times, support relative to revenue from the United States and European Union has been even higher than China's for some clean technologies, albeit for much shorter durations and for much smaller manufacturing bases. Recent policy measures in the United States, notably the IRA, have significantly increased its support levels for solar PV, while the European Union had the highest relative levels of support at the beginning of the 2010s. In the last decade, the absolute scale of support has been much higher in China, as the industries have much higher revenues. Financial support has generally been larger for solar PV module producers than for wind turbine manufacturers, with the notable exception of China, where the wind sector has benefited from substantial below-market loans. In the automotive sector, encompassing both EV and internal combustion engine manufacturing, support in China is more evenly distributed across different policy instruments.

The MAGIC database represents a major step forward in tracking industrial subsidies, but it does not capture all forms of government support. Some channels, such as preferential regulatory treatment or export restrictions on upstream inputs that can lower financial and input costs, are only partially reflected. Others, such as the provision of energy or land at below-market prices, are inherently difficult to quantify, despite offering potentially significant cost advantages to firms. This inevitably incomplete picture makes it harder to distinguish genuine productivity-driven advantages from those arising from policy-induced distortions, both domestically and internationally. The estimates of financial support presented here should therefore be considered as a lower-bound indication.

References

Alliance News. (2024). *Enel keeps 3Sun USA on hold and waits for elections*. Retrieved from Market Screener: https://www.marketscreener.com/quote/stock/ENEL-S-P-A-70935/news/Enel-keeps-3Sun-USA-on-hold-and-waits-for-elections-48149269/

Australian Government. (2025). *Pioneering Aussie solar tech to kickstart $1bn Solar Sunshot program*. Retrieved from https://www.dcceew.gov.au/about/news/pioneering-aussie-solar-tech-kickstart-1bn-solar-sunshot-program

Australian Renewable Energy Agency. (2025). *Battery Breakthrough Initiative*. Retrieved from https://arena.gov.au/funding/battery-breakthrough-initiative/

Avila, L. (2025). Stellantis scraps plans for Illinois battery plant, parts hub: UAW. *Automotive Dive*. Retrieved from https://www.automotivedive.com/news/stellantis-uaw-belvidere-assembly-battery-plant/749830/

Benchmark Mineral Intelligence. (2024). *Benchmark Minerals Lithium Ion Battery Gigafactory Assessment*. Retrieved from https://www.benchmarkminerals.com/

Bhambhani, A. (2024). Risen Energy Delays Manufacturing Projects; Posts Net Loss in H1 2024. *Taiyang News*. Retrieved from https://taiyangnews.info/business/risen-energy-delays-manufacturing-projects-posts-net-loss-in-h1-2024

Bloomberg. (2024). *Longi Delays Solar Module Plant in China as Sector Struggles*. Retrieved from Energy Connects: https://www.energyconnects.com/news/renewables/2024/december/longi-delays-solar-module-plant-in-china-as-sector-struggles/

BNEF. (2025). *Data service*. Retrieved from https://about.bnef.com/

Brown, C. P. (2025). Trump's trade war timeline 2.0: An up-to-date guide. *PIIE*. Retrieved from https://www.piie.com/blogs/realtime-economics/2025/trumps-trade-war-timeline-20-date-guide

Chetwynd, G. (2025). GE Vernova closing wind blade factory with 1,000 jobs to go. *ReCharge*. Retrieved from https://www.rechargenews.com/wind/ge-vernova-closing-wind-blade-factory-with-1-000-jobs-to-go/2-1-1777552

Chiba, D. (2025). Japan to raise local content target for offshore wind farms to 70%. *Nikkei Asia*. Retrieved from https://asia.nikkei.com/business/energy/japan-to-raise-local-content-target-for-offshore-wind-farms-to-70

China, Ministry of Commerce. (2023). *Announcement No. 39 of 2023 of the General Administration of Customs of the Ministry of Commerce on Optimizing and Adjusting Temporary Export Control Measures for Graphite Items*. Retrieved from https://www.mofcom.gov.cn/zcfb/blgg/art/2023/art_f6b1bc49e2c8482f8eb749012bc66dec.html

China, Ministry of Commerce. (2024). *Announcement No. 46 of 2024 Announcement on Strengthening Export Controls on Relevant Dual-Use Items to the United States*. Retrieved from https://www.mofcom.gov.cn/zwgk/zcfb/art/2024/art_3d5e990b43424e60828030f58a547b60.html

China, Ministry of Commerce. (2025a). *Announcement No.18 of 2025 of The Ministry of Commerce and The General Administration of Customs of The People's Republic of China Announcing the decision to implement export control on some medium and heavy rare earth related items*. Retrieved from https://english.mofcom.gov.cn/Policies/AnnouncementsOrders/art/2025/art_0dd87cbee7b045bf93fabe6ab2faceee.html

China, Ministry of Commerce. (2025b). *Announcement No. 58 of 2025 announced the decision to implement export controls on items related to lithium batteries and artificial graphite anode materials*. Retrieved from https://www.mofcom.gov.cn/zwgk/zcfb/art/2025/art_79646f0161564975a938fe00fee158d5.html

China, Ministry of Commerce and Ministry of Science and Technology. (2025). *Announcement No. 28 of 2025 Announcement on the adjustment and issuance of the "Catalogue of China's Prohibited and Restricted Export Technologies"*. Retrieved from https://fms.mofcom.gov.cn/zcfg/jsjckzcfg/art/2025/art_ba35a101c22c4f6e844f749cb0a98552.html

China, Ministry of Finance. (2025). *The State Council Tariff Commission announced adjustments to tariffs on imported goods originating from the United States*. Retrieved from https://gss.mof.gov.cn/gzdt/zhengcejiedu/202505/t20250513_3963685.htm

China, Ministry of Industry and Information Technology. (2025). *The Ministry of Industry and Information Technology and other departments held a symposium on the new energy vehicle industry to deploy work to further standardize the competitive order of the new energy vehicle industry*. Retrieved from https://www.miit.gov.cn/xwfb/bldhd/art/2025/art_3d4d963739924503872222a3a2a54c77.html

Clean Investment Monitor. (2025). *The State of US Clean Energy Supply Chains in 2025*. Retrieved from https://www.cleaninvestmentmonitor.org/

Climate Cooperation China. (2022). *China released its 14th Five-Year Plan for Renewable Energy with quantitative targets for 2025*. Retrieved from https://climatecooperation.cn/climate/china-released-its-14th-five-year-plan-for-renewable-energy-with-quantitative-targets-for-2025/

Collins, L. (2025). Nel temporarily halts hydrogen electrolyser manufacturing at flagship 1 GW factory in Norway. *Hydrogen Insight*. Retrieved from https://www.hydrogeninsight.com/electrolysers/nel-temporarily-halts-hydrogen-electrolyser-manufacturing-at-flagship-1gw-factory-in-norway/2-1-1763764

Colthorpe, A. (2025). US BESS startup KORE Power no longer building Arizona cell gigafactory. *Energy Storage News*. Retrieved from https://www.energy-storage.news/us-bess-startup-kore-power-no-longer-building-arizona-cell-gigafactory/

CoolingPost. (2025). *Bosch halts Polish heat pump factory plans*. Retrieved from https://www.coolingpost.com/world-news/bosch-halts-polish-heat-pump-factory-plans/

Diário Oficial da União [Official Diary of the Union]. (2025). *Imprensa Nacional [National Press]*. Retrieved from https://www.in.gov.br/leiturajornal

Electrive. (2025a). Turkey introduces new car tariffs. Retrieved from https://www.electrive.com/2025/09/22/turkey-introduces-new-car-tariffs/

Electrive. (2025b). *Brazil's import tariffs on EVs moved forward*. Retrieved from https://www.electrive.com/2025/08/01/brazil-accelerates-tariff-hike-on-disassembled-ev-imports/#:~:text=Brazil%E2%80%99s%20foreign%20trade%20committee%2C%20Gecex-Camex%2C%20has%20announced%20an,the%2035%25%20import%20tax%20forward%20by%2018%20months

Energy Watch. (2024). *Chinese wind OEMs sign pact to end price war*. Retrieved from https://energywatch.com/EnergyNews/Renewables/article17545173.ece

Energy World. (2025). Joshi urges wind industry to raise local content to 85% from 64% by 2030. 1. Retrieved from https://energy.economictimes.indiatimes.com/news/renewable/indias-wind-energy-industry-urged-to-boost-local-content-to-85-by-2030/124979542

European Commission. (2024). *EU Commission imposes countervailing duties on imports of battery electric vehicles (BEVs) from China.* Retrieved from https://trade.ec.europa.eu/access-to-markets/en/news/eu-commission-imposes-countervailing-duties-imports-battery-electric-vehicles-bevs-china

European Commission. (2025a). Joint Statement on a United States-European Union framework on an agreement on reciprocal, fair and balanced trade. Retrieved from https://policy.trade.ec.europa.eu/news/joint-statement-united-states-european-union-framework-agreement-reciprocal-fair-and-balanced-trade-2025-08-21_en

European Commission. (2025b). *Publications Office of the European Union*. Retrieved from https://op.europa.eu/en/

European Commission. (2025c). *The Net-Zero Industry Act*. Retrieved from https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en#net-zero-strategic-project-status

EV Volumes. (2025). *Global Electric Vehicle Sales Data, Market Trends & Forecasts You Can Trust*. Retrieved from https://ev-volumes.com/

Financial Times. (2025a). *Russia imposes fees to stem flood of low-cost Chinese cars*. Retrieved from https://www.ft.com/content/48cb143e-03ce-4e23-bc6a-7e47d673f1d8

Financial Times. (2025b). *Markets tumble as China announces 34% retaliatory tariffs on US import.* Retrieved from https://www.ft.com/content/84fe4e66-74ef-4517-8733-2c84f77ea3b7

Government of Canada. (2025). *Canada's response to U.S. tariffs on Canadian goods*. Retrieved from https://www.canada.ca/en/department-finance/programs/international-trade-finance-policy/canadas-response-us-tariffs.html

Government of India. (2025). GST Reforms Power India’s Green Transition. *Press Information Bureau*, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2167486&reg=3&lang=2#:~:text=The%20rationalization%20of%20GST%20rates,farmers%2C%20industries%2C%20and%20developers

Herh, M. (2023). Korean Gov’t to Lower Dependence on Specific Countries for Advanced Materials, Components. *Business Korea*. Retrieved from https://www.businesskorea.co.kr/news/articleView.html?idxno=207805

IEA. (2022). *Special Report on Solar PV Global Supply Chains.* Retrieved from https://www.iea.org/reports/solar-pv-global-supply-chains

IEA. (2025a). *Global Critical Minerals Outlook 2025*. Retrieved from https://www.iea.org/reports/global-critical-minerals-outlook-2025

IEA. (2025b). *With new export controls on critical minerals, supply concentration risks become reality*. Retrieved from https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality

IEA. (2025c). *Global EV Outlook 2025*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2025

IEA. (2025d). *The battery industry has entered a new phase*. Retrieved from https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase

IEA. (2025e). *Global Hydrogen Review 2025*. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2025

IEA. (2025f). *The State of Energy Innovation*. Retrieved from https://www.iea.org/reports/the-state-of-energy-innovation

IEA. (2026). *Manufacturing and Trade Model Documentation.* Retrieved from https://www.iea.org/reports/manufacturing-and-trade-model

InfoLink. (2025). *InfoLink Consulting*. Retrieved from https://www.infolink-group.com/

International Trade Administration. (2025b). *International Trade Administration*. Retrieved from https://www.trade.gov/

Ivanova, T. (2025, 10 24). *Siemens Gamesa halts nacelle factory project in Denmark*. Retrieved from Renewables Now: https://renewablesnow.com/news/siemens-gamesa-halts-nacelle-factory-project-in-denmark-1283852/

Japan, Ministry of Economy, Trade and Industry. (2025). Retrieved from https://www.meti.go.jp/shingikai/enecho/denryoku_gas/saisei_kano/yojo_furyoku/pdf/037_03_00.pdf

JMK. (2025). *India Pushing for Wind Turbine Manufacturing Indigenization*. Retrieved from https://jmkresearch.com/indias-latest-push-for-a-holistic-domestic-wind-turbine-manufacturing-market/

Maisch, M. (2025). *Freyr cancels $2.6 billion gigafactory in Georgia, sells site*. Retrieved from https://www.ess-news.com/2025/02/10/freyr-cancels-2-6-billion-gigafactory-in-georgia-sells-site/

Markosyan, M. (2025, 09 02). *Nucera closes buy of bankrupt Danish electrolyser maker GHS assets*. Retrieved from Renewables Now: https://renewablesnow.com/news/nucera-closes-buy-of-bankrupt-danish-electrolyser-maker-ghs-assets-1281040/

Meyer Burger. (2025). *Meyer Burger shuts down solar module production and lays off 282 employees in the U.S.* Retrieved from https://www.meyerburger.com/cs/newsroom/artikel/meyer-burger-shuts-down-solar-module-production-and-lays-off-282-employees-in-the-us

Midea. (2025, February). *Midea Completes Acquisition of ARBONIA climate*. Retrieved from https://mbt.midea.com/global/news/midea-completes-acquisition-of-arbonia-climate.mobile.mobile

Northvolt. (2024). *Northvolt takes major actions to support and enhance homegrown battery production platform*. Retrieved from https://northvolt.com/articles/chapter11/

Northvolt. (2025). *Northvolt files for bankruptcy in Sweden*. Retrieved from https://northvolt.com/articles/northvolt-files-for-bankruptcy-in-sweden/

OECD. (2025). *How governments back the largest manufacturing firms*. Retrieved from https://www.oecd.org/en/publications/how-governments-back-the-largest-manufacturing-firms_d93ed7db-en.html

Office of the United States Trade Representatives. (2025). *Office of the United States Trade Representatives*. Retrieved from https://ustr.gov/

Oxford Economics Limited. (2025). *Global Industry Service*. Retrieved from https://www.oxfordeconomics.com/service/subscription-services/industries/global-industry-service/

Panasonic Group. (2025, August). *Panasonic officially started operations at the new building in its Czech factory, a production site for Air-to-water heat pumps*. Retrieved from https://news.panasonic.com/global/press/en250829-4

Randall, C. (2024). *SVOLT confirms cancellation of its Saarland plans*. Retrieved from https://www.electrive.com/2024/10/28/svolt-confirms-cancellation-of-its-saarland-plans/

Reid, M. (2025). China’s overcapacity: Will its battery industry consolidate? *CRU*. Retrieved from https://www.crugroup.com/en/communities/thought-leadership/2025/chinas-overcapacity-will-its-battery-industry-consolidate/

Reuters. (2025a). *Exclusive: BYD slows production, delays capacity expansion at China factories, sources say*. Retrieved from https://www.reuters.com/business/autos-transportation/byd-slows-production-delays-capacity-expansion-china-factories-sources-say-2025-06-25/

Reuters. (2025b). *China's rare earth export curbs hit the auto industry worldwide*. Retrieved from https://www.reuters.com/business/autos-transportation/some-european-auto-supplier-plants-shut-down-after-chinas-rare-earth-curbs-2025-06-04/

S&P Global. (2025). *Commodity Insights*. Retrieved from https://www.spglobal.com/commodity-insights/en

Sharma, Y. S. (2024). NITI Aayog proposes a minimum 60% local sourcing requirement by value for wind energy plants. *The Economic Times*. Retrieved from https://economictimes.indiatimes.com/industry/renewables/niti-aayog-proposes-a-minimum-60-local-sourcing-requirement-by-value-for-wind-energy-plants/articleshow/111754690.cms

Shaw, V. (2025). *Chinese PV industry Brief: Zhejiang Bangjie drops 18 GW factory plan.* Retrieved from https://www.pv-magazine.com/2025/07/18/chinese-pv-industry-brief-zhejiang-bangjie-scraps-plans-to-build-18-gw-solar-factory/

Shaw, V., & Thompson, V. (2024). *Chinese PV Industry Brief: JinkoSolar breaks ground on 56 GW solar factory*. Retrieved from https://www.pv-magazine.com/2024/03/29/chinese-pv-industry-brief-jinkosolar-breaks-ground-on-56-gw-pv-panel-factory-in-shanxi/

Sinoimex. (2025). *Global Trade & Industry Growth Lab*. Retrieved from https://www.sinoimex.com/en/index

Sitharaman, N. (2025). *Budget 2025-2026*. Retrieved from https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/feb/doc202521493201.pdf

The Budget Lab. (2025). *The Fiscal and Economic Effects of the Revised April 9 Tariffs*. Retrieved from https://budgetlab.yale.edu/research/fiscal-and-economic-effects-revised-april-9-tariffs

The White House. (2025a). *Amendments to adjusting imports of automobiles and automobile parts into the United States*. Retrieved from https://www.whitehouse.gov/presidential-actions/2025/04/amendments-to-adjusting-imports-of-automobiles-and-automobile-parts-into-the-united-states/

The White House. (2025b). *Fact Sheet: President Donald J. Trump Strikes Deal on Economic and Trade Relations with China*. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/11/fact-sheet-president-donald-j-trump-strikes-deal-on-economic-and-trade-relations-with-china/

The White House. (2025c). *Briefings & Statements.* Retrieved from https://www.whitehouse.gov/briefings-statements/

The White House. (2025d). *Fact Sheet: President Donald J. Trump Imposes Tariffs on Imports from Canada, Mexico and China*. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/02/fact-sheet-president-donald-j-trump-imposes-tariffs-on-imports-from-canada-mexico-and-china/

The White House. (2025e). *Fact Sheet: President Donald J. Trump Increases Section 232 Tariffs on Steel and Aluminum*. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/06/fact-sheet-president-donald-j-trump-increases-section-232-tariffs-on-steel-and-aluminum/

The White House. (2025f). Adjusting Imports of Medium- and Heavy-Duty Vehicles, Medium and Heavy-Duty Vehicle Parts, and Buses into the United States. Retrieved from https://www.whitehouse.gov/presidential-actions/2025/10/adjusting-imports-of-medium-and-heavy-duty-vehicles-medium-and-heavy-duty-vehicle-parts-and-buses-into-the-united-states

The White House. (2025g). *Further Modifying the Reciprocal Tariff Rates*. Retrieved from https://www.whitehouse.gov/presidential-actions/2025/07/further-modifying-the-reciprocal-tariff-rates/

The White House. (2025h). Fact Sheet: President Donald J. Trump Implements A Historic U.S.-Japan Framework Agreement. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/09/fact-sheet-president-donald-j-trump-implements-a-historic-u-s-japan-framework-agreement/

The White House. (2025i). Joint Fact Sheet on President Donald J. Trump’s Meeting. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/11/joint-fact-sheet-on-president-donald-j-trumps-meeting-with-president-lee-jae-myung/

UN Comtrade. (2025). *UN Comtrade Database*. Retrieved from https://comtradeplus.un.org/

UN Trade & Development. (2025). *Merchandise: Total trade and share*. Retrieved from https://unctadstat.unctad.org/datacentre/dataviewer/US.TradeMerchTotal

United Kingdom, Department for Business and Trade. (2025). *General terms for the United States of America and the United Kingdom of Great Britain and Northern Ireland Economic Prosperity Deal*. Retrieved from https://assets.publishing.service.gov.uk/media/681d327d43d6699b3c1d2a9d/US_UK_EPD_050825_FINAL_rev_v2.pdf

US Congress. (2025). *H.R.1 - One Big Beautiful Bill Act*. Retrieved from https://www.congress.gov/bill/119th-congress/house-bill/1

US National Archives. (2025). *Federal Register*. Retrieved from https://www.federalregister.gov/

Vachkova, R. (2025, 10 22). *Vestas halts project for Polish wind blade factory - report*. Retrieved from Renewables now: https://renewablesnow.com/news/vestas-halts-project-for-polish-wind-blade-factory-report-1283652/

Wood Mackenzie. (2025). *Wind Supply Chain Service*. Retrieved from https://www.woodmac.com/lens/lens-wind/

WoodMackenzie. (2024). *Record highs for global wind turbine order intake in 2023*. Retrieved from https://www.woodmac.com/press-releases/2024-press-releases/record-highs-for-global-wind-turbine-order-intake-in-2023

World Bank. (2025). *Indicators*. Retrieved from https://data.worldbank.org/indicator

World Trade Organization. (2025). *WTO Tariffs & Trade Data*. Retrieved from https://ttd.wto.org/en

Xue, X., & Larsen, M. (2025). China's Green Leap Outward: The rapid scale-up of overseas Chinese clean-tech manufacturing investments. *Net Zero Industrial Policy Lab*. Retrieved from https://static1.squarespace.com/static/64ca7e081e376c26a5319f0b/t/68c09417468c2975452a39d1/1757451287251/PB+-11+China+Low+Carbon+FDI-vf.pdf

Chapter 5. Outlook for manufacturing and trade

Highlights

- Due to a large overhang of manufacturing capacity for several clean energy technologies – notably solar PV and batteries – the investment in manufacturing capacity needed to keep pace with global demand in the Stated Policies Scenario (STEPS) over the next decade is just 40% of the historic peak in 2023. Despite recent increases in tariffs and duties in some countries, trade remains central to meeting rising demand, with the value of global net trade over the next decade rising to more than double that of 2024.
- China's net exports of clean energy technologies more than double to 2035 in the STEPS, at which point they are around four-fifths of the combined value of crude oil export revenues across OPEC countries in 2025. Despite this, several countries reduce their dependence on Chinese imports in relative terms at certain steps in the value chain – particularly downstream. EU net imports of battery cells from China drop from around half of domestic demand levels in 2025 to around a quarter by 2035. Dependency on Chinese cathode imports jumps from around 15% to 45% over the same period; for anodes it remains at today's elevated levels of around 75%.
- China remains by far the largest producer of solar PV modules and components in the STEPS, though its market share declines somewhat. It supplies over 70% of projected global module demand in 2030 (compared with 80% in 2024) and more than 80% of upstream wafer and polysilicon (90% in 2024). India sees the biggest increase in global market share, rising from 3% in 2024 to 10% in 2030 and 12% in 2035, and becomes a net exporter by 2030. The policies in place in the United States lead to near-self-sufficiency for modules by 2030.
- Several emerging economies are playing a growing role in the global wind supply chain. Nacelle and blade exports account for about 20% of India's production in 2035, mainly serving Asia Pacific and European markets. Brazil is projected to export 10% of its nacelle production and 30% of blade production to other Latin American countries. North Africa, particularly Morocco, is emerging as a blade manufacturing hub, supplying around 5% of EU wind imports by 2035.
- The share of domestic electric vehicle (EV) demand met by imports in the European Union remains below one-third in the STEPS, with China supplying around 70% of these imports in 2035, up from 60% in 2024, despite countervailing duties (or equivalent measures) being maintained. The North American car market remains virtually closed to Chinese imports due to even higher tariff and duty rates. The US project pipeline for battery cell manufacturing is sufficient to supply local demand through to 2030 in view of weaker projected demand.

Global trends

This chapter sets out projections of manufacturing activity and inter-regional trade for clean energy technologies to 2035 under two scenarios: the Stated Policies Scenario (STEPS) and the Net Zero Emissions by 2050 Scenario (NZE Scenario).[1] These projections are derived from the IEA's Manufacturing and Trade (MaT) model, which simulates investment, production and trade by technology through global optimisation of production and trade costs [see IEA (2026) for more information].

The analysis in this chapter focuses primarily on the STEPS, reflecting the substantial changes to industrial and trade policy since *ETP-2024*. Two major sources of uncertainty shape the outlook: potential future shifts in policy – including tariffs and other trade measures – and the trajectory of demand. These are explored through sensitivity analysis of alternative policy assumptions and modelling of a range of deployment levels (see Box 5.1).

Box 5.1 Deployment uncertainty in context

While deployment for clean energy technologies grows in all IEA scenarios, a key source of uncertainty in this outlook for manufacturing and trade stems from the extent to which it does so. IEA modelling scenarios embody a wide range of future deployment levels for the key clean energy technologies in focus in Part B of this *ETP* (Figure 5.1).

The Current Policies Scenario (CPS), which sets out a pathway for the future of the energy system in which no change in energy-related policies is assumed beyond what is already in place, constitutes the lower bound of deployment in all cases for these technologies. Deployment levels in the STEPS, which also takes account of those policies that have been formally tabled but not yet adopted, are 25% higher for solar PV than in the CPS by 2035; 15% higher for wind; 20% higher for EVs and over 20% higher for batteries. In the NZE Scenario, deployment levels are substantially higher for these four technologies: 120-170% higher than in the CPS and 80-135% higher than in the STEPS by 2035.

Existing and announced manufacturing capacity levels help put this deployment uncertainty in context. For solar PV modules, for example, there is enough existing and committed announced (i.e. those facilities that have reached a final investment

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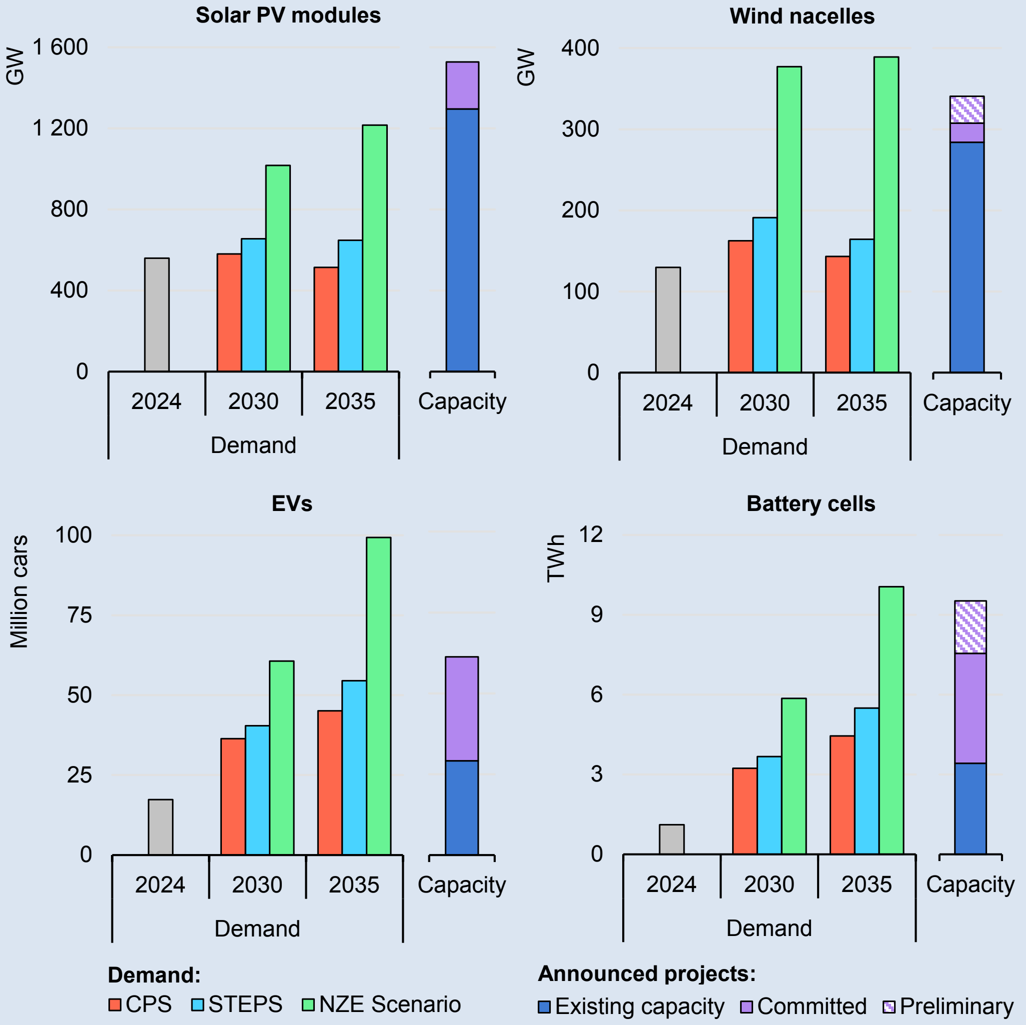
[1] See the Introduction for a detailed description of the scenarios.

decision (FID) or are under construction) capacity to supply deployment levels across all IEA scenarios, even when considering a maximum practical utilisation rate of 85% of nameplate capacity and 2035 deployment levels in the NZE Scenario. While that is not the case for other key technologies like EVs, battery cells and wind nacelles (nor it is true for several of these technologies' components), there is ample existing and committed announced capacity to meet the deployment levels in both the CPS and the STEPS to 2030.

Figure 5.1 Global demand by scenario and capacity of existing and announced projects for key clean energy technologies, 2024-2035



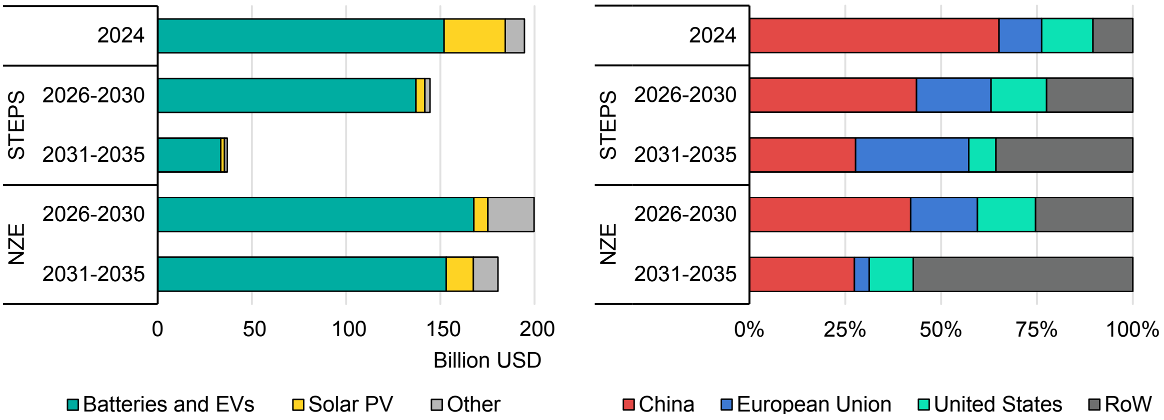
Notes: CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE Scenario = Net Zero Emissions by 2050 Scenario.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Manufacturing investment

In the STEPS, which reflects government policies and measures already in place or under active development, global investment in clean technology manufacturing is projected to continue to decline through to 2035. After peaking at nearly USD 220 billion[2] in 2023, investment in manufacturing capacity for the six key clean energy technologies – solar PV, wind turbines, EVs and batteries, electrolysers and heat pumps – dropped to just under USD 200 billion in 2024. It then averages around USD 145 billion per year over 2026-30 and drops below USD 50 billion per year over 2031-35 (Figure 5.2). EVs and batteries see the largest decline in absolute terms, though solar PV sees the steepest percentage drop. This downturn reflects exceptionally high recent investment, especially in solar PV, which has resulted in global manufacturing capacity being more than sufficient to meet projected demand to 2035, reducing the need for new plants. Between 2026 and 2035, nearly all investment goes to EVs and batteries.

Figure 5.2 Global annual average investment in clean energy technology manufacturing in the Stated Policies Scenario and Net Zero Emissions by 2050 Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; RoW = Rest of World. Investment for 2026-30 and 2031-35 refers to annual averages. Batteries and EVs includes anode and cathode active materials, battery cells and electric cars. Solar PV includes polysilicon, wafers, cells and modules. Other includes electrolysers, heat pumps, and wind turbine blades, towers and nacelles.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Manufacturing investment diversifies geographically over time, with emerging economies making in-roads after 2030 in the STEPS and even more so in the NZE Scenario.

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[2] Unless stated otherwise, USD figures are real 2024 dollars in market exchange rate terms throughout this report.

The faster clean energy technology deployment projected in the NZE Scenario requires a very different investment trajectory. Near-term investment remains close to peak levels, reflecting the stronger policy support and higher demand required to align with a 2050 net zero pathway. Over 2026-30, average annual spending remains just under USD 200 billion – close to the 2023 high – before declining in 2031-35. It nonetheless remains far above the levels in the STEPS across all major technologies. Compared with the STEPS, investment in 2031-35 is over four times higher for EVs and batteries, three times higher for heat pumps and more than ten times higher for wind. For instance, EV sales in 2035 in the NZE Scenario are nearly double those in the STEPS, sustaining elevated battery demand and driving higher investment along the EV supply chain.

Investment in clean energy technology manufacturing shifts decisively away from the People’s Republic of China (hereafter, “China”) in both scenarios. In the STEPS, China’s share of global investment in new and refurbished factories for producing the six technologies drops from 65% in 2024 to around 45% in 2030 and little less than 30% in 2035, largely reflecting energy, industrial and trade policies in other regions. The European Union sees the biggest increase, with its share rising from over 10% in 2024 to nearly 30% by 2035. This growth is driven by long-term demand certainty underpinned by ambitious EV targets, and industrial policies such as the Net-Zero Industry Act (NZIA), which is considered in the STEPS. This outlook depends on the timely completion of committed projects, which generally face higher production costs than in other regions, and on maintaining ambitious deployment policies and targets. China continues to leverage its ample existing capacity and remains the largest producer in the STEPS, with its share of global output of these technologies declining only slightly, from around 60% in 2024 to 45% in 2035.

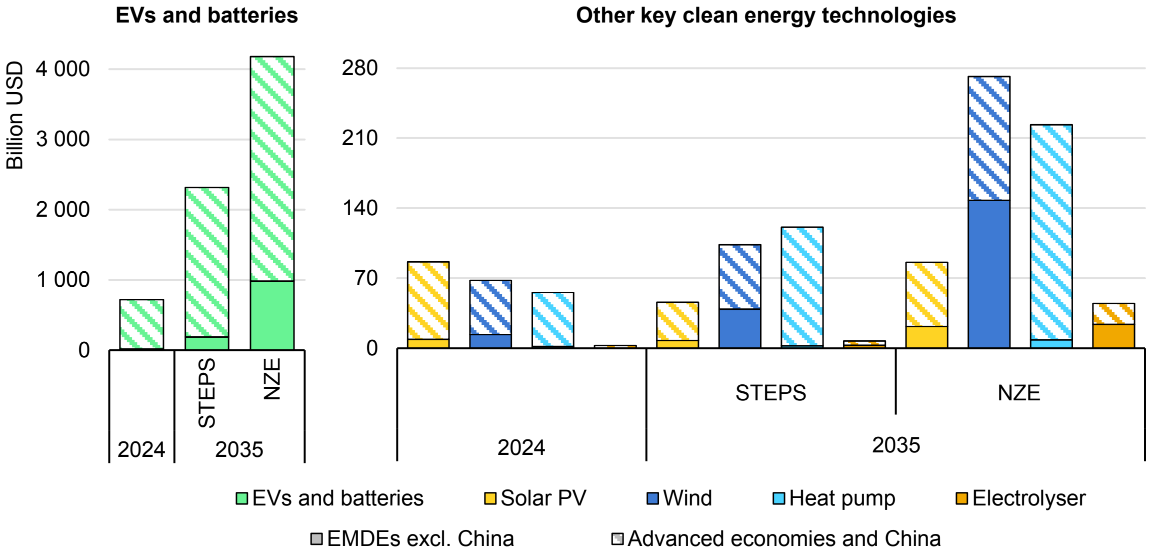
In the NZE Scenario, an even bigger share of investment flows to emerging markets and developing economies (EMDEs) other than China – 20% in 2026-35, compared with close to 10% in the STEPS. This scenario assumes these economies can overcome investment barriers, implement effective policies, build industrial capacity and develop the necessary skills. Many EMDEs also benefit from improved access to raw materials, affordable renewable energy and large workforces, creating strong potential to develop clean technology manufacturing (IEA, 2024b) (IEA, 2024a).

Production and trade

Building on this foundation, EMDEs scale up production of clean energy technologies across nearly all segments by 2035 in both scenarios, with a much faster expansion projected in the NZE Scenario. In the STEPS, countries with an established industrial base, such as an automotive sector, see clean technology manufacturing beginning on a significant scale only in the 2030s;

for those with minimal industrial capacity today, it starts after 2040. EVs remain the leading technology by production value in both scenarios, with EMDEs increasing their share of global production of all technologies, particularly EVs and wind. In the NZE Scenario, EMDEs excluding China increase their share of production of EVs from 1% in 2024 to nearly 25% in 2035, while they increase their wind manufacturing share from less than 20% to over 50%.

Figure 5.3 Estimated output value from clean technology manufacturing by technology in the Stated Policies Scenario and Net Zero Emissions by 2050 Scenario, 2024-2035



Notes: STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; EMDE = emerging markets and developing economies.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

EMDEs other than China scale up production of clean energy technologies rapidly to 2035 in both scenarios, with a much faster expansion projected in the NZE Scenario.

International trade remains a central component in meeting rising demand for clean energy technologies in both scenarios, as manufacturing capacity continues to be concentrated in China and a small number of other countries and demand is much more dispersed. In the STEPS, average annual global trade in 2035 is more than double that of 2024, while in the NZE Scenario it is more than six times higher (Figure 5.4).[3] China's position as a net exporter of clean energy technologies strengthens in absolute terms in the STEPS, thanks

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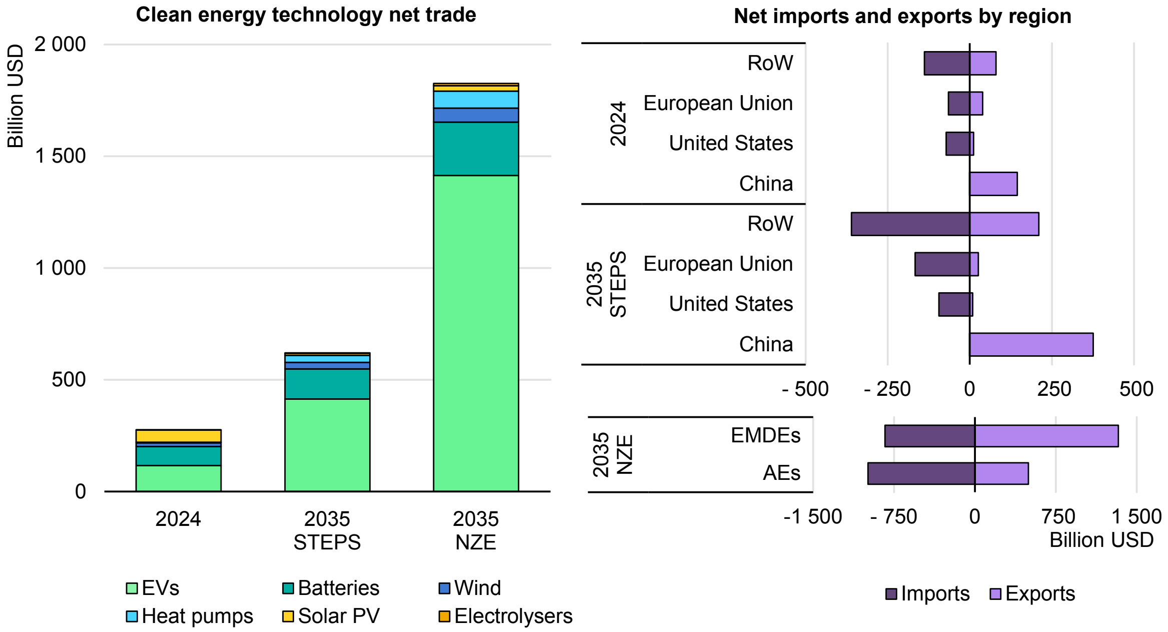
[3] Unless specified otherwise, all traded value and volume figures in Chapter 5 are stated on a net, inter-regional basis. This is contrast to Chapter 4, where statistical data on gross international trade are used.

to its large amount of existing manufacturing capacity and – in almost all cases – having the lowest production costs. China's net exports of clean energy technologies increase from around USD 145 billion in 2024 to USD 375 billion in 2035. To put this latter figure in context, it represents around 10% of China's total goods exports in 2024 (around USD 3.6 trillion) (State Council, 2025), which is around four-fifths of the combined value of crude oil export revenues across OPEC countries in 2025 (USD 455 billion) (EIA, 2025).

Despite this rapid growth, several countries lower their dependency on Chinese imports in relative terms at certain steps in the value chain – particularly those downstream. For example, the European Union's net imports of battery cells from China drop from around half of domestic demand levels in 2025 to around a quarter by 2035. At the same time, the dependency on Chinese cathodes imports jumps from around 15% to 45% over the same period; for anodes it remains at today's elevated levels of around 75%. A similar pattern can be seen in the profile of Chinese import dependence across the solar PV supply chain; several countries reduce their dependence on Chinese module and cell imports, but to a lesser extent – or not at all – for wafers and polysilicon.

Figure 5.4 Inter-regional net trade in clean energy technologies in the Stated Policies Scenario and Net Zero Emissions by 2050 Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; EVs = electric vehicles; EMDEs = emerging markets and developing economies; AEs = advanced economies. Trade is in net terms by technology, based on the regional groupings used in the Manufacturing and Trade model, which align with those used in the Global Energy and Climate model. Intra-regional trade is not included.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

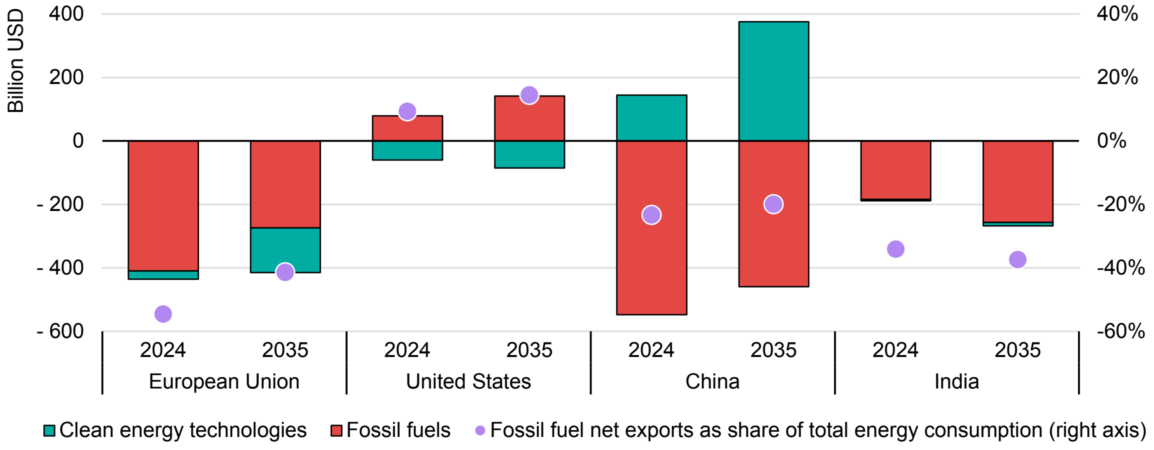
Clean energy technology trade over the next decade reaches more than double that of 2024 in the STEPS and more than six times higher in the NZE Scenario.

Trade remains a key enabler of clean energy technology deployment, which has far-reaching effects on the need to trade fossil fuels. Between 2024 and 2035 in the STEPS, changes in total energy supply are relatively small in the United States (0%), European Union (-8%) and China (4%), while India sees a larger increase (32%). Across all countries, electricity plays a growing role, increasingly generated and transformed using clean energy technologies, which must be imported where domestic manufacturing falls short, as in most countries other than China.

The European Union sees its net imports of fossil fuels drop from around USD 410 billion in 2024 to USD 275 billion in 2035 in the STEPS. Fossil fuel imports drop by more than 30% over that period, pushing down their share in total energy consumption from 55% in 2024 to around 40% in 2035. Over the same period, net imports of clean energy technologies increase from around USD 65 billion to USD 165 billion, resulting in a broadly flat import bill for fossil fuels and clean energy technologies combined. Similarly, China cuts net fossil fuel imports to USD 460 billion, while substantially increasing net exports of clean energy technologies, leading almost to a balancing of the value of imports and exports across these two categories of goods.

The United States and India follow different paths. The United States reduces fossil energy use but increases net exports, with shortfall replaced by renewables-based electricity, driving growth in clean energy technology imports. India, on the other hand, sees an increase in fossil fuel demand, but expanding domestic manufacturing allows it to meet nearly all EV, solar PV module and wind demand by 2035, limiting imports.

Figure 5.5 Net trade in clean energy technologies and fossil fuels in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

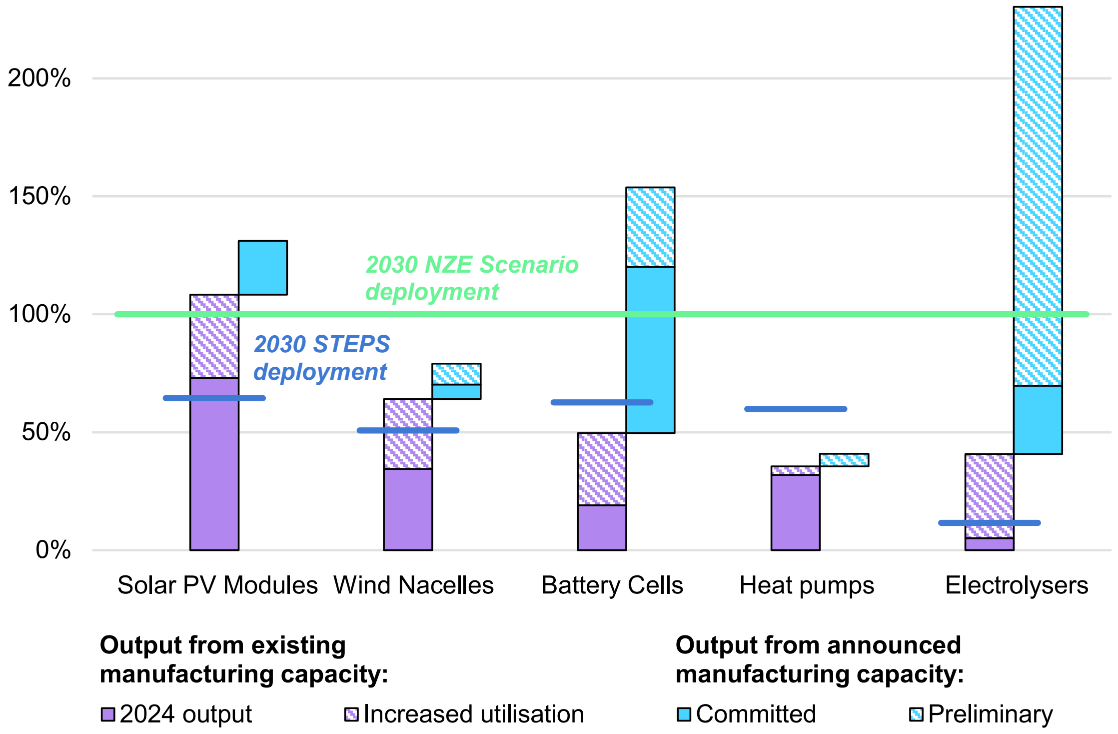
Note: Positive values are net exports; negative values are net imports.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Fossil fuel imports fall sharply in the European Union and China over the next decade in the STEPS, owing to widespread deployment of clean energy technologies.

For several technologies, the global manufacturing capacity needed to meet projected 2030 production levels in both the STEPS and NZE Scenario is already in place, under construction or planned. Battery manufacturing capacity, including committed projects with an FID, is sufficient even in the NZE Scenario (Figure 5.6). For solar PV, existing capacity alone exceeds projected demand. Wind nacelles fall short when considering existing and committed capacity at full utilisation. Electrolysers require a large share of announced projects, including those not yet at the FID stage, to meet demand. Heat pumps face the biggest gap, needing more than a doubling of capacity by 2030 to meet NZE Scenario requirements.

Figure 5.6 Projected output from existing and announced manufacturing capacity relative to deployment in the Stated Policies Scenario and Net Zero Emissions by 2050 Scenario, 2030



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario; NZE Scenario = Net Zero Emissions by 2050 Scenario. Committed capacity refers to projects that have reached a final investment decision or are under construction. Increased utilisation refers to the gap between 2024 production levels and existing capacity being utilised at 85%. That rate is assumed for both existing and announced manufacturing capacity in 2030. For heat pumps, the project pipeline is concentrated in Europe, where manufacturers announced new plans after the 2022 surge in sales, though this reflects the fact that new manufacturing projects are commonly not announced publicly by heat pump manufacturers in other regions.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Manufacturing project pipelines for solar PV modules, battery cells and electrolysers are sufficient to achieve the production levels projected for 2030, even in the NZE Scenario.

Solar PV

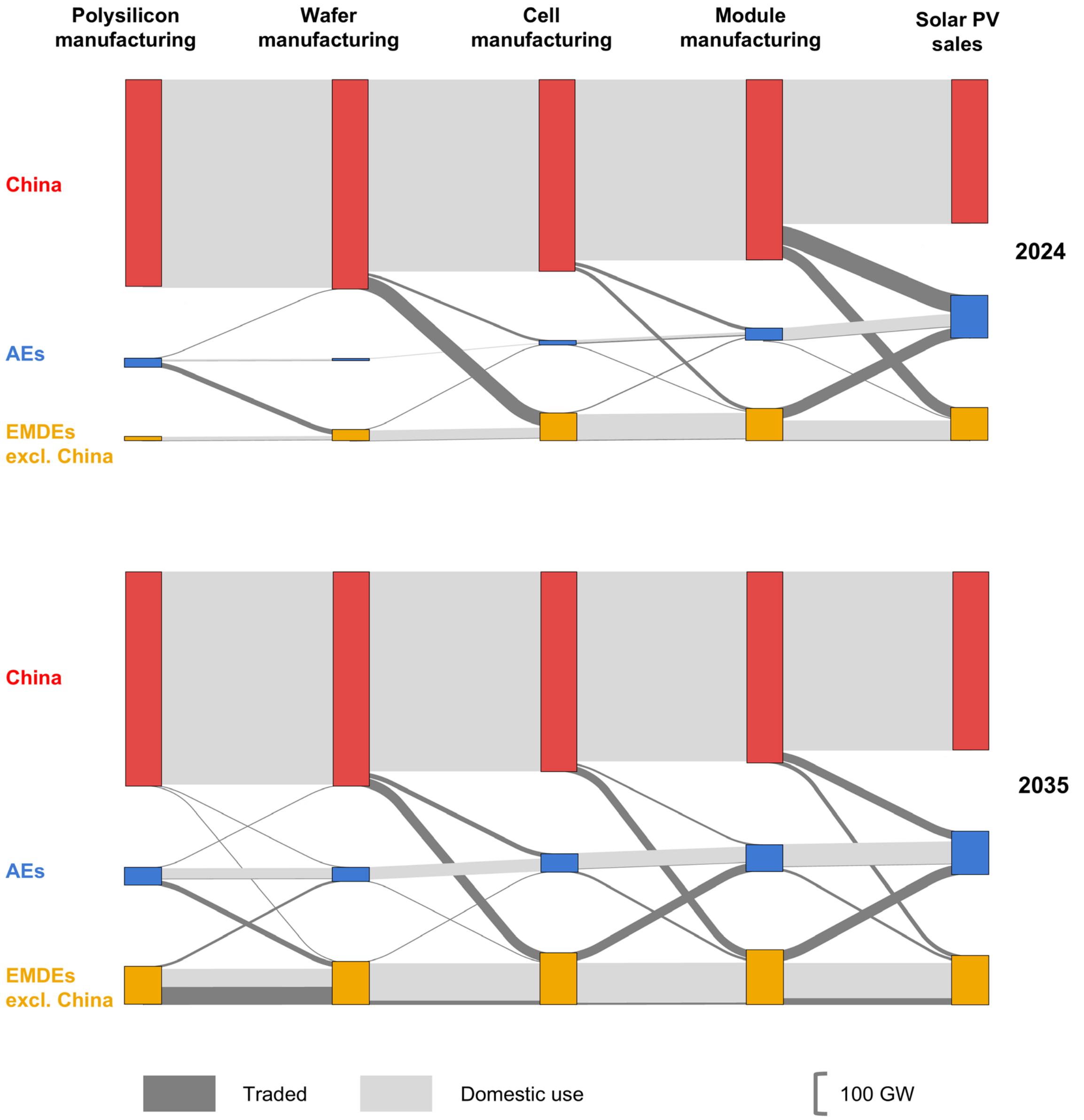
Global trends

Solar PV deployment maintained strong momentum in 2024, with installed generating capacity increasing by 540 GW (around 25% higher than the capacity additions in 2023). Almost 60% of this growth came from China, with most of the remainder from the European Union, the United States and India (see Chapter 2). China continued to dominate the global solar PV manufacturing supply chain, adding substantial capacity across all major production stages: polysilicon, wafers, cells, and modules. Yet the manufacturing capacity growth in China was lower than in 2023 in most segments, except for polysilicon manufacturing – the bottleneck at the end of 2023 – which expanded by more than 50% and accounted for virtually all global capacity additions in 2024.

In recent years, rapid capacity growth has created a substantial overhang, driving down prices and profits. As a result, several previously announced projects have been cancelled or delayed over the past year (see Table 4.2). Part of this overcapacity stems from internal competition between provinces in China and from investments in more advanced cell technologies, which have made much of the existing capacity obsolete (though it remains operational). Most new manufacturing facilities are designed to produce Tunnel Oxide Passivated Contact (TOPCon) cells, while many existing Passivated Emitter Rear Contact (PERC) plants have been retrofitted to produce this technology. The increased conversion efficiency of TOPCon may translate to multiple GWh of additional solar power generated in the coming years.

Lower prices have given installers and utilities in China and elsewhere an opportunity to purchase PV modules at reduced cost, boosting both deployment and stockpiles in Europe and North America. Concerns over the possible introduction of high tariffs and duties have also fuelled inventory building in importing countries, particularly in the United States. Trade volumes and patterns remained largely unchanged in 2024, with over one-quarter of modules being traded between regions (excluding changes to inventories). Our estimates for 2025 show a slight fall in trade volumes because of the build-up of domestic capacity in the United States and India, and a slowdown in US solar PV deployment. Modules remain by far the most traded component both in terms of value (four times that of cells) and capacity (two times more). In fact, the trade of modules roughly matches the traded capacity of cells and wafers combined.

Figure 5.7 Global manufacturing and inter-regional net trade flows in the solar PV supply chain in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: AEs = advanced economies; EMDEs excl. China = emerging markets and developing countries excluding China. Flows have been normalised to global demand and excludes inventory changes.

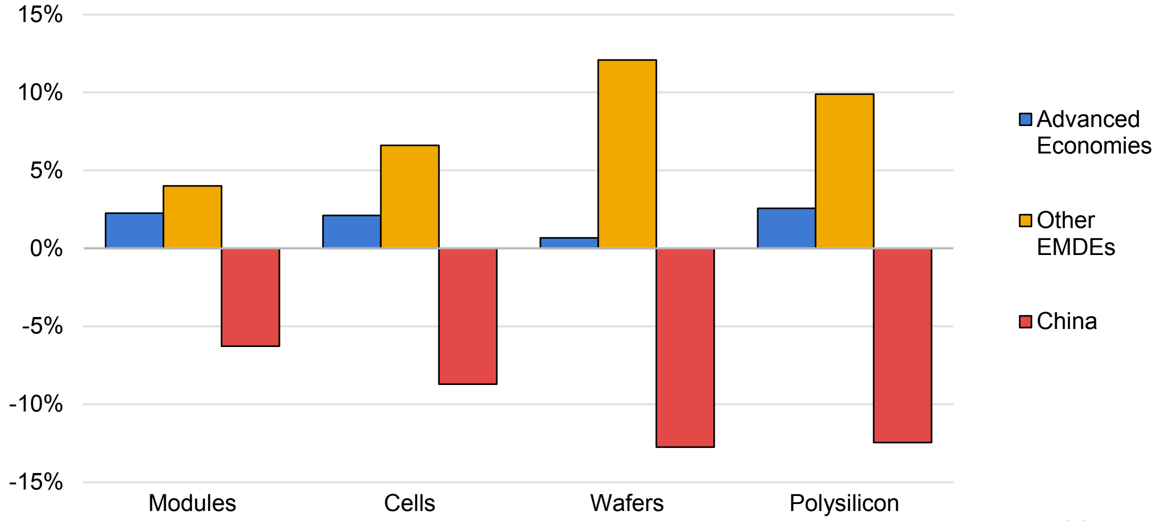
Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

China continues to dominate the solar PV supply chain and deployment of generating capacity, though the market share of other EMDEs is set to grow rapidly.

Medium-term prospects for manufacturing and trade in solar PV modules and components are shaped by the current supply overhang, which is slowing capacity additions, and influencing trade policies. China remains by far the largest producer across all components and final modules in the STEPS (Figure 5.7). Though its market share declines by 6%, it still supplies nearly 75% of the projected 660 GW of global module demand in 2030 (compared with 80%

of 560 GW in 2024) and about the same share of the 650 GW of demand in 2035. Its share of supply of components falls more, but remains at around 80% given that it starts from a higher base (Figure 5.8).

Figure 5.8 Change in regional shares of global production along the solar PV supply chain in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

China's share of solar PV production globally is set to fall as new facilities come online in other EMDEs and advanced economies.

India experiences the largest increase in global share of production, rising from 3% in 2024 to 10% in 2030 and reaching about 12% by 2035. Association of Southeast Asian Nations (ASEAN) countries see a regional reshuffling of capacity and production as a result of US trade policies, but maintain a share of around 5% of global production through 2030 and beyond. Other EMDEs are entering the supply chain as well; for example, the Middle East is establishing new capacity, with a polysilicon production facility coming online in Oman, leveraging its competitive energy costs.

In the NZE Scenario, global demand for solar PV is more than 50% higher than in the STEPS in 2030 and almost 90% higher in 2035, reaching almost 1.2 TW. This stronger outlook allows more room for new entrants, especially in EMDEs other than China. By 2030, these economies widen their lead over advanced economies in module production, and by 2035 they account for 35% of global output, with similarly increasing shares along the supply chain.

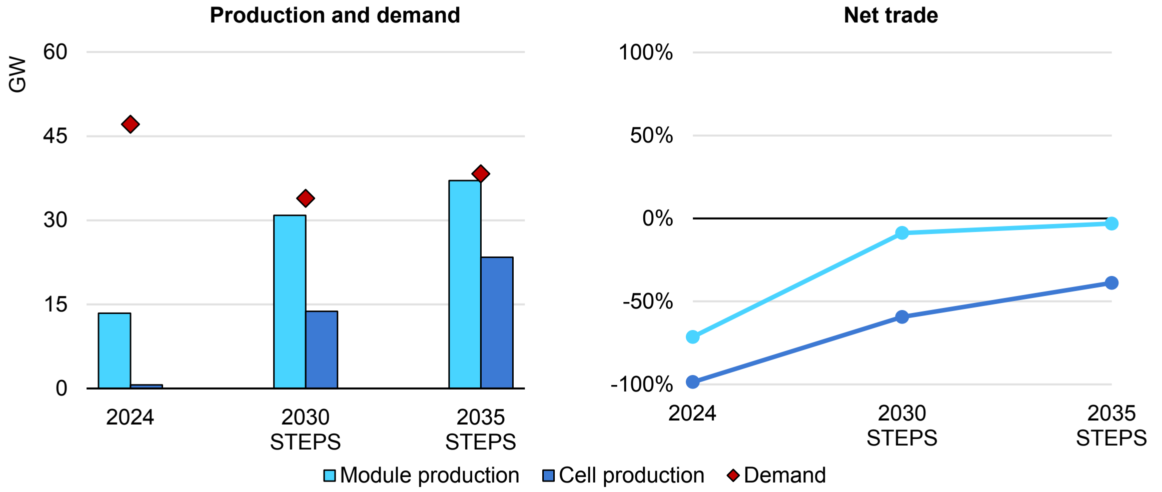
In addition to the main four components, inverters – an essential piece of equipment for connecting PV modules to the grid – also have ample supply, with around 1 200 GW of annual output in 2024. Manufacturing capacity for inverters is relatively well distributed at present compared with other components, with the European Union and India able to meet their own demand, and the United States capable of covering the majority of its requirements domestically. Rising global requirements to 2035 are expected to be met comfortably in both scenarios, although a modest expansion of around 10% will be needed under the NZE Scenario.

Impact of US and Indian industrial and trade policies

Alongside China's extensive use of tax concessions, grants and below-market loans (see Chapter 4), the United States and India are the only major economies offering explicit financial support for solar PV manufacturing as part of their clean energy industrial policies. The US Inflation Reduction Act (IRA) continues to lower the levelised cost of production (LCOP) for modules from around USD 0.21/W to USD 0.14/W, while India's Production Linked Incentive scheme provides substantial capital expenditure support. Both countries complement these incentives with trade measures that increase import costs and enforce local content requirements; for example, India mandates the use of locally sourced cells as per its Approved List of Models and Manufacturers.

The impact of these policies is already evident. Between 2022 and 2024, module and cell manufacturing capacity expanded threefold in India and fivefold in the United States. This growth is projected to continue under the STEPS, with an additional 30 GW of module capacity projected in the United States (Figure 5.9) and 70 GW in India by 2030 (Figure 5.10). Upstream capacities also continue to expand rapidly: wafer manufacturing, which was previously negligible in both countries, is projected to reach 5 GW in the United States and over 65 GW in India by 2030, while India's polysilicon capacity is projected to rise to 25 GW, from zero in 2024.

Figure 5.9 Solar PV module and cell production, demand and net trade in the United States in the Stated Policies Scenario, 2024-2035



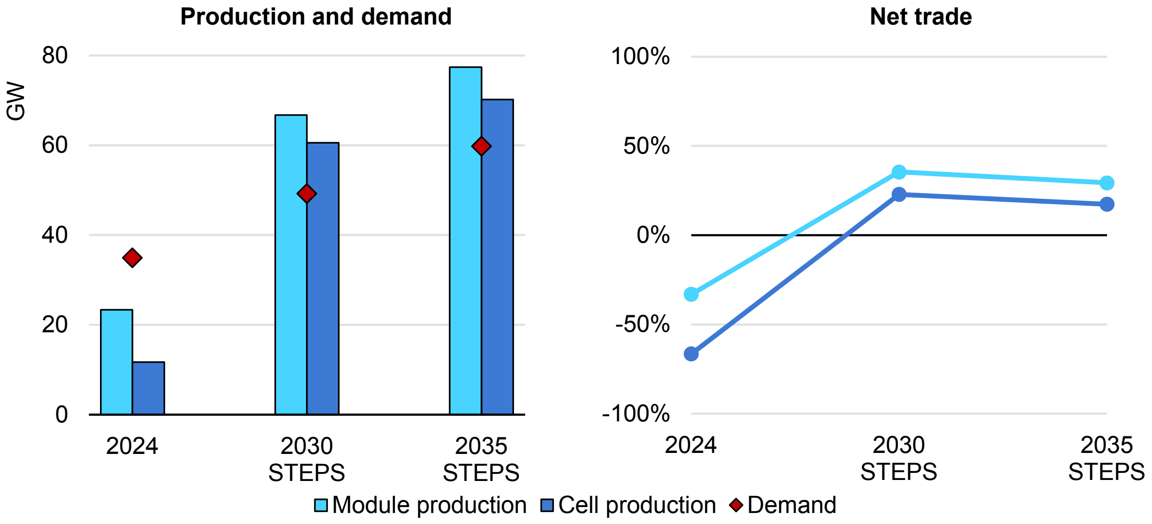
Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Financial support under the IRA and protective trade policies are set to continue to drive up solar PV module and cell production – and reduce imports – in the United States.

Higher domestic production costs combined with substantial import duties mean that solar PV module and component prices in India (around USD 0.15/W) and the United States (close to USD 0.30/W) are far higher than the USD 0.09/W price of Chinese modules – the global price benchmark. Part of the reason for this price gap is that Chinese modules are currently estimated to sell at a small loss. Under the STEPS, the gap narrows, reflecting both current policies and structural cost factors. In the United States, an additional driver of higher prices is the significant share (around 20%) of thin-film manufacturing, which is more expensive per unit of power output than crystalline silicon-based production.

Despite higher prices, solar PV deployment in both countries in the STEPS is not significantly affected, as module costs represent only a small share of total PV installation/plant costs. Most of the projected slowdown *vis-à-vis* the projections for the United States in *ETP-2024* stems instead from policy changes and resulting uncertainty, which dampen investor confidence. In contrast, India continues rapid capacity additions in that scenario. Strong policy support and aggressive manufacturing expansion are enabling newer, more advanced facilities to replace outdated, uncompetitive plants – previously a cause of very low utilisation rates. As a result, India is expected to achieve its first module trade surplus as early as 2026 and is projected to be able to produce sufficient modules and cells before the end of the decade to meet domestic demand entirely, with surplus capacity maintained beyond 2030.

Figure 5.10 Solar PV module and cell production, demand and net trade in India in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

India's solar PV manufacturing capacity is set to outstrip deployment, with the country reaching self-sufficiency in both module and cell production before 2030 in the STEPS.

Box 5.2 The impact of new US import duties on Southeast Asian solar PV manufacturing

The solar PV manufacturing capacity of Southeast Asian countries increased steadily until 2023, making the region as a whole the second-largest holder of manufacturing capacity outside China. Southeast Asia has highly competitive production costs and benefits from a strong manufacturing base, favourable policy frameworks and a skilled workforce. These factors have supported the expansion of an export-oriented industry, with an LCOP for modules about 10% above China's – well below the global median, which is around 30% higher.

Most of this capacity is in downstream components, with Chinese-based companies accounting for more than 60% of total production capacity. Given the highly standardised nature of solar PV products and manufacturing processes, the move into Southeast Asia has led to a significant transfer of know-how. Proximity to China has facilitated smooth integration into Chinese supply chains, particularly through the import of upstream components from the same companies' integrated infrastructure in China.

Recent shifts in US trade policy threaten to severely disrupt solar PV manufacturing in Southeast Asia. Following an investigation by the Department of Commerce, the US International Trade Commission determined that imports of modules and cells were damaging the US industry, prompting the government to impose countervailing duties (CVD) and antidumping duties (ADD) in June 2025 (Table 5.1) (International Trade Administration, 2025a).

Table 5.1 US duties on solar PV imports from Southeast Asia, from June 2025

Country	ADD rates	CVD rates
Cambodia	125%	535-3 404%
Malaysia	0-81%	15-171%
Thailand	111-203%	255-775%
Viet Nam	62-271%	68-543%

Note: Numbers are rounded to the nearest percentage point.

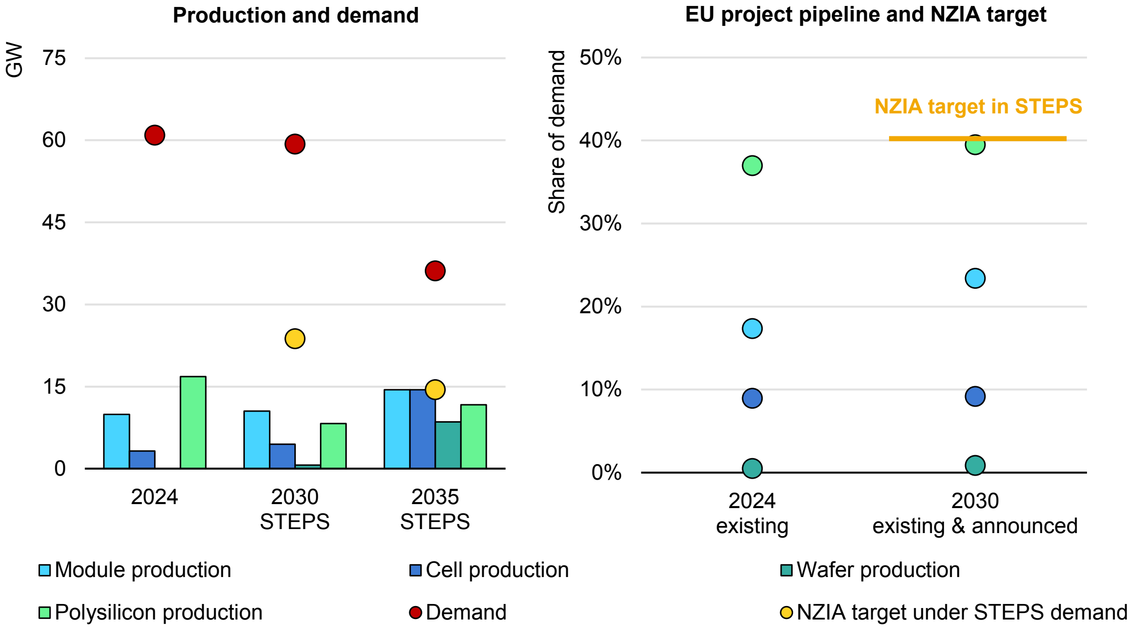
Historically, the United States has been the main importer of solar PV modules and cells from Southeast Asia, as US imports from China have been heavily restricted in recent years. With the new tariff and duty rates in place, import prices of Southeast Asian products now exceed the breakeven level for US-based production. This appears to be triggering a slump in exports to the United States and a sharp contraction in ASEAN manufacturing, with 2025 output projected to fall by around 50% compared with the previous year based on data covering the first half of 2025. This has led to a drop in new project announcements and the decommissioning of some existing plants.

Impact of EU targets for solar PV manufacturing

Even though the European Union recorded the second-highest solar PV capacity additions as a region in 2024, domestic production remains very limited along the entire supply chain and is virtually non-existent for wafers. As a result, the European Union imports over 85% of its requirements, with more than three-quarters coming from China.

The NZIA designates solar PV as a “net-zero technology of interest”, making it eligible for support to speed up permitting for manufacturing facilities. However, among all the technologies covered by the NZIA, the solar PV supply chain appears the most difficult to develop, given the region’s high production costs, the absence of systematic financial support schemes (such as those in place in the China, United States and India) and the European Union’s continued openness to solar PV imports.

Figure 5.11 Solar PV module and component production and demand and announced projects in the European Union in the Stated Policies Scenario, 2024-2035



Notes: STEPS = Stated Policies Scenario; NZIA = Net-Zero Industry Act. The NZIA target is defined as 40% of total demand for a clean technology being accommodated with domestic production at all steps in the supply chain. The ‘2024 existing’ and ‘2030 existing & announced’ values on the right-hand graph show the projected output from existing capacity and announced projects assumed a utilisation rate of 85%.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

The NZIA target calls for a rapid ramp-up of EU solar PV module and component production to 2030 and beyond, but capacity in the pipeline is insufficient to meet this goal.

The absence of specific support mechanisms to make the NZIA target achievable is reflected in the modest growth of manufacturing capacity and related announcements in 2024 and 2025. Announcements have not increased significantly since the policy was adopted. Given the lead times for building capacity in Europe and the lack of incentives, especially compared with the United States, neither the 2030 nor 2035 targets are assumed to be met in the STEPS. Moreover, the prospect of a significant increase in production incentives is looking less likely in view of the gradual shift in EU spending priorities, notably towards defence. In addition, the prospects for achieving competitiveness appear more promising for some other clean energy technologies, including wind and batteries.

Among components, only polysilicon production is relatively well-positioned, supported by the region’s strong chemical industry, notably Germany’s Wacker Chemie. However, high energy costs limit expansion in the STEPS, while exports to China are falling as Chinese producers increase both output and product purity. For modules, the target is more attainable – though likely only after 2030, by when demand will have peaked – as announced capacity would need to increase by three-quarters by then. By contrast, cells and wafers must climb from a much lower base, making progress considerably harder.

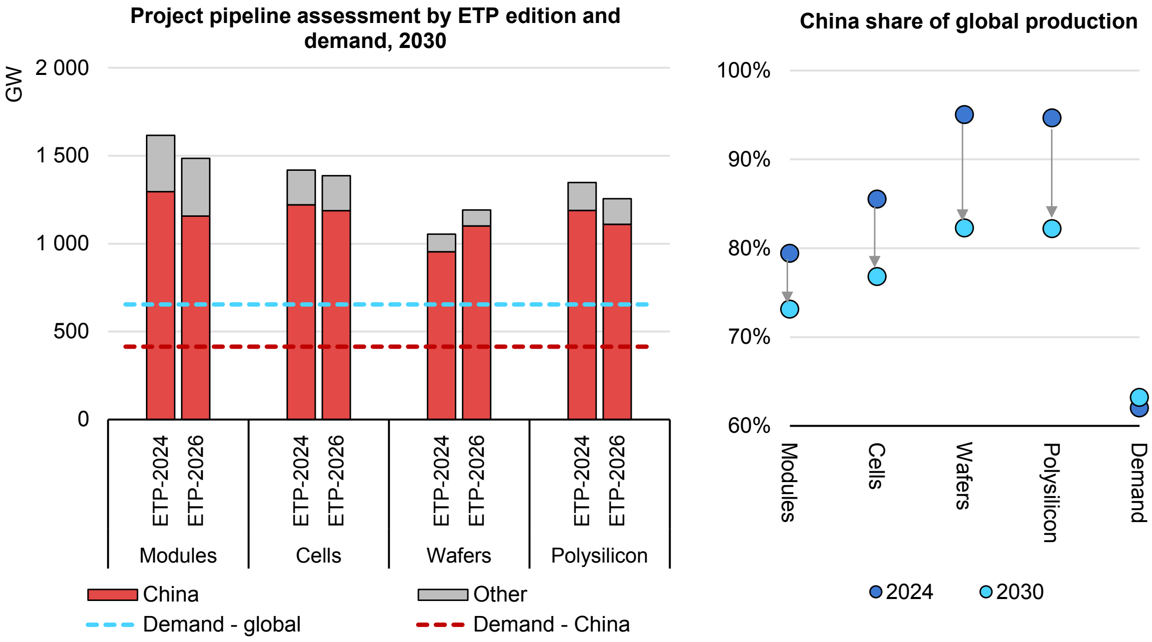
Solar PV supply chain concentration in China

The concentration of solar PV manufacturing in China has continued to rise across all parts of the supply chain over the past 5 years, with the greatest clustering upstream in polysilicon and wafer production. Its polysilicon production capacity has expanded particularly quickly: in 2024 alone, it increased by more than 50% compared with end-2023. This rapid expansion has closed the gap between domestic supply and demand for solar-grade polysilicon, enabling China to achieve near self-sufficiency. Its share of global polysilicon production has risen to almost 95% – higher than its share for modules and cells, and more than 25 percentage points above the level of 5 years ago.

Wafers are the only PV supply chain segment for which new project announcements have outstripped project cancellations since *ETP-2024*; project pipelines for modules and cells have been revised downward or remain stagnant, as is the case for polysilicon. Almost all cancellations and downscaling for modules and cells have come from China, where companies have entered a phase of consolidation. Although these changes have not yet led to a dramatic drop in China’s share of global capacity, the impact will be more evident in production output in the near future. In the STEPS, China’s production share is projected to decline by 6-13 percentage points by 2030, remaining above 70% for downstream components – which are more directly targeted by US and Indian policies – and above 80% for upstream components, which benefit from vertical integration and economies of scale. Despite this fall, China remains the leading exporter of PV components due to the scale of its capacity and cost-competitiveness.

Historically, polysilicon and wafer supply has been more concentrated than modules, both in terms of the number of countries hosting production and the number and size of facilities. In 2024, modules were produced in 40 countries and wafers in 15, but only six countries manufactured polysilicon. Energy costs play a critical role in determining cost-competitiveness, favouring regions with abundant low-cost energy, such as certain provinces of China, emerging producers in the Middle East, some parts of Southeast Asia and India. Moreover, upstream segments attract fewer financial incentives, as they account for a relatively small share of total value added in the solar PV supply chain. However, building a more resilient supply chain would require less concentrated manufacturing across all steps. Given that these upstream stages are not substitutable, expanding wafer and polysilicon capacity represents a logical upstream extension for countries that have already established robust module and cell manufacturing.

Figure 5.12 Global solar PV manufacturing capacity announcements and China's share of global production and demand in the Stated Policies Scenario, 2024-2030



Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Chinese companies have slashed their plans to add manufacturing capacity for solar PV modules and cells, which is set to moderate their combined global market share in 2030.

Wind

Global trends

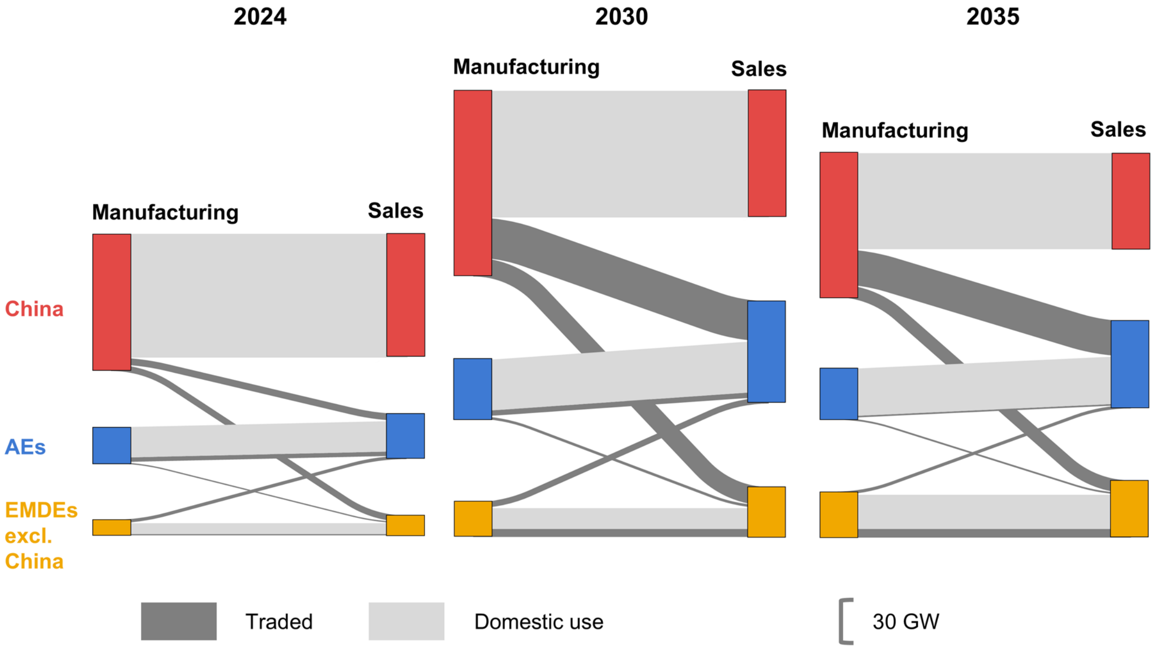
Wind turbine deployment reached 115 GW in 2024 and is projected to have risen by over 25% to 145 GW in 2025. Global wind manufacturing capacity reached over 280 GW in 2024. This surge is driven mainly by China's rapid expansion of wind installations, which are expected to have reached 90 GW in 2025 – about 60% of global added capacity that year. The acceleration reflects upcoming changes to China's electricity pricing system, which is moving towards a more market-based approach. However, the global speed of deployment and manufacturing to meet the sector's needs are set to slow significantly after 2025. In the STEPS, global wind additions grow by a little over 2% per year on average to 2035, with strong growth in Europe offset by a marked slowdown in China. In advanced economies, most of the growth comes from Europe, while additions in the United States fall due to recent policy changes.

As components are costly to transport over long distances, production tends to be located close to markets. Among the three main components analysed, blades and nacelles have the highest trade volumes, while towers are traded the least, with only about 10% of production currently exported. Nacelle assembly is more geographically concentrated than blade or tower assembly, mainly due to higher labour costs and the complexity of subcomponents, which benefit from proximity to established industrial clusters. In 2024, inter-regional trade in nacelles was equivalent to around 12% of global production. Blade manufacturing is more geographically dispersed. While many plants are located in major deployment markets, significant production hubs also operate just across borders from these markets. For example, Mexico supplies about 40% of US blade demand, while Türkiye supplies around 10% of the European Union's.

The geographic distribution of wind turbine manufacturing is poised to shift over the coming decade, largely reflecting differences in deployment prospects. In the STEPS, China's share of global production of the three main components drops from 65-75% in 2024 to 45-65% in 2030 and 40-60% in 2035, as domestic production stagnates and production in other EMDEs and advanced economies continues to expand. Inter-regional trade in wind components is also projected to increase as regional demand shifts, although manufacturing capacity centres remain largely unchanged. By 2030, global exports of nacelles, blades and towers rise by 240%, 190% and 85%, respectively. In the case of nacelles, the share of trade in global production rises to nearly 30%, mainly due to weak demand in China, which frees up capacity for export (Figure 5.13).

In the same scenario, the United States substantially reduces its reliance on imports. All nacelles deployed domestically are expected to be assembled in the country, while the domestic share of blade production increases from 35% to 80% by 2030. This shift sharply reduces projected imports from Europe, India and Mexico: nacelle imports fall from 6 GW to near zero, while blade imports are six times lower. Smaller emerging suppliers such as Brazil and other Central and South American countries are also affected, having previously been identified as potential sources under the IRA renewable energy targets.

Figure 5.13 Global manufacturing and inter-regional net trade flows of wind turbine nacelles in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: AEs= advanced economies, EMDEs = emerging markets and developing economies excluding China.
Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

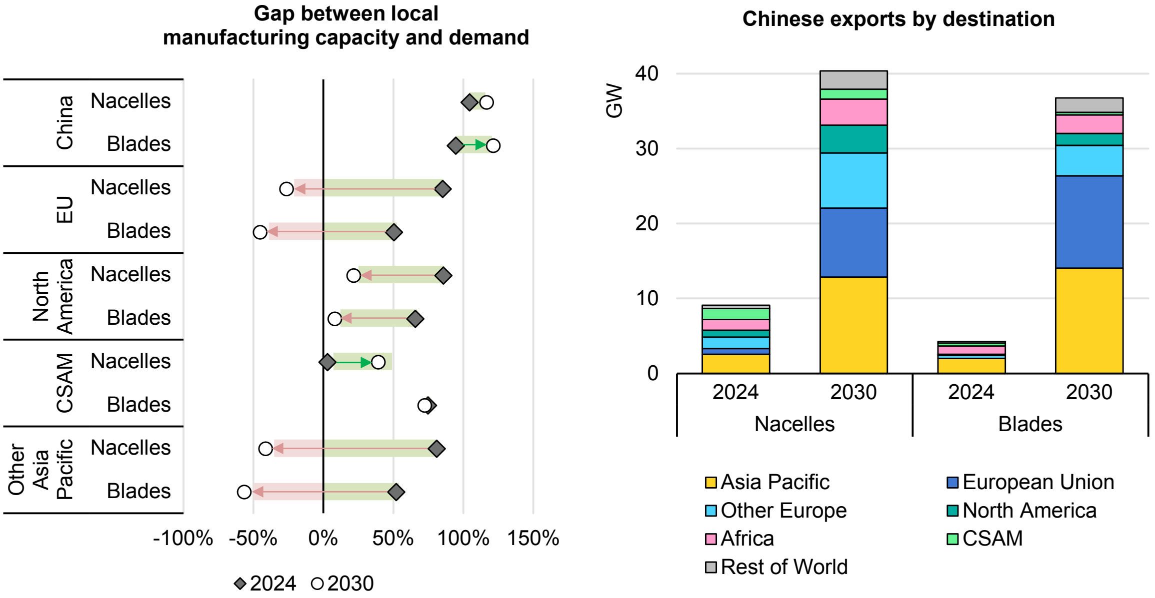
China's share of global nacelle production drops sharply to 2035, with a bigger share of its output going to exports, reflecting weaker domestic deployment.

Global wind manufacturing expands much faster in the NZE Scenario than in the STEPS to meet stronger demand. Wind capacity additions reach close to 390 GW by 2035, before easing to about 315 GW in the early 2040s. The difference is largest in EMDEs other than China, which in aggregate see their additions increase more than double – twice the rate of the increase advanced economies observe in the NZE Scenario. By 2040, these countries supply over 45% of global wind turbine components, compared with about 30% in the STEPS.

Prospects for China's exports

China is set to retain its position as the world's largest manufacturer of wind turbines and components in the medium term. In 2024, it accounted for about 70% of global manufacturing capacity for nacelles and blades, and around 45% for towers. With few new capacity announcements elsewhere, this dominance – particularly in nacelle and blade production – is expected to persist. In the STEPS, the surplus of domestic manufacturing capacity relative to demand shrinks and even turns into a gap in several regions (Figure 5.14). The European Union shifts from being a net exporter in 2024, exporting around 2 GW of nacelles (over 10% of domestic demand) to becoming a net importer of nearly 15% of its demand by 2030.

Figure 5.14 Difference between projected output from existing and announced projects and local demand by country/region and Chinese exports by destination for wind turbine blades and nacelles in the Stated Policies Scenario, 2024-2030



IEA. CC BY 4.0.

Notes: CSAM = Central and South America. The difference in the left-hand graph is calculated based on existing and committed announced projects, assuming a utilisation rate of 85%.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

In many regions, growth in domestic demand is set to outpace growth in manufacturing capacity, resulting in large increases in exports from China, where deployment is slowing.

A similar trend emerges in the Asia Pacific region excluding China, where several countries are currently net exporters. In the STEPS, imports meet around 35% of that region's demand for nacelles and 50% of demand for blades by 2030. Because many nacelle facilities in these countries primarily serve overseas markets, they need to rely on net imports to meet growing domestic demand for these components in this scenario.

This growing global reliance on imports in the STEPS is met largely by Chinese exports. This is due to lower-priced Chinese turbines on overseas markets, which today are on average about 40% cheaper than those from other manufacturers (BNEF, 2025a). The price gap is not uniform: in EMDEs in Africa and parts of Asia Pacific, Chinese turbines can be 10-45% less expensive, while in European and North American markets, the difference narrows to 10-25%, reflecting stricter quality requirements, trade measures and the high cost of shipping from China to those markets (see also Chapter 4).

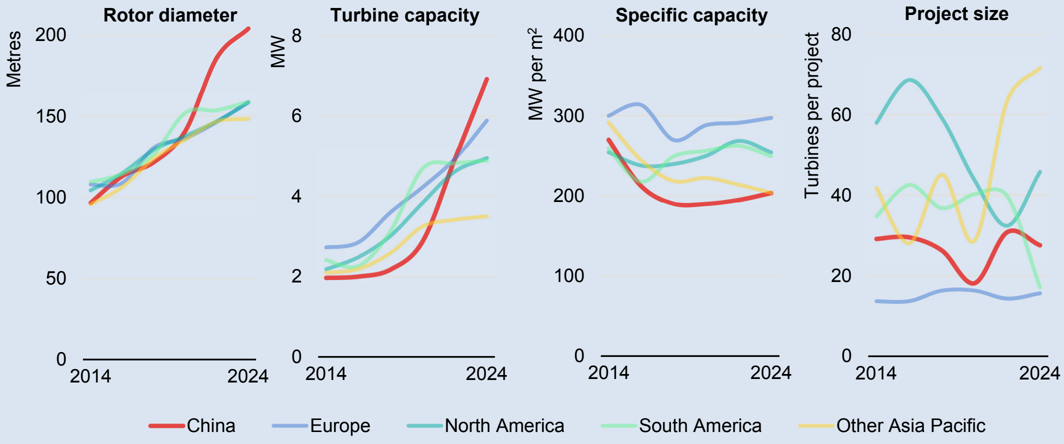
However, the potential for further growth in Chinese exports is constrained by three main factors:

- **Turbine design differences:** There are significant differences in the design of turbines across regions. For instance, the average rotor diameter of onshore turbines in the European Union is around 160 metres, compared with over 200 metres in China (Figure 5.15). This makes some Chinese-designed turbines less compatible with project specifications in many overseas markets.
- **Legacy of excess capacity:** Much of China's current excess capacity stems from factories built between 2020 and 2023, primarily serving low wind-speed Chinese regions. More recently, new facilities in northern China have been developed for high wind-speed and offshore projects. It is uncertain whether the older production lines can be adapted or maintained as demand shifts toward different turbine types and performance requirements.
- **Industrial policies:** Many governments are strengthening domestic wind supply chains through a mix of trade measures and targeted industrial policies:
  - In the **European Union**, the NZIA does not impose local content quotas. Instead, it introduces non-price criteria, such as those relating to sustainability, innovation and resilience, that can be used as pre-qualification or award criteria in public procurement and renewable energy tenders. These measures can encourage local component manufacturing. In May 2025, the European Commission issued new secondary legislation clarifying that the definition of covered components includes permanent magnets, gearboxes, drivetrains and bearings. It also specified that, from 30 December 2025, 30% of new auction volumes must apply the rules on the inclusion of non-price criteria (European Commission, 2025b).
  - In **India**, a draft regulation proposes geographic sourcing requirements for turbine components, aiming to localise a greater share of the value chain (see Box 5.4) (India, Ministry of New and Renewable Energy, 2025).
  - In **Japan**, the government has set a target of 60% domestic content in offshore wind projects by 2040, with a likely revision to 70%, as part of its offshore wind deal. This target is backed by subsidies for local production facilities (Japan, Ministry of Economy, Trade and Industry, 2020); by the end of 2024, five Japanese companies had been around USD 85 million (GX, 2025).

Box 5.3 Differences in regional configurations and the complexity of onshore and offshore wind technologies

In many respects, the onshore and offshore wind sectors operate as distinct manufacturing industries, each with its own complexities and at a different stage of maturity. Onshore wind technology has reached a relatively mature phase, with rotor diameters increasing only slightly in all regions except China. Current manufacturing innovation is focused less on size and more on materials and processes. For example, hybrid towers are becoming more common in China, though adoption is slower in other markets. In blade manufacturing, research is increasingly directed toward recyclability and the transition from thermosetting to thermoplastic materials. In recent years, the share of direct drive turbines has fallen sharply, from over 20% in 2022, to just below 9% in 2024, and medium-speed gear drive models are emerging as the preferred option. This shift has further increased standardisation in the onshore sector.

Figure 5.15 Regional differences in onshore wind turbine configurations, 2014-2024



Notes: Weighted averages for rotor diameter, capacity and specific capacity are calculated based on the number of turbines per firm project order. The analysis covers future wind projects on order.

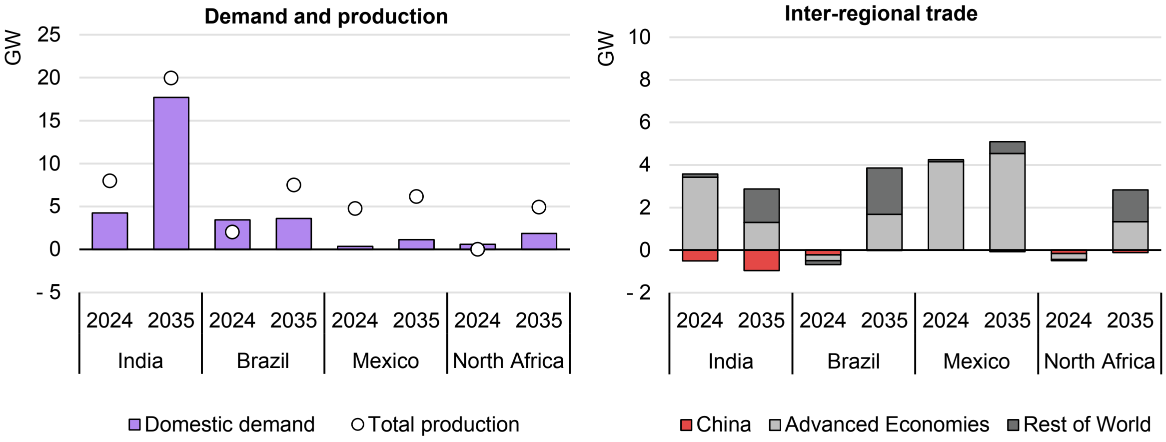
Source: IEA analysis based on S&P Global (2025).

By contrast, offshore wind remains at the stage of scaling and technological diversification. Rotor sizes and turbine capacities (MW per unit) continue to grow, and floating wind is still at an early commercial stage – the first large-scale projects of over 50 MW were completed only in 2021. This ongoing evolution adds complexity to both component standardisation and logistics.

Several emerging economies are also playing a growing role in the global wind supply chain:

- **India** remains a major global supplier and is reinforcing its industrial base. Under a revised certification policy introduced in April 2025 (India, Ministry of New and Renewable Energy, 2025), local sourcing of blades, towers, gearboxes and generators is mandatory for all new wind projects, with limited initial exemptions. Under the STEPS, both nacelles and blades exports account for about 20% of production in 2035, mainly serving Asia Pacific and European markets.
- **Brazil** has shifted from solely meeting domestic demand to serving regional markets too, with production facilities for all major components. It is projected to export 10% of nacelle production and 30% of blade production to other Latin American countries in 2035 in the STEPS.
- **North Africa**, particularly Morocco, is emerging as a blade manufacturing hub. By 2035, around 5% of EU wind imports are expected to come from the region, benefiting from proximity and shorter logistics chains.
- **Southeast Asia** is expanding its role as local deployment grows. Existing facilities include GE's onshore wind generator production in Viet Nam and CS Wind's tower manufacturing. Indonesia and the Philippines have potential to expand further, leveraging their steel, shipbuilding and automotive sectors. Tower production offers an accessible entry point for countries with limited turbine manufacturing experience.

Figure 5.16 Wind blade demand, production and inter-regional trade in selected emerging economies in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

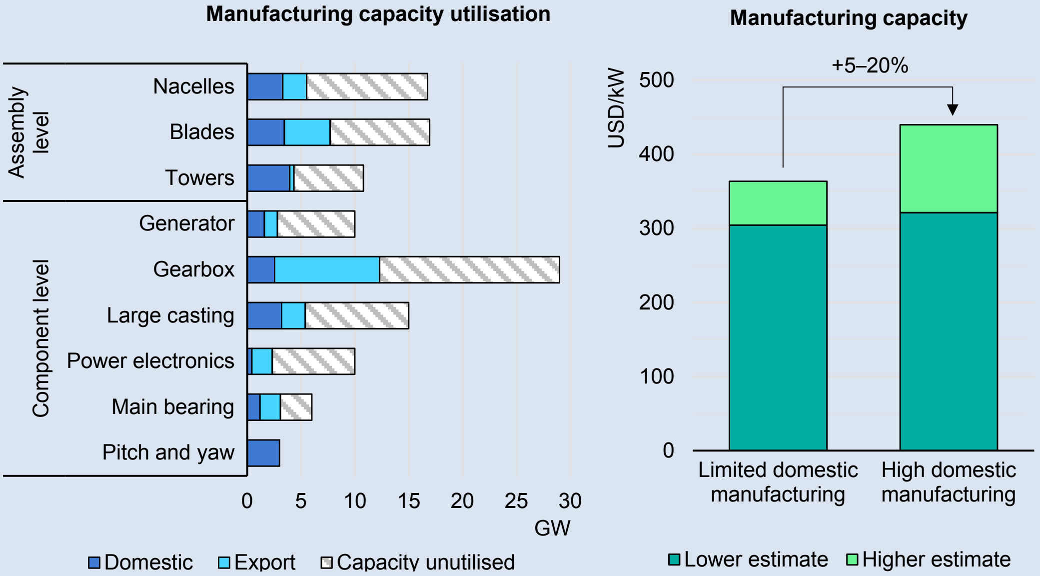
Emerging economies with established wind component industries are set to expand exports to advanced economies as well as meet growing domestic and regional demand.

Box 5.4 Local content requirements in India's wind energy industry

India's wind deployment is set to accelerate, supported by a 10 GW per year tendering trajectory to help double onshore wind capacity by 2030. Under the Atmanirbhar Bharat (Self-Reliant India) agenda, the government is strengthening domestic manufacturing through measures such as Concessional Custom Duty Certificates (CCDCs) for import of critical components. It is also aiming to improve quality by requiring original equipment manufacturers (OEMs) to source towers, blades, gearbox, generators and special bearings from facilities inspected under a standard operating procedure.

A baseline assessment of India's wind manufacturing industry by MEC+, supported by the Asian Development Bank, analysed 12 turbine models covering 80% of installations in financial year (FY) 2024 (MEC+, 2025). India now has over 15 GW of nacelle manufacturing capacity serving domestic and export markets, alongside sizeable capacity for blades, towers, gearboxes and generators, ranging from 10-29 GW (Figure 5.17). However, manufacturing of more upstream components remains limited in scale and capability.

Figure 5.17 Manufacturing capacity and costs of wind turbine components in India, 2024



IEA. CC BY 4.0.

Notes: In the graph on the right, the lower end of turbine costs reflects larger 5 MW platforms, while the higher end reflects the costs of 3 MW turbines. "Limited domestic manufacturing" assumes manufacturing in India is limited to towers and blades, with the subcomponents of the nacelle imported. "High domestic" assumes high reliance on domestic manufacturing of those same components.

Source: IEA analysis based on MEC+ (2025)

The assessment found that India's wind sector witnessed a steady rise in local content between FY2022 and FY2024. Local content in the assembly of nacelles, towers and rotors grew from 40% to over 70%, while growth at the system-level, such as the production of gearboxes, control systems and generators, was more modest, rising from about 30% to 50%. At an end-to-end level, which includes sub-systems and raw materials, local content remained much lower, reflecting continued reliance on imported systems or sub-systems and the limited scale of upstream production.

Bottlenecks were assessed across supplier availability, manufacturing capacity and capability, quality and pricing. Pricing is the most significant barrier: domestic component costs remain 20-25% higher than imports, mainly due to raw material costs and higher cost of financing. Import duties and logistics reduce but do not eliminate the gap. Capability and scale for newer turbine models also lags, especially for upstream components, creating continued dependence on imports.

Strengthening India's wind manufacturing ecosystem will require clear enforceable policies that provide long-term procurement visibility and export facilitation. Regulatory measures, including domestic content requirements, targeted fiscal incentives and concessional finance, could support this transition. Enhanced quality assurance frameworks, securing raw material supply, R&D for next-generation turbines and skilled workforce development will be important to build a competitive and resilient industry.

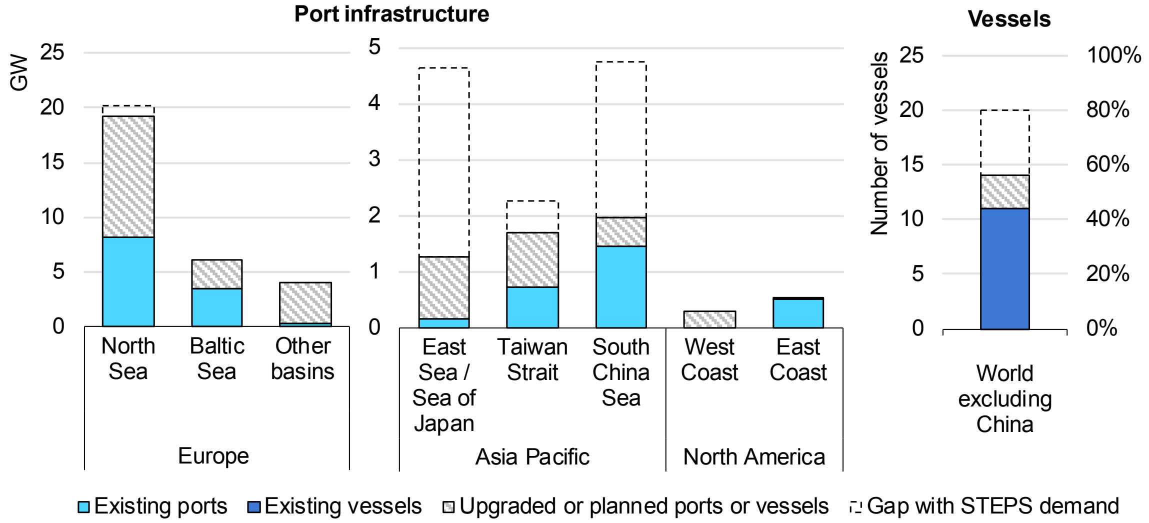
Supply chain bottlenecks

Complex installation processes and lengthy permitting procedures can create bottlenecks in the wind power supply chain for both onshore and offshore projects, though the underlying causes differ (Box 5.3). In the case of offshore wind, the scale and technical complexity of projects have prompted governments to play a more active role in auction design. Measures include centralised tenders, government-led zoning and pre-surveyed sites, all aimed at reducing risk and uncertainty for developers. For example, the Netherlands holds annual tenders with clear multi-GW targets and pre-developed sites. Japan is moving towards a similar co-ordinated approach by publishing pre-auction site surveys and establishing centralised zoning. In the European Union, the updated Renewable Energy Directive, known as RED III, adopted in 2023, introduced binding deadlines for permitting and required member states to digitalise their permitting procedures. In addition, in 2024, the European Union adopted a series of recommendations and guidance to streamline permitting procedures (European Commission, 2025a).

Port capacity and the availability of installation vessels could also become bottlenecks for turbine deliveries and installations, particularly in the offshore sector. Outside China, sufficient port space hinges on new or announced expansions of ports. But even when all plans materialise, half of all basins analysed would face shortages to meet capacity additions projected for 2030 under the STEPS. In absolute terms, the largest shortfall is in the East Sea/ Sea of Japan basin (Figure 5.18). In the Asia Pacific region, port capacity constraints are likely to be more persistent as offshore projects accelerate in Japan, Korea, the Philippines and Viet Nam. Other areas, such as the Mediterranean and offshore United States and Mexico, are expected to experience less severe capacity pressures, reflecting lower projected additions from Southern European countries and the United States.

The availability of wind turbine installation vessels (WTIVs) is another potential bottleneck for offshore wind. Globally, excluding China, the current fleet of WTIVs is insufficient to meet the deployment needs projected for 2030 in the STEPS. Even accounting for vessels that are due to be commissioned by 2026 and others that are planned, the fleet would still reach only 14 vessels – 6 short of the estimated 20 vessels required worldwide in 2030. Beyond global availability of vessels, local factors also play a role: cabotage rules in countries such as Brazil and Japan limit the use of foreign vessels, which can delay the completion of offshore projects and significantly increase costs. These constraints highlight that, alongside scaling manufacturing, timely investment in specialised installation vessels and clearer regulatory frameworks will be critical to meeting offshore wind targets.

Figure 5.18 Port and vessel capacity for handling offshore wind installations outside mainland China in the Stated Policies Scenario, 2030



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario. Assumes an average turbine size of 15 MW and that each turbine requires 1.3 hectares in a port. Peak demand is scaled by a factor of 1.5, reflecting the assumption that each offshore wind project occupies the port for 2 years during installation; thus, in a 3-year window, a given berth can service 1.5 projects. Each port is assumed to operate at 60% utilisation. Demand allocated to different basins based on current port capacity. Only wind turbine installation vessels with a main-crane capacity over 1 500 tonnes and a minimum lifting height of 150 metres are considered here.

Sources: IEA analysis based on S&P Global (2025); UN Trade & Development (2025); Rystad Energy (2023); and WindEurope (2023).

The projected expansion in wind turbine trade hinges on large additional investments in expanding port capacity and vessels beyond current plans, especially in Asia Pacific.

Electric cars and batteries

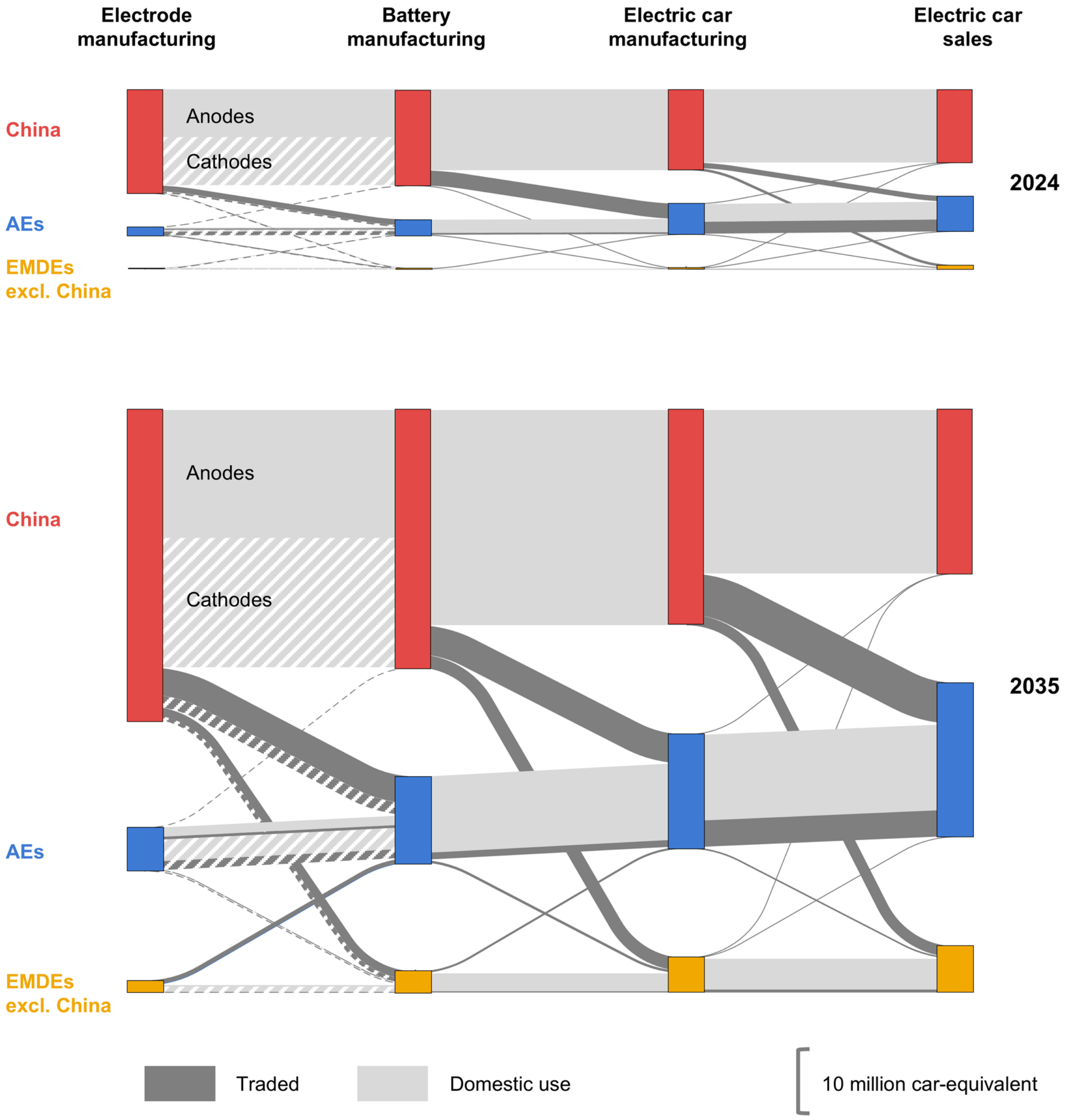
Global trends

Electric car and battery markets remain highly concentrated, shaped by the industry's history and economics. Commercial lithium-ion battery production began in Japan in 1991, proving a platform for electric car production, and has since been dominated by Asian firms, headquartered mostly in China, Japan and Korea. A major turning point came in the early 2010s, when strong Chinese government support boosted EV demand and offered the opportunity for today's leading EV manufacturers, such as BYD and Tesla, to scale up production. Growing demand, combined with the requirement to use Chinese-made batteries to access EV subsidies between 2015 and 2019, enabled companies like CATL and BYD, which now account for over half the global EV battery market, to build manufacturing expertise, workforce capacity and scale, underpinning lower costs and faster innovation cycles.

The concentration of demand and production in China has created a tightly clustered supply chain – from critical mineral refining and component production to battery and EV manufacturing. In 2024, China accounted for over 90% of anode active material (AAM), almost 85% of cathode active material (CAM), 80% of battery cell and 70% of electric car production. Outside China, virtually only Korea and Japan have sizeable CAM and AAM output, while most other battery cell manufacturing occurs in Europe and the United States – nearly all by companies headquartered in Asia (IEA, 2025a). Electric car manufacturing is somewhat less concentrated due to the strong automotive industry presence in Europe, North America and Japan.

In the STEPS, the electric car and battery supply chain diversifies as demand grows, investment rises and specialised workforces expand outside China. Yet diversification remains limited, with China still the largest source of demand and production in 2035 (Figure 5.19). By then, it supplies nearly 90% of AAM, about three-quarters of CAM and two-thirds of batteries. The advanced economies drive most diversification, accounting for almost 10% of AAM, 20% of CAM and about 25% of battery output, with the European Union and United States together providing close to 10% of CAM and 20% of battery production. EMDEs other than China produce nearly 5% of AAM and CAM but increase their battery and electric car output share to about 6% and 10% respectively – five and ten times their 2024 shares. Electric car production in advanced economies also rises, reducing China's share to just below 55%.

Figure 5.19 Global manufacturing and inter-regional net trade flows of electric cars, lithium-ion batteries and key components in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: AE = advanced economies; EMDEs = emerging markets and developing economies. “Car-equivalent” is a combined unit of measure for electric cars, batteries and battery components, with the latter two expressed as the number of cars that could be produced with a given quantity thereof.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

China is set to continue to dominate the electric car and battery supply chain, though its market share declines to 2035 with rapid growth taking place in other EMDEs.

While EV production expands in the advanced economies, the share of demand met by domestic manufacturing does not increase. Despite increased trade restrictions, such as EU countervailing duties on Chinese-made battery electric cars, tariff reinstatements in Brazil and Mexico and new levies in Türkiye, Chinese exports continue to dominate global trade. With unmatched capacity and low costs across the EV supply chain, China's exports are set to grow, with over one in four electric cars sold in advanced economies made in China by 2035 (6 million vehicles) – up from 800 000 in 2024 (15% of sales).

EMDEs other than China gain ground as domestic manufacturers grow and Chinese firms open new assembly plants in South America (e.g. BYD's facility in Brazil) and Southeast Asia (projected to host over a quarter of China's overseas EV capacity by 2030). Asian, western and domestic carmakers are also retooling assembly lines and setting up new production facilities in India, increasing the country's capacity more than tenfold to 1.8 million electric cars by 2030. In the STEPS, electric car production in EMDEs other than China reaches over 5 million by 2035 – about 10% of global output and up from just 1% in 2024.

In the NZE Scenario, electric car production volumes are significantly higher than in the STEPS across all regions, driven by much stronger demand. This growth supports greater diversification in manufacturing, particularly among EMDEs. Advanced economies increase their production by about 60% compared with STEPS by 2035; however, their share of the global market declines as EMDE production ramps up to supply close to 30% of the global electric car market, tripling relative to STEPS over the same period. This shift reflects expanding industrial capacity and rising domestic demand in EMDEs, reshaping the global EV landscape.

Impact of weaker US demand-side policy support

Several recent policy shifts are dampening the outlook for electric car demand and production in the United States. They include the repeal of the Clean Vehicle Tax Credit (US Congress, 2024), ongoing efforts to revise the National Highway Traffic Safety Administration fuel economy standards (US Department of Transportation, 2025) and to eliminate GHG regulations for road vehicles (US Environmental Protection Agency, 2025), and the revocation of California's waiver to adopt stricter emission standards than federal law (US Congress, 2025a). In 2024, US electric car sales totalled 1.6 million and are expected to have remained somewhat unchanged in 2025, despite weaker policy incentives, as consumers take advantage of the tax credits before they end. Although demand is still projected to double by 2030 in the STEPS, this would represent just 20% of total new car sales – down from the over 50% that would previously have been needed to comply with fuel economy standards.

These demand-side revisions have three main implications for the supply side:

- **Sufficient domestic capacity:** Despite several US carmakers pivoting focus back to internal combustion engine (ICE) cars and delaying their pure EV strategies following recent policy shifts (ICCT, 2025), US pure electric car manufacturing capacity is still expected to exceed 3.5 million units by 2030, complemented by nearly 8 million units of flexible ICE/EV car manufacturing capacity (BNEF, 2025b). This project pipeline enables US plants to meet domestic demand through 2035 in the STEPS without the need for additional investment.
- **Reduced import needs:** A greater share of demand served by domestic production sharply cuts import dependency. Remaining imports are costly due to a 25% tariff on all electric cars. While US tariff and duty hikes increase import costs from all countries, they do so to a lesser extent for imports from Canada or Mexico that meet United States-Mexico-Canada Agreement (USMCA) trade agreement content rules, giving North American producers a competitive edge over other importing regions (The White House, 2025). By 2035, imports reach 1.5 million units – almost entirely from Mexico – covering roughly one-third of domestic demand, compared with 4.5 million (40% of demand) in *ETP-2024*.
- **Weaker battery demand:** Lower EV sales also reduce domestic battery needs, weighing heavily on the US battery industry. Committed battery capacity by 2030 could produce nearly double projected US demand in 2035 in the STEPS.

The recent increases in tariffs and duties are expected to have a significant impact on US battery supply chains in the short term, accelerating the shift toward domestic production, but have limited effects over the medium term. By 2030 and 2035, projections remain broadly consistent with those outlined in the *ETP-2024*. Battery production – supported by IRA tax credits and the resulting wave of investment – is expected to be able to satisfy most domestic demand, while the supply of cathode and anode active materials remains constrained by available manufacturing capacity. The main change is a markedly lower projection for battery demand.

Momentum in battery and battery component manufacturing investment in the United States has nonetheless slowed, with some projects cancelled or paused (Clean Investment Monitor, 2025). In the STEPS, US battery cell production reaches less than 350 GWh in 2030 and just over 400 GWh in 2035, primarily serving domestic needs with the remainder exported to Mexico – equivalent to less than 40% and 50% of the nameplate capacity of currently committed projects, respectively.

This shift reflects weak domestic demand rather than insufficient production incentives. Recent legislative updates preserve IRA tax credits for battery production while tightening long-term rules on prohibited foreign entities (PFEs) (US Congress, 2025b), but also introduce greater short-term flexibility (Zhang, 2025). As a result, investment continues to focus on the development of non-PFE supply chains for the US market. However, scaling these supply chains will require additional overseas production capacity, as domestic CAM and AAM committed capacity remains insufficient. Domestic production meets about half of CAM demand and about one-quarter of AAM demand by 2035 in the STEPS, leaving the United States reliant on imports. The shortfall is projected to be largely met by imports from Korea for CAM, while AAM supply is projected to depend on imports from China, Southeast Asia and Korea.

Box 5.5 The impact of weaker EV demand for the battery industry in the United States

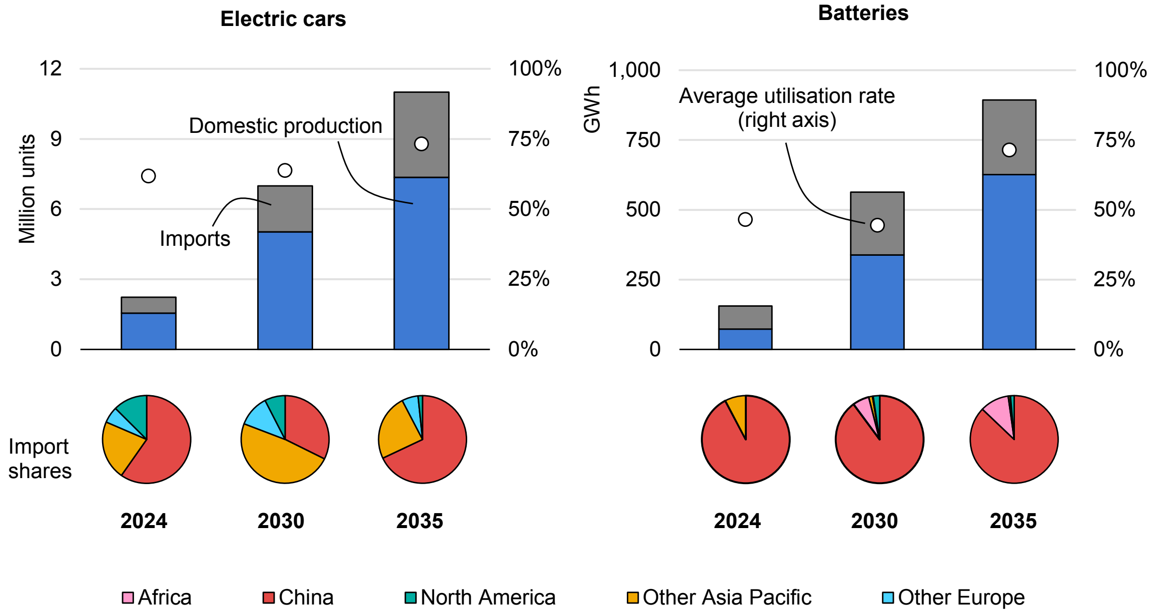
As in the European Union, battery production costs in the United States remain well above those in China. However, the US investment environment is more favourable, largely due to the 45X manufacturing tax credit, which provides up to USD 35/kWh for battery cell production – roughly half the cost of producing lithium nickel manganese cobalt oxide (NMC) batteries in China and enough to bridge the underlying cost gap between the two countries in 2024. In 2025, rising costs of imported materials and components are expected to have left US production almost 10% more expensive than Chinese production, even after IRA support. While counter to global trends, this differential remains relatively modest, helping to sustain the economic case for US-based battery manufacturing.

Incentives alone, however, cannot guarantee competitiveness. Achieving lower unit costs depends on economies of scale, which require strong and sustained demand. Recent policy developments have softened the outlook for EV sales in the United States, dampening battery demand projections. This creates problems for battery manufacturers that have committed substantial investments in US facilities. In addition, these firms may face increasingly stringent conditions to access tax credits. As a result, more than half of committed manufacturing capacity in the United States is projected to be unutilised in 2030 in the STEPS.

EU trade policies

The European Union’s automotive industry – one of its most important industrial sectors – stands at a crossroads, as high EV and battery production costs continue to weigh on the world’s second-largest car producer. Recent policy measures, including the EU Automotive Action Plan (European Commission, 2025c) and the NZIA (European Commission, 2025d), aim to strengthen competitiveness while re-affirming the overall impetus towards the 100% CO_2 emission reduction target for new car sales by 2035. In the STEPS, the European Union remains the world's second-largest electric car market after China, with around 11 million units sold in 2035 – accounting for one in five sales worldwide.

Figure 5.20 EU electric car and battery supply by origin in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: Utilisation rate refers to production for both domestic use and exports divided by installed manufacturing capacity.
Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

EU output of electric cars grows almost fourfold and EU battery output eightfold by 2035, assuming duties on Chinese car imports are extended beyond their current end-date of 2029.

Price-competitiveness remains a key barrier to mass-market adoption of electric cars in the European Union (IEA, 2025a). Waning purchase subsidies in major markets such as Germany (Reuters, 2023) and France (Légifrance, 2024) contributed to the first-ever drop in EU sales in 2024, with the share of electric cars in total car sales decreasing from nearly 22% in 2023 to 20% in 2024. Output also stalled at 2.4 million units, exceeding EU demand by more than 5%. High labour costs, elevated battery prices (making up around 25% of the price of an average battery electric car) and lesser economies of scale and supply chain integration than China continue to hinder affordable EV offerings (IEA, 2025c). In 2024, nearly a quarter of available ICE models were priced below EUR 30 000, compared with only around 5% of electric models.

The EU electric car market has since shown signs of recovery. Despite the recent increase in flexibility for carmakers to comply with their 2025 CO_2 emissions targets, electric car sales reached a record high in the first half of 2025 with around 25% of new cars sold being electric (ACEA, 2025). Current emission standards give a clear and robust signal for EV demand and production scale-up, but the availability of affordable models remains essential to ensure emission targets are met. More, lower-cost models are expected soon (IEA, 2025a), but achieving scale and cutting production costs will be critical. This may require deeper collaboration in battery manufacturing – such as through joint ventures – with established Asian battery manufacturers, some of which are already present in Europe, including LG Energy Solution, CATL, SK On and Samsung.

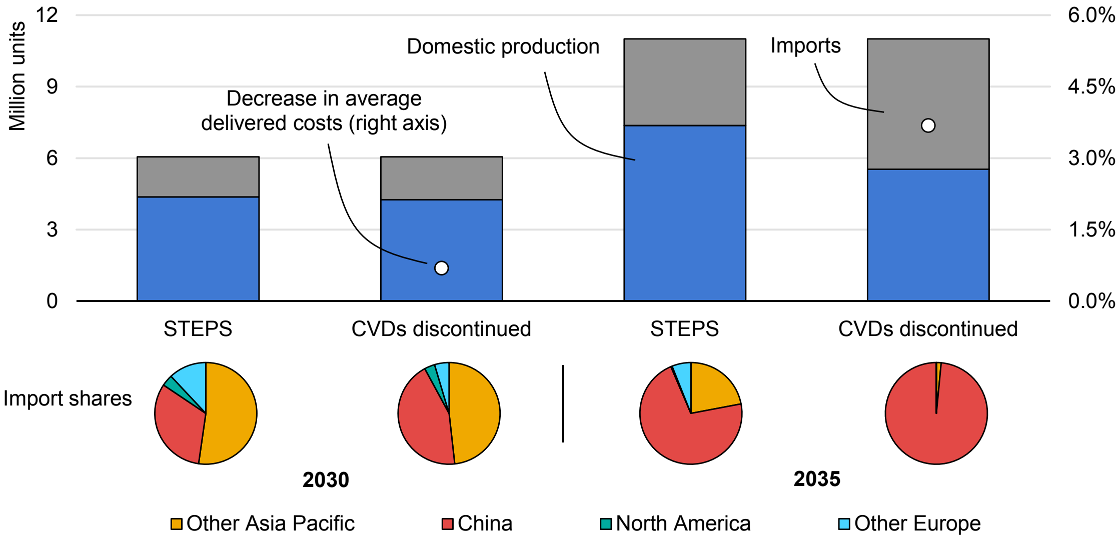
Current trade policies partly shield the EU automotive industry from lower-cost Chinese car imports, though the risk of retaliation remains significant given the European Union's strong position as an exporter. The OEM-specific CVDs implemented in July 2024, following an anti-subsidy investigation initiated in October 2023, have helped to keep the share of Chinese imports in total EU electric car sales below 20%. EU manufacturing capacity is unlikely to constrain supply, as many existing ICE assembly lines can be quickly retooled: of 13 EV manufacturing projects announced in 2025, only five are greenfield investments, with the remainder involving conversions (T&E, 2025).

Based on current project pipelines, EU EV manufacturing capacity could reach 9 million units by 2030, exceeding domestic demand standing at just under 7 million in the STEPS. Under this scenario, the share of domestic demand met by imports remains below one-quarter through 2035 – with a growing number of cost-competitive imports from Korea, the rest of Europe and Japan, reducing China's share of EU imports to around 30% in 2030. From 2030 onward, limited manufacturing capacity among other exporters makes China's unused capacity increasingly relevant to meeting the European Union's growing demand. While imports from other regions remain unchanged in absolute terms, China's share rises again, capturing more than two-thirds of EU imports by 2035, close to the 60% share observed in 2024.

Current EU trade policy maintains CVDs on imports of Chinese battery electric cars through the end of 2029. Discussions in Beijing at the end of 2024 between the European Union and Chinese officials explored a potential agreement to set floor prices for Chinese EV exports to the region (European Commission, 2024a). This "price undertaking" was presented as an alternative to CVDs and, notably, was not proposed with a specific expiry date. At the 25th EU-China Summit in 2025, the European Union re-iterated its commitment to take proportionate, legally compliant action to counter trade-distorting practices by China, stressing that its protective trade policy instruments would remain in place (European Council, 2025).

The STEPS assumes these CVDs continue beyond 2029, thereby constraining the market share of lower-priced Chinese models. Nonetheless, given the uncertainty over future EU trade measures, we have devised a sensitivity case, which explores the impact of lifting CVDs as scheduled in 2029. In this case, the strong price-competitiveness of Chinese-made battery electric cars spurs much higher exports to the European Union, lowering the average retail prices of battery electric cars in the region (if tariff and duty savings are fully passed through) but at the expense of EU-based production (Figure 5.21). Chinese imports could exceed 10% of EU battery electric car demand by 2030 and rise to close to 50% by 2035, cutting the domestic share by more than 15 percentage points down to 50%. This higher penetration of low-priced Chinese models would reduce the average delivered unit costs in the region by around 1% in 2030 and 4% in 2035.

Figure 5.21 China's share of the EU battery electric car market in the Stated Policies Scenario and in a sensitivity case with import duties ending in 2029, 2030-2035



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Notes: STEPS = Stated Policies Scenario; CVDs = countervailing duties. Plug-in hybrid electric vehicles are excluded from this analysis. In the STEPS, CVDs already in place at the end of 2024 – or equivalent measures – are assumed to remain in perpetuity, whereas in the 'CVDs discontinued' sensitivity case they are discontinued at the end of that year. No explicit interactions between car prices and demand levels are considered in this analysis.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

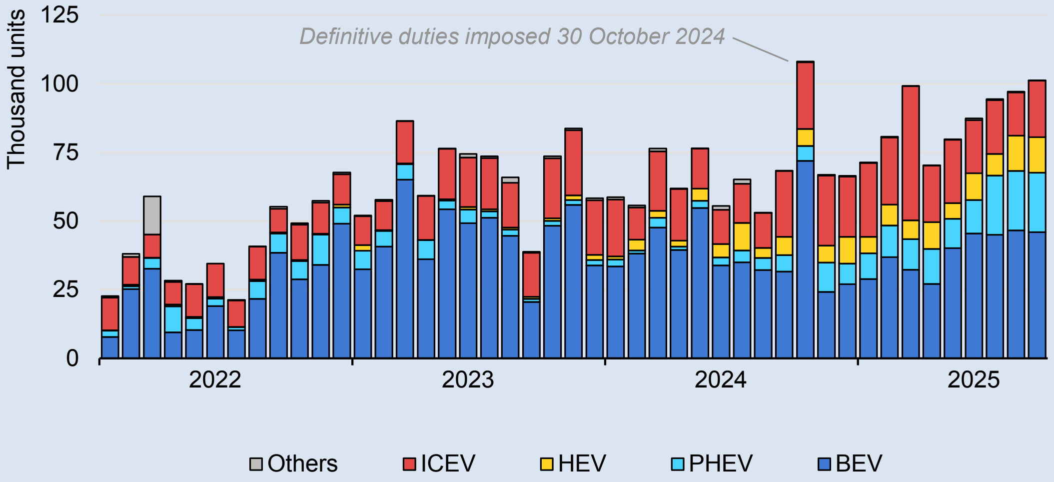
Lifting duties on Chinese EV imports would cut the share of domestic carmakers in meeting EU demand from 70% to 50% by 2035, while average delivered costs fall 4%.

Box 5.6 Current EU trade policy design opens the door to Chinese hybrid car imports

In 2023, the European Union launched an investigation into Chinese government subsidies to battery electric car manufacturers. In response to the findings, provisional CVDs were imposed in July 2024, and the final measures took effect on 30 October 2024 (European Commission, 2024b). In October 2024 – the last month before the CVDs took effect – EU imports of Chinese battery electric cars leapt up, more than doubling month-on-month, as Chinese OEMs accelerated shipments to avoid the additional costs.

The CVDs explicitly exclude plug-in hybrid electric cars (while including extended-range electric cars) from their scope. As a result, immediately after the duties came into force, imports of both plug-in and non-plug-in hybrids from China rose sharply, accounting for more than one in four EU car imports from China in the first three quarters of 2025, compared with about 10% in the same period the previous year. While imports of Chinese hybrids are likely to grow further if current EU trade policy remains unchanged, this trend is expected to be short-lived. Indeed, if the upcoming formal review of EU CO_2 standards for cars confirms the 100% fleet-wide tailpipe emission reduction target by 2035, no hybrids would qualify as compliant powertrain technologies and would, therefore, lose significant market share.

Figure 5.22 Monthly gross EU car imports from China by powertrain, 2022-2025



IEA. CC BY 4.0.

Notes: ICEV = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; BEV = battery electric vehicle. 2025 data is up to September. Please see IEA (2026) for details of the harmonized system (HS) code and powertrain mapping used in this analysis.

Source: IEA analysis based on Sinoimex (2025).

Chinese EV exports to emerging economies

Chinese electric car exports diversified significantly in 2024, spurred by rising trade restrictions in traditional markets and growing demand in other EMDEs. Europe, still the largest overseas destination, accounted for nearly 40% of export value, but that was down from 70% three years earlier. Southeast Asia, Mexico, Brazil, Russian Federation and Caspian Sea countries now take a growing share. In 2024, Chinese-made EV sales outside of Europe nearly doubled to over 550 000 units, making up close to half of overseas sales.

Low-cost Chinese imports have pushed down electric car prices in EMDEs (IEA, 2025a). In Brazil, their share in electric car imports climbed from 60% in 2023 to 85% in 2024, narrowing the electric-ICE car price gap from over 100% to 25%. In Indonesia, import duty waivers tied to local EV investment boosted the share of Chinese EV sales from 10% to 66%, cutting the price premium from over 100% to 50%. The first three quarters of 2025 saw Chinese electric car imports in Indonesia and Southeast Asia more broadly continue to grow – already exceeding full-year sales of Chinese imports in 2024.

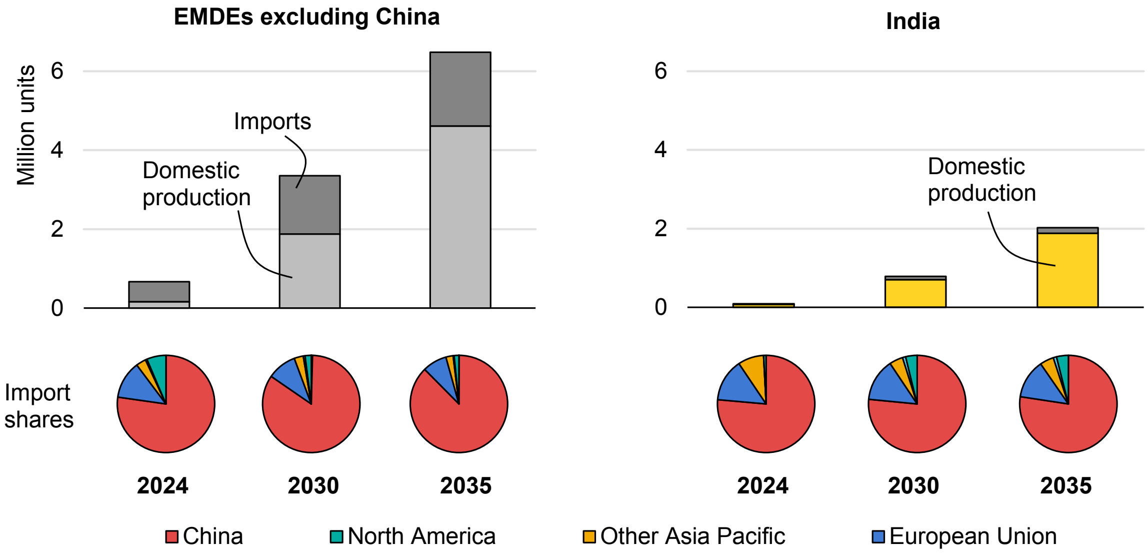
To sustain growth, Chinese OEMs are expanding shipping capacity. In 2025, BYD commissioned the world’s largest roll-on/roll-off vessel, bringing its capacity to nearly 50 000 electric cars across six ships (Ren, 2025). SAIC’s fleet reached 37 vessels with capacity for roughly 300 000 cars (Kang, 2025). Shipping firms such as COSCO Shipping Car Carriers (Finn, 2025) and China Merchants (The Maritime Executive, 2025) are also playing an important role in serving fast-growing overseas markets.

Chinese exports to other EMDEs are set to rise, underpinned by competitive pricing and expanding shipping capacity. Yet local production will intensify competition. Chinese OEMs, domestic brands such as Viet Nam’s VinFast and India’s Tata and Mahindra, as well as established western automakers are building or repurposing plants in EMDEs to serve local and export markets, benefiting from lower labour and energy costs. Policy support, such as duty waivers for EV makers investing in India, Indonesia, Thailand and Viet Nam, is fuelling this trend. Chinese OEM capacity in Southeast Asia could almost triple between 2024 and 2026 to 1.2 million cars based on current projects (IEA, 2025a). Japanese and Korean incumbents in India and Southeast Asia, and European brands in South America, are also retooling lines. In India, capacity could hit 1.8 million units by 2030, more than double the projected domestic demand in the STEPS.

Trade restrictions are, nonetheless, set to rise as investment-linked waivers expire: Indonesia (Medina, 2024), Thailand (Baker McKenzie, 2024) and Malaysia (Yusry, 2024) end theirs in 2025; India’s Scheme to Promote Manufacturing of Electric Passenger Cars in India limits exemptions to 5 years

(India, Ministry of Heavy Industries, 2024); and Brazil has already reinstated tariffs on hybrids and electric cars (Brazil, Ministry of Development, 2023). In 2024, nearly two-thirds of electric car sales in EMDEs other than China were Chinese imports, a share that is expected to have remained roughly unchanged through 2025. By 2030, in the STEPS, although Chinese exports to other EMDEs triple from 2024 levels to exceed 1.2 million units, their share in domestic sales in these markets falls below 40% as local output grows. By 2035, exports could reach around 1.6 million units – one-fifth of China's total – but make up only 25% of other EMDE sales.

Figure 5.23 Electric car supply by origin in emerging markets other than China and India in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: EMDEs = emerging markets and developing economies. Electric cars refer specifically to passenger cars and pick-up trucks, and include battery electric and plug-in hybrids. Domestic refers to vehicles produced and sold in the focus region. Electric car stockpiling is excluded from the analysis.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Chinese electric car exports to other EMDEs triple from 2024 to over 1.2 million units by 2030, but China's share of that market falls below 40% as local output grows.

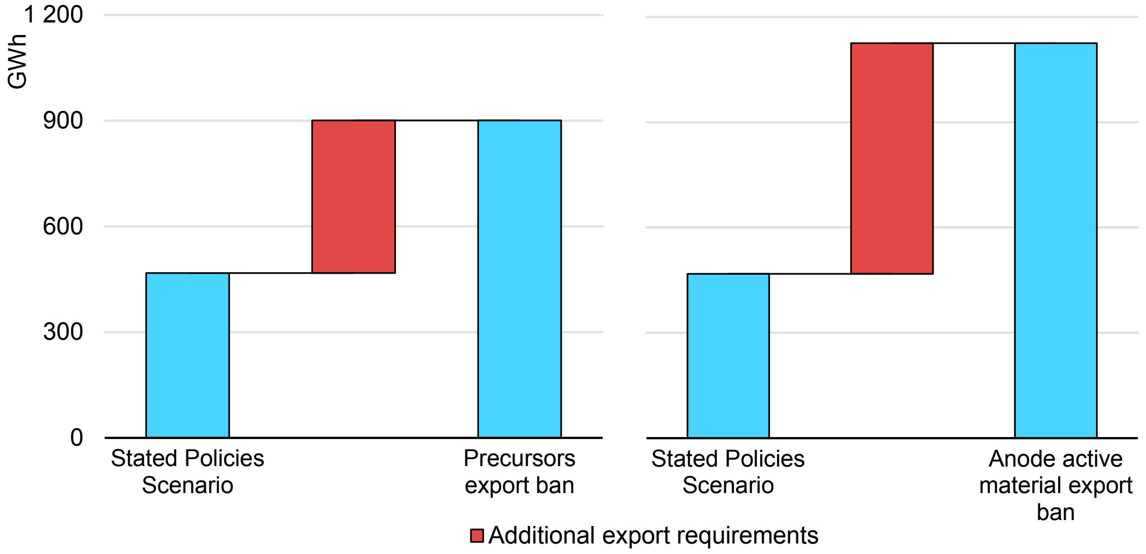
Battery supply chain dependence on China

Without stronger efforts to diversify battery supply chains, Chinese export controls – if fully enforced – could severely disrupt battery production outside China (see Chapters 1 and 4). Despite substantial recent investment in cell manufacturing in the United States and Europe, midstream segments remain a major vulnerability. Production of cathode precursors and cathode and anode active materials is still heavily concentrated in China.

Korea currently leads diversification efforts for battery components, but these have focused mainly on NMC cathode materials. Capacity for lithium iron phosphate (LFP) materials, NMC and LFP cathode precursors, and graphite anodes remains limited. Much of the technical expertise and manufacturing know-how for these critical steps is still held by Chinese companies.

Project pipelines indicate that this imbalance will persist through 2030, leaving China with considerable leverage. If exports of these components were fully restricted in 2030, up to two-thirds of battery cell production outside China could be curtailed. Meeting demand would require higher imports of completed batteries from China, potentially more than doubling Chinese exports in 2030 – an additional 400-650 GWh. This would be equivalent to roughly USD 30-50 billion in additional imports on a net basis.[4]

Figure 5.24 Chinese battery exports in the Stated Policies Scenario and additional export requirements if key component precursor exports were halted, 2030



IEA. CC BY 4.0.

Notes: Additional export requirements reflect the reliance on imports of battery to meet demand outside China, where battery demand is assumed to be inflexible. Export bans are assumed to take effect in 2030, at a point in time that is here assumed would hinder new manufacturing investments from becoming operational in order to ease supply constraints during that year. The analysis assumes a complete halt in Chinese exports of all cathode precursors or anode active materials. Precursors refer to intermediate compounds used in the production of cathode active materials, accounting for differences in cathode chemistry.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Were Chinese battery precursor exports to be fully restricted in 2030, two-thirds of cell production outside China could be curtailed, potentially doubling Chinese battery exports.

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[4] This includes both additional battery imports and reduced battery component imports. The analysis assumes an average battery price across all applications of USD 85/kWh, an average precursor materials price of USD 10/kWh and an average anode active materials price of USD 5/kWh.

Electrolysers

Global trends

Electrolysers, which use electricity to split water into hydrogen and oxygen, are a key technology for producing low-emissions hydrogen from renewable or nuclear power. Global installed electrolyser capacity is rising rapidly, driving most of the growth in low-emissions hydrogen supply in 2024 (with most of the remainder from natural-gas-based hydrogen facilities equipped with carbon capture and storage). In 2024, electrolytic hydrogen accounted for around 20% of total low-emissions hydrogen output, up from just 4% in 2020, and is set to reach 50% within 2 years based on committed capacity additions.

Medium-term demand prospects remain strong. In the STEPS, global electrolyser demand grows from about 3 GW[5] in 2024 to 9 GW in 2030 and 17 GW in 2035. This is driven by policy measures to support hydrogen demand and lower the cost of electrolytic hydrogen to end users, as the cost of production remains far higher than that of hydrogen produced conventionally (see Chapter 2). China remains the largest market, representing over 30% of demand in 2030, while other EMDEs emerge as notable buyers, accounting for 20% of sales. In 2024, two-thirds of deployment was concentrated in China and most of the rest in advanced economies (Figure 5.25). In the NZE Scenario, demand for electrolysers grows much faster, reaching 80 GW in 2030 and 150 GW in 2035.

At present, almost all electrolyser demand is met by domestic manufacturing, with little trade across major regions. This reflects the market's early stage, the localised nature of production and the high cost of shipping bulky equipment. For large-scale projects, building near the end-use site or shipping semi-assembled components is typically cheaper, especially when plants are tailored to local conditions. However, rising global demand is set to change this. In the STEPS, the share of exports in China's electrolyser output climbs from almost zero in 2024 to more than 40% by 2030, with EMDEs emerging as the primary destinations over this period. India is building manufacturing capacity under its National Green Hydrogen Mission, which is sufficient to meet all domestic needs in the STEPS by 2030.

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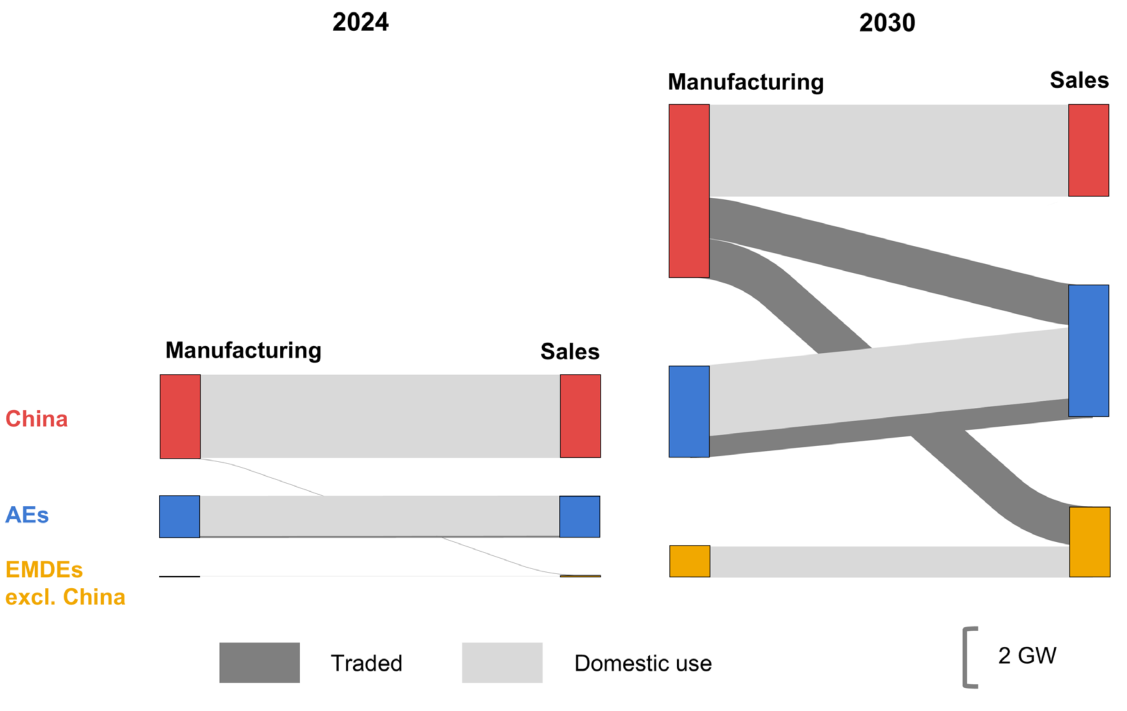
[5] This only includes manufacturing for water electrolysis. Taking into account manufacturing for chlor-alkali, global electrolyser demand reached around 4 GW in 2024 (IEA, 2025b).

Figure 5.25 Global manufacturing and inter-regional net trade flows of electrolysers in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: AEs = advanced economies; EMDEs = emerging markets and developing economies.
Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Inter-regional trade in electrolysers is set to take off in the next 5 years as demand surges worldwide, with China emerging as a major exporter to advanced and emerging economies.

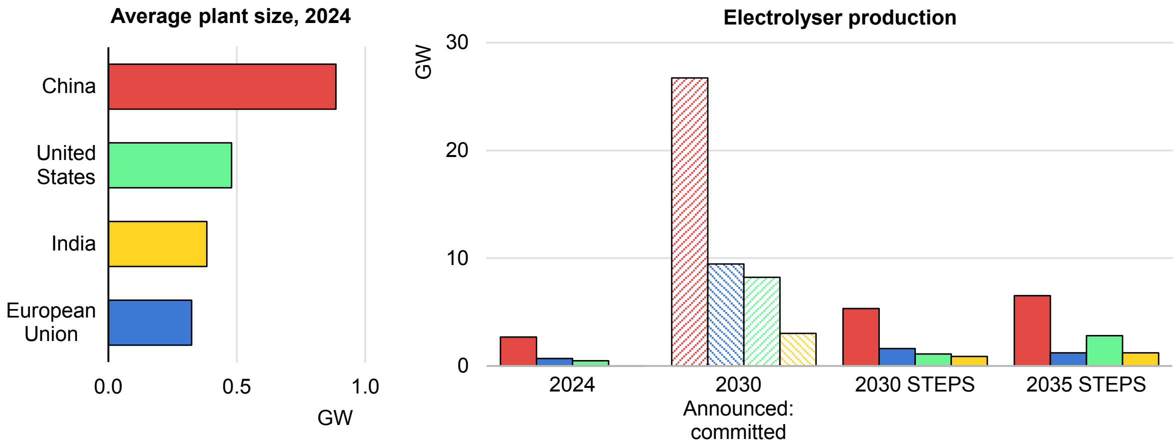
Alkaline electrolysers – a more mature technology with a long history of deployment in the chlor-alkali industry – are expected to remain the leading technology in the medium term, accounting for almost 60% of manufacturing capacity by 2030 based on project announcements. The technology is particularly dominant in China, accounting for more than 90% of existing manufacturing capacity. As with other mass-manufactured clean energy technologies, Chinese plants are generally very large, their size averaging three times those in Europe. This allows Chinese companies to take advantage of economies of scale to lower the costs.

Manufacturing capacity overhang

Electrolyser manufacturing capacity reached 38 GW by the end of 2024, based on nominal facility sizes from company announcements – an increase of more than 11 GW from 2023. However, utilisation rates remain at around 10%, as demand has grown more slowly than was anticipated when much of this capacity was planned. Several installation projects have been delayed or cancelled as developers struggle with high costs, uncertain demand and regulatory environments, and slow infrastructure development (IEA, 2025b). As a result, many manufacturers have faced mounting losses; in some cases this has led to bankruptcy, as with French producer McPhy, which entered judicial liquidation in July 2025, with part of its assets being acquired by John Cockerill (McPhy, 2025). Others have paused factory operations and announced job cuts.

The imbalance between capacity and demand is set to worsen through the late 2020s, with announced manufacturing additions continuing to outpace growth in installations – despite a sharp slowdown in new manufacturing project announcements and project cancellations over the past year, particularly in advanced economies. If all planned projects proceed, global electrolyser manufacturing capacity would approach 190 GW by 2030 – far above the projected demand of around 9 GW in the STEPS but broadly aligned with the requirements of the NZE Scenario. However, less than 15% of these planned additions have reached FID to date.

Figure 5.26 Average electrolyser plant size by region, and projected output from existing and committed manufacturing capacity in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: STEPS = Stated Policies Scenario. The projections assume an 85% utilisation rate for the announced committed capacity in 2030, which is the sum of the announced committed capacity and the existing capacity at the end of 2024.

Sources: IEA analysis based on a range of data sources; see IEA (2026) for details.

Announced electrolyser manufacturing capacity additions continue to outstrip projected demand growth in the STEPS, aggravating the already existing large capacity overhang.

Heat pumps

Global trends

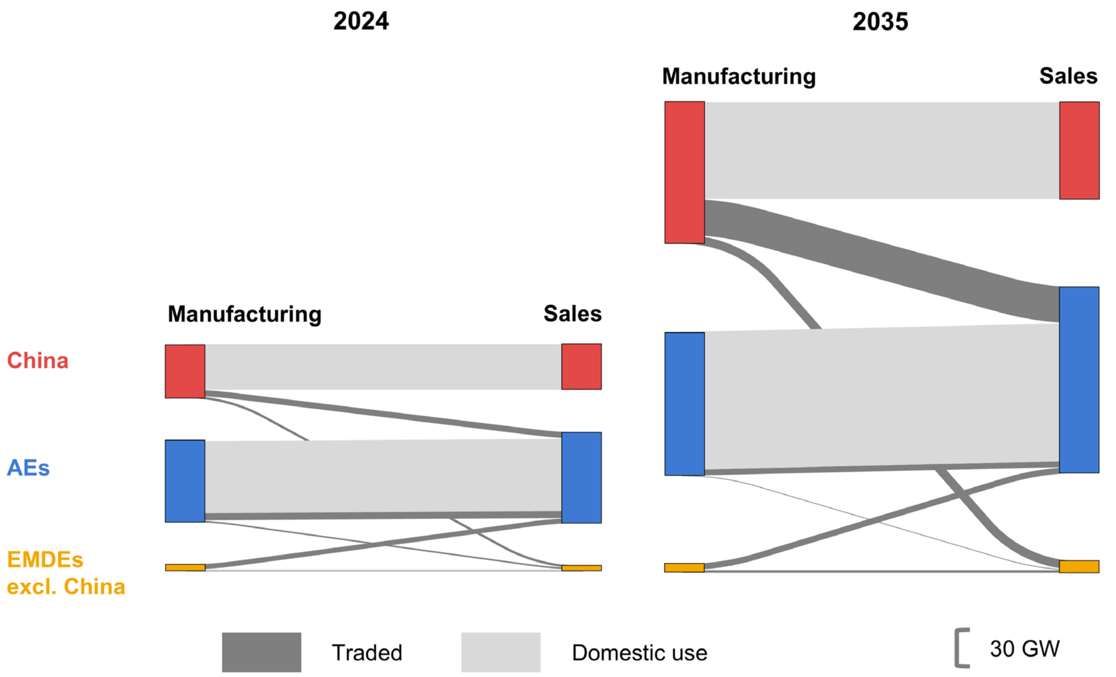
The manufacturing of heat pumps for building applications remains geographically diverse, though upstream segments such as component production are more concentrated. In 2024, only around 15% of heat pumps installed worldwide by capacity were traded across borders, with most demand met by domestic production. All major markets – China, the United States, Europe and Japan – sourced over 70% of their heat pump supply locally. Global manufacturing capacity is around 145 GW led by China (35%), followed by the United States (25%) and the European Union (20%).

Global demand remained sluggish in 2023 and 2024, prompting little change in manufacturing capacity. The surge of factory expansion plans announced in 2022 – mainly in Europe, where sales had doubled in 2 years – has stalled after two consecutive annual declines: falling 10% in 2023 and more than 20% in 2024, in capacity terms. This downturn has weighed on international trade. The largest recent trade flow – Chinese exports to Europe – peaked in 2022 alongside record regional sales but has since fallen 40%, in line with installation declines.

Product types vary by region: central ducted air distribution systems dominate in the United States, hydronic units are common in parts of Europe, while in Japan and central-southern China, multiple reversible air conditioners are often used for space heating. Local manufacturers benefit from tailoring products to national standards and consumer preferences, with after-sales service and brand familiarity reinforcing domestic sourcing. Industrial policies, such as the EU NZIA, which supports manufacturing ecosystems including through streamlined permitting, further support local production. Ongoing discussions in France on linking heat pump subsidies to products “made in Europe”, and in Poland on regulatory changes that could disadvantage imported certified models, also reflect this broader push toward local manufacturing.

Heat pump manufacturing is projected to grow sharply over the next decade on the back of a sales rebound. Key policy drivers include heat pump subsidies, building energy codes, carbon pricing, national heat plans and heat pump targets, as well as policies aimed at training and skills development. In the STEPS, capacity rises 80% in China, more than doubles in the United States and rises by about 40% in the European Union by 2035. By then, these three markets account for 85% of global manufacturing capacity and 80% of demand, cementing their central role in shaping the industry’s future. Trade follows a similar path, with inter-regional heat pump flows more than doubling by 2035, though the share of traded equipment in global sales remains at 20%, as today, reflecting the dominance of domestic production (Figure 5.27). Modest demand growth in other EMDEs (excluding China) – mostly in smaller Asian economies, as well as in Eastern Europe and Latin America – is met largely by Chinese exports, reinforcing China's position as the leading supplier.

Figure 5.27 Global manufacturing and inter-regional net trade flows of heat pumps in the Stated Policies Scenario, 2024-2035



IEA. CC BY 4.0.

Notes: AEs = advanced economies; EMDEs = emerging markets and developing economies.
Source: IEA analysis based on a range of data sources; see IEA (2026) for details.

Global heat pump trade is set to more than double by 2035, though the major markets continue to source most of their heat pumps domestically.

The heat pump market grows even faster in the NZE Scenario, with global sales more than quadrupling to 2035 on the back of far stronger policy measures than those currently in place. Global manufacturing capacity grows at a similar pace to domestic demand, but at a slightly faster pace in China than in advanced economies. Some other EMDEs, especially those with strong air conditioner industries, expand production of reversible heat pumps, though their share in global output remains modest at around 5%. International trade grows in parallel with rising demand, increasing fivefold between 2024 and 2035. However, most installations rely on domestic supply: by 2035 only one in four heat pumps is traded inter-regionally, while three-quarters are produced and installed locally.

The Kigali Amendment to the Montreal Protocol – an international agreement to phase down the consumption and production of hydrofluorocarbons (HFCs) – is prompting heat pump manufacturers, which use these gases, to adapt their product offerings, with potentially significant effects on global trade flows. HFCs, which replaced ozone-depleting refrigerants, are potent GHGs. The pace of their phase-down under the agreement varies by country, with the most developed economies required to act fastest. In response, manufacturers are redesigning products and adjusting supply chains. This shift creates strategic opportunities for first movers – particularly those investing early in potential technologies with low global warming potential – to secure a competitive edge in future export markets.

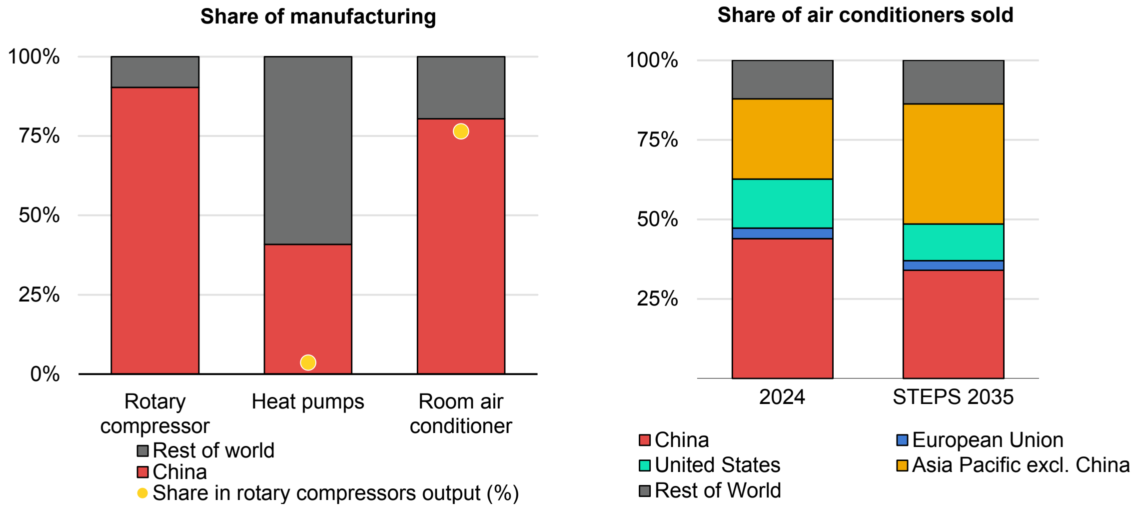
Role of air conditioning component manufacturers

Many components used in heat pumps are similar to those used in the air conditioning industry; a reversible air conditioner is essentially a heat pump. Consequently, countries and companies with strengths in cooling equipment manufacturing – such as for compressors, heat exchangers and inverters – are often well-positioned to lead on component supply for heat pump manufacturers.

Although the market for heat pumps used as primary heat equipment is expanding quickly, it remains far smaller than the global cooling market, which is an order of magnitude larger. For example, around 2.5 million heat pumps were sold in Europe in 2024 – the same number of air conditioners (ACs) produced in China in only around four days. This disparity reflects the maturity and scale of air conditioning demand, and points to significant potential for technology transfer, supply chain synergies and economies of scale as heat pump adoption accelerates.

Unlike heat pump assembly, which is relatively geographically diverse, some upstream components common to both technologies, such as compressors, remain heavily concentrated in China. In 2024, manufacturers based in China represented 90% of global air conditioner manufacturing capacity. This concentration extends upstream: China is the largest global producer and exporter of rotary compressors, used in most small-capacity residential cooling and heat pump systems, with 90% of global rotary compressor manufacturing capacity in 2024. Scroll compressor production – more common in larger residential and light commercial systems – is somewhat more geographically distributed, but China remains a key player in this segment as well.

Figure 5.28 Global manufacturing of heat pumps and components (compressor units), 2024, and sales of air conditioners in the Stated Policies Scenario, 2024-2035



Notes: STEPS = Stated Policies Scenario. Manufacturing capacity in this figure refers to number of units. For heat pumps, rotary compressors are mostly used in small size units, especially air-to-air units.

Sources: IEA analysis based on ChinaOL (2025) and Sinoimex (2025).

China's 90% share of rotary compressor manufacturing is advantageous for its AC producers, with sales projected to remain ten times higher than heat pumps through 2035.

Compressor supply chains also underline the scale gap between the two markets. Roughly 75% of rotary compressor output is used in air conditioners, while only 5% goes into heat pumps. In addition, most major heat pump and air conditioning manufacturers are vertically integrated with compressor production, either through in-house facilities or joint ventures. Companies such as Panasonic, Daikin, Midea, Gree and Carrier produce compressors directly, giving them greater control over cost, performance and supply chain resilience. This integration allows them to tailor compressor designs to specific product lines, secure critical components during supply disruptions and strengthen their competitive position across both heating and cooling markets.

These synergies between air conditioners and heat pump supply chains, along with the competitive advantage of air conditioner manufacturers, are expected to persist in the future. In the STEPS, air conditioner sales increase by 20% to 2035. While heat pumps sales grow more rapidly, doubling over the same period, the total number of air conditioners sold remains far more than five times higher than that of heat pumps.

References

ACEA. (2025, July 24). *New car registrations*. Retrieved from https://www.acea.auto/pc-registrations/new-car-registrations-1-9-in-h1-2025-battery-electric-15-6-market-share/

Baker McKenzie. (2024). *Thailand: Extension of the customs duty incentives for completely built-up BEVs imported from 1 January 2024 to 31 December 2025*. Retrieved from https://insightplus.bakermckenzie.com/bm/tax/thailand-extension-of-the-customs-duty-incentives-for-completely-built-up-bevs-imported-from-1-january-2024-to-31-december-2025

BNEF. (2025a). *China Wind Turbine Export Update: Momentum Builds.* BNEF.

BNEF. (2025b). *Tariffs lift output at US car plants, shift focus from EVs.* BNEF.

Brazil, Ministry of Development. (2023). *Minutes of the 209th regular meeting of the executive management committee (GECEX) of the chamber of foreign trade (CAMEX)*. Retrieved from https://www.gov.br/mdic/pt-br/assuntos/camex/atas/gecex/2023/ata-da-209a-reuniao-ordinaria-do-gecex.pdf

ChinaOL. (2025). *Monthly China's Household EC Production*. Retrieved from https://data.chinaiol.com/ecdata/index

Clean Investment Monitor. (2025). *The State of US Clean Energy Supply Chains in 2025*. Retrieved from https://www.cleaninvestmentmonitor.org/reports/q3-2025-update

EIA. (2025). *OPEC Revenues Fact Sheet*. Retrieved from https://www.eia.gov/international/analysis/special-topics/OPEC_Revenues_Fact_Sheet

European Commission. (2024a). *Discussions on undertakings for electric vehicles in Beijing*. Retrieved from https://policy.trade.ec.europa.eu/news/discussions-undertakings-electric-vehicles-beijing-2024-11-08_en

European Commission. (2024b). *EU Commission imposes countervailing duties on imports of battery electric vehicles (BEVs) from China*. Retrieved from https://trade.ec.europa.eu/access-to-markets/en/news/eu-commission-imposes-countervailing-duties-imports-battery-electric-vehicles-bevs-china

European Commission. (2025a). *Enabling framework for renewables*. Retrieved from https://energy.ec.europa.eu/topics/renewable-energy/enabling-framework-renewables_en

European Commission. (2025b). *Net-Zero Industry Act to further accelerate decarbonisation technologies manufacturing in the EU*. Retrieved from https://ec.europa.eu/commission/presscorner/detail/en/ip_25_1324

European Commission. (2025c). *Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions*. Retrieved from https://transport.ec.europa.eu/document/download/89b3143e-09b6-4ae6-a826-932b90ed0816_en?filename=Communication%20-%20Action%20Plan.pdf

European Commission. (2025d). *The Net-Zero Industry Act*. Retrieved from https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

European Council. (2025). *EU-China summit, 24 July 2025*. Retrieved from https://www.consilium.europa.eu/en/meetings/international-summit/2025/07/24/

Finn, R. (2025). COSCO SHIPPING Launches New Vehicle Carrier Service at Port of Piraeus, Bolstering Transshipment Hub Status. *Logistic Manager*. Retrieved from https://logistics-manager.com/cosco-shipping-launches-new-vehicle-carrier-service-at-port-of-piraeus-bolstering-transshipment-hub-status/

GX. (2025). *第二回公募 [2nd Round Public Offering]*. Retrieved from https://gx-supplychain.jp/assets/pdf/gx_list_saitaku20250124.pdf

ICCT. (2025). *Record electric vehicle sales show American demand - Will U.S. automakers deliver or retreat?* Retrieved from https://theicct.org/record-electric-vehicle-sales-show-american-demand-will-us-automakers-deliver-or-retreat-nov25/

IEA. (2024a). *Advancing Clean Technology Manufacturing.* Retrieved from https://www.iea.org/reports/advancing-clean-technology-manufacturing

IEA. (2024b). *Energy Technology Perspectives 2024.* Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2024

IEA. (2025a). *Global EV Outlook 2025*. Retrieved from https://www.iea.org/reports/global-ev-outlook-2025

IEA. (2025b). *Global Hydrogen Review 2025*. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2025

IEA. (2025c). *The battery industry has entered a new phase*. Retrieved from https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase

IEA. (2026). *Manufacturing and Trade Model Documentation.* Retrieved from https://www.iea.org/reports/manufacturing-and-trade-model

India, Ministry of Heavy Industries. (2024). *Scheme to Promote Manufacturing of Electric Passenger Cars in India*. Retrieved from https://heavyindustries.gov.in/scheme-promote-manufacturing-electric-passenger-cars-india-0

India, Ministry of New and Renewable Energy. (2025). *No. 293/8/2017-Wind*. Retrieved from https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2025/04/20250417480611676.pdf

International Trade Administration. (2025a). *Crystalline Silicon Photovoltaic Cells, Whether or Not Assembled Into Modules From the Socialist Republic of Vietnam: Amended Final Antidumping Duty Determination; Crystalline Silicon Photovoltaic Cells, Whether or Not Assembled Into Modules From Cambodia*. Retrieved from https://www.federalregister.gov/documents/2025/06/24/2025-11588/crystalline-silicon-photovoltaic-cells-whether-or-not-assembled-into-modules-from-the-socialist

Japan, Ministry of Economy, Trade and Industry. (2020). *Overview of the Vision for Offshore Wind Power Industry*. Retrieved from https://www.enecho.meti.go.jp/category/saving_and_new/saiene/yojo_furyoku/dl/vision/vision_first_overview_en.pdf

Kang, L. (2025). SAIC adds new 9,500-car cargo ship, bringing its fleet to 36 car carriers. *CnEVPost*. Retrieved from https://cnevpost.com/2025/06/13/saic-adds-new-9500-car-cargo-ship/

Légifrance. (2024). *Décret n° 2024-102 du 12 février 2024 relatif aux aides à l'achat ou à la location de véhicules peu polluants [Decree No. 2024-102 of 12 February 2024 on aid for the purchase or rental of low-emission vehicles]*. Retrieved from https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000049130533

McPhy. (2025). *John Cockerill Hydrogen appointed as the buyer of the majority of McPhy's activities, including the Belfort Gigafactory*. Retrieved from https://www.mcphy-finance.com/images/PDF/cp/gb/2025/McPhy_PR_LJ_Opening_EN_97f7c.pdf

MEC+. (2025). *Ramping up Local Manufacturing for Wind Turbines in India.* MEC+. Retrieved from https://mecintelligence.com/mec-perspectives/adb-mec-report/adb-wind-manufacturing

Medina, A. F. (2024). Indonesia Issues New Tax Incentives to Spur EV Production and Sales. *ASEAN Briefing*. Retrieved from https://www.aseanbriefing.com/news/indonesia-issues-new-tax-incentives-to-spur-ev-production-and-sales/

Ren, D. (2025). China's BYD expands car-carrier fleet to bolster EV exports amid furious domestic competition. *South China Morning Post*. Retrieved from https://www.scmp.com/business/china-business/article/3315626/chinas-byd-expands-car-carrier-fleet-bolster-ev-exports-amid-furious-domestic-competition

Reuters. (2023). *Germany to end e-vehicle subsidy programme*. Retrieved from https://www.reuters.com/business/autos-transportation/germany-end-e-vehicle-subsidy-programme-2023-12-16/

Rystad Energy. (2023). *The State of the European Wind Energy Supply Chain*. Retrieved from https://windeurope.org/intelligence-platform/product/the-state-of-the-european-wind-energy-supply-chain/

S&P Global. (2025). *Commodity Insights*. Retrieved from https://www.spglobal.com/commodity-insights/en

Sinoimex. (2025). *Global Trade & Industry Growth Lab*. Retrieved from https://www.sinoimex.com/en/index

State Council. (2025). *China's foreign trade hits new high in 2024*. Retrieved from https://english.www.gov.cn/archive/statistics/202501/13/content_WS6784a546c6d0868f4e8eec59.html?

T&E. (2025). *Europe's automotive industry at a crossroads*. Retrieved from https://www.transportenvironment.org/articles/europes-automotive-industry-at-a-crossroads

The Maritime Executive. (2025). China Puts Largest Car Carrier into Service, Launches First Methanol PCTC. Retrieved from https://maritime-executive.com/article/china-puts-largest-car-carrier-into-service-launches-first-methanol-pctc

The White House. (2025). *Fact Sheet: President Donald J. Trump Adjusts Imports of Automobiles and Automobile Parts into the United States*. Retrieved from https://www.whitehouse.gov/fact-sheets/2025/03/fact-sheet-president-donald-j-trump-adjusts-imports-of-automobiles-and-automobile-parts-into-the-united-states/

UN Trade & Development. (2025). *Merchandise: Total trade and share*. Retrieved from https://unctadstat.unctad.org/datacentre/dataviewer/US.TradeMerchTotal

US Congress. (2024). *S.4237 - ELITE Vehicles Act*. Retrieved from https://www.congress.gov/bill/118th-congress/senate-bill/4237/text

US Congress. (2025a). *H.J.Res.88 — 119th Congress (2025-2026)*. Retrieved from https://www.congress.gov/bill/119th-congress/house-joint-resolution/88/text

US Congress. (2025b). *H.R.1 - One Big Beautiful Bill Act*. Retrieved from https://www.congress.gov/bill/119th-congress/house-bill/1

US Department of Transportation. (2025). *Resetting the Corporate Average Fuel Economy Program*. Retrieved from https://www.federalregister.gov/documents/2025/06/11/2025-10586/resetting-the-corporate-average-fuel-economy-program

US Environmental Protection Agency. (2025). *Proposed Rule: Reconsideration of 2009 Endangerment Finding and Greenhouse Gas Vehicle Standards*. Retrieved from https://www.epa.gov/regulations-emissions-vehicles-and-engines/proposed-rule-reconsideration-2009-endangerment-finding

WindEurope. (2023). *The State of the European Wind Energy Supply Chain*. Retrieved from https://windeurope.org/data/products/the-state-of-the-european-wind-energy-supply-chain/

Yusry, M. (2024). Going EV: What the Malaysian government is doing to charge up the transition. *Malay Mail*. Retrieved from https://www.malaymail.com/news/malaysia/2024/07/09/going-ev-what-the-malaysian-government-is-doing-to-charge-up-the-transition/141965?

Zhang, L. (2025). *The One Big Beautiful Bill Act that redefines the US clean energy initiatives*. Retrieved from https://www.crugroup.com/en/communities/thought-leadership/2025/the-one-big-beautiful-bill-act-that-redefines-the-us-clean-energy-initiatives/

Part C

Supply chain risks and industrial competitiveness

Enhancing supply chain security and industrial competitiveness are important policy objectives that, if not addressed, could form stumbling blocks for energy and climate policy goals. Clean energy technology supply chains encompass a broad set of components and materials: for most countries, it is not possible to compete in all steps of a technology supply chain, let alone in all supply chains. Measures to enhance security of supply or boost competitiveness can entail significant costs. Governments can therefore benefit from data-driven insights into their countries' relative strengths and weaknesses in different supply chains when designing industrial strategies and prioritising action.

Part C of this report assesses the risks posed by high levels of concentration in the supply chains of selected clean energy technologies (Chapter 6), examines the drivers and trends in industrial competitiveness across regions, and explores strategies for narrowing competitiveness gaps in selected clean energy technologies as a means of promoting diversification and reducing the concentration of supply (Chapter 7). It ends with an overview of strategic considerations for navigating tensions and trade-offs between different policy goals in view of security risks and competitiveness challenges (Chapter 8).

Chapter 6. Supply chain risks

Highlights

- Supply chain security remains a challenge: Clean energy technology manufacturing is highly geographically concentrated, with China as the main supplier in most supply chain stages. China accounts for around 85% of solar and 80% of lithium-ion battery supply chain production capacity, and even higher shares for PV wafers (95%) and anode materials (97%). Cybersecurity considerations further enhance the importance of addressing security of supply.
- An "N-1" assessment, which models the impact of losing the largest exporter in each supply chain, shows that for the final downstream stages of most of the four technologies examined – solar PV, wind, batteries and heat pumps – capacity outside China could, in theory, have met most non-Chinese demand in 2024. Yet each of these supply chains contains several steps where production outside the largest exporter is not sufficient to meet demand, and at least one step where it covers less than one-quarter. A supply chain is only as secure as its weakest link.
- No major change in the security of global clean energy technology supply chains is likely before the end of the current decade, based on committed manufacturing and mining projects and projected market trends based on today's stated policy settings.
- The impact of Chinese clean energy technology manufacturing companies extends beyond the country's borders. Chinese firms account for a large portion of the production capacity located outside China in the solar PV industry. Such high market concentration can create risks, particularly in the event of major firms facing financial difficulties, labour disputes or being targeted by sanctions. For most technologies, the largest company holds between 5% and 20% of global production capacity.
- Applying the "N-1" analysis to the *facility* level for each of supply chains reviewed above reveals that, in each segment, the largest facility had the capacity to supply between 2% and 17% of global demand in 2024. Solar PV wafer manufacturing sits towards the top of this range, with one facility in the Inner Mongolia province, China, capable of producing the equivalent of the entire solar PV demand of the European Union and India combined. Fires at Chinese polysilicon plants in 2020 and 2022 caused major global price spikes and supply bottlenecks.
- Concentration is also high in metal and mineral refining. China processes over 70% of lithium, cobalt, graphite and rare earths. Similarly, in mining, two-thirds of cobalt comes from the Democratic Republic of the Congo, and 85% of natural graphite from China. This heightens exposure to risks of disruption.
- Around half of global clean energy technology trade passes through the Strait of Malacca, the sector's most critical shipping chokepoint. Blockages at Malacca, Suez, or other major routes could increase transit times, fuel use and freight costs, underscoring the importance of diversified transport networks for supply security.

Supply chain security

The supply chains for clean energy technologies differ markedly from those for fossil fuels, with far-reaching implications for energy security and resilience to supply disruptions. The transition to clean energy puts the spotlight on critical minerals and other inputs needed to manufacture clean technologies. The supply of both the material inputs and final technologies is often far more geographically concentrated than for fossil fuels. Global market concentration – measured as the share of a given market held by a small number of businesses – is also very high for several technologies.

While global supply chains are not inherently more vulnerable than domestic ones, dependence on imports can pose risks, particularly when a large share of supply comes from countries facing acute geopolitical threats such as conflict, social instability, unfair trade practices or human rights concerns. Concentrated supply chains are also more exposed to natural disasters, industrial accidents and deliberate efforts to manipulate supply or prices. The concentration of production in a single or small number of countries also heightens dependence on specific maritime trade routes, which can be vulnerable to disruption – especially where they pass through critical chokepoints. Trade-related policy changes can further disrupt markets when exporters or importers rely too heavily on a single trading partner.

The energy security paradigm is evolving with the growing use of clean energy technologies. Disruptions to their supply chains typically have less immediate and severe economic effects than disruptions to fossil fuel supplies. This is because fossil fuels are primary energy sources, whereas clean energy technologies are assets that generate electricity or deliver energy services. For example, a shortage of new solar PV panels does not affect electricity output from existing installations, but it does limit *future* capacity. Nonetheless, over time, prolonged supply constraints could slow the deployment of clean energy technologies and raise costs. Meanwhile, the growing reliance on electricity underscores the need to strengthen power system security and reliability.

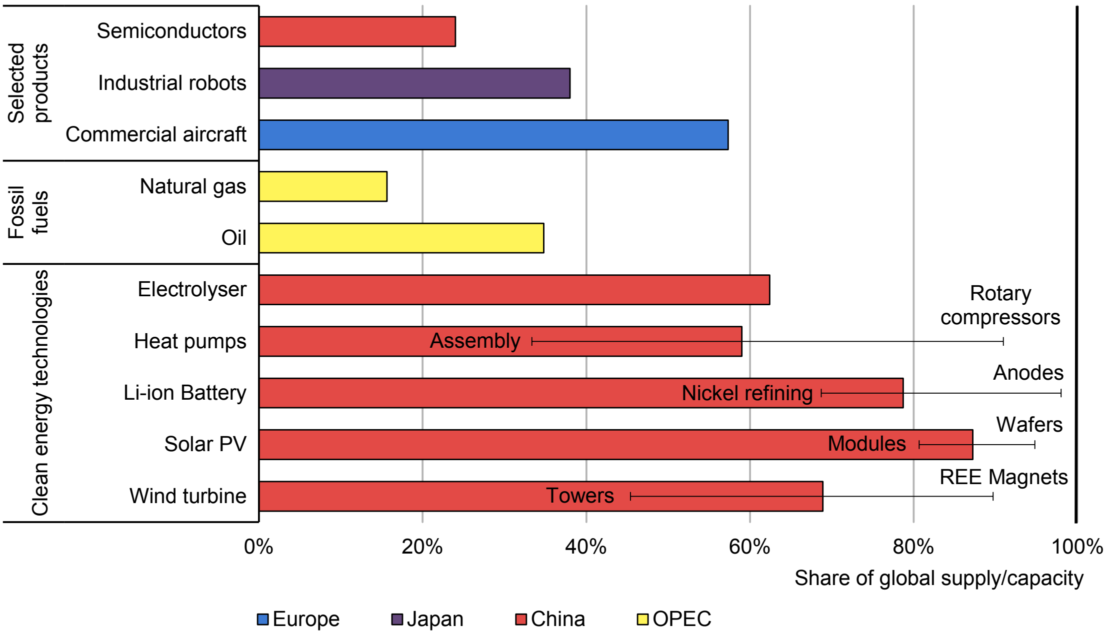
Geographical diversification of supply chains – including greater use of domestic resources and manufacturing, and reduced reliance on imports from a small number of countries – can be an effective means of improving security and resilience. However, for certain stages of production, this is not always feasible due to limited or uneconomic production capacity. At present, clean energy technology manufacturing and trade are highly concentrated, with People's Republic of China (hereafter, "China") commanding global output. This reflects a combination of relatively low production costs, government policy and trade-related measures.

This chapter assesses the risks posed by high levels of regional concentration in the supply of final clean energy technology products and key components.

Concentration of supply

Clean energy technology supply chains are significantly more concentrated geographically than those of fossil fuels. Each step of the supply chain has different levels of concentration; by weighting the concentration of each step by their respective contribution to the value of final technologies, it is possible to obtain a single concentration metric. On this measure, a single producer – China – provides over 85% and 80% of the global supply capacity of solar PV and batteries, respectively (Figure 6.1). Of the five main technologies, China's supply chain dominance is the lowest for heat pumps, for which it has just under a 60% share of global capacity. By contrast, the members of the Organization of the Petroleum Exporting Countries (OPEC) together account for only around one-third of global oil supply and 15% of gas supply.

Figure 6.1 Geographic concentration of supply chains for selected industrial products, fossil fuels and clean energy technologies by region, 2024



IEA. CC BY 4.0.

Notes: OPEC = Organization of the Petroleum Exporting Countries; Li-ion = lithium-ion; REE = rare earth elements Bars show the value-weighted average geographical concentration of the leading producer across the entire supply chain, excluding resource extraction (mining). The whiskers represent the least and most concentrated step within the industrial process stages of the supply chain for each technology. For fossil fuels and selected products, geographical concentration refers to production. For semiconductors and clean energy technologies, it refers to manufacturing capacity. Heat pumps include both assembly and compressors manufacturing. Battery refers to battery cells and anodes to anode active materials. Nickel refining for li-ion batteries refers to nickel sulphate.

Sources: IEA analysis based on BCG-SIA (2024), Meier (2025), IFR (2024).

China controls 60-85% of the five key clean energy technology supply chains – a far higher level of concentration than for oil and gas and most other strategic products.

The degree of concentration in clean energy technology manufacturing in China surpasses the levels of industrial specialisation observed in other leading economies. By comparison, Japan accounted for around 38% of global industrial robotics output in 2024, while Europe supplied just under 60% of worldwide commercial aircraft deliveries. China's position reflects the sustained effectiveness of its manufacturing-oriented policies, underpinned by cost competitiveness, innovation, extensive materials production capabilities and consistent policy support, which together have enabled the country to achieve a high degree of industrial self-reliance across a wide range of sectors, extending well beyond clean energy technologies.

China's strength in the clean energy technology sector is especially pronounced for mass-produced technologies and components. Elsewhere in the Asia Pacific region, manufacturing remains concentrated in technologies where countries hold strong intellectual property and manufacturing advantages, such as batteries and solar PV. By contrast, production of large, site-specific technologies, such as low-emissions fuel facilities and wind turbine towers, is less concentrated, reflecting the high cost of shipping bulky equipment and the need for substantial local infrastructure.

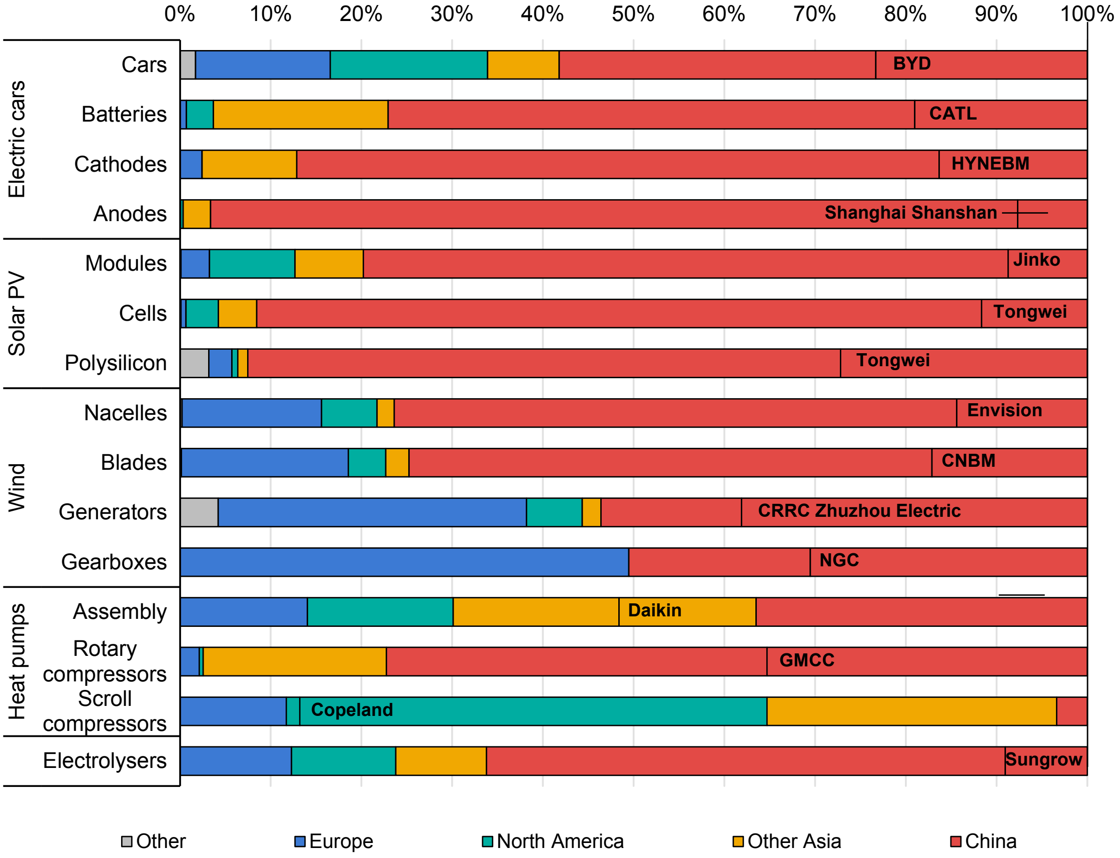
Concentration levels vary along clean energy technology supply chains, with final products generally displaying lower geographic concentration than intermediate components. In the solar PV supply chain, for example, China accounts for around 80% of global module production capacity, compared with about 95% for wafers. A similar pattern is observed in batteries: China holds roughly 85% of global cell assembly capacity but as much as 97% for anode active material.

Intermediate products are typically more energy-intensive, require specialised technical capabilities while offering lower profit margins. As a result, diversifying production outside China tends to be harder for these stages than for final product manufacturing. In addition, producers of manufacturing equipment for goods that are almost exclusively made in China are themselves predominantly Chinese, as demand for their machine tools constitutes nearly their entire market.

Further upstream, mineral refining also shows very high geographical concentration. China processes more than 70% of global lithium, cobalt, graphite and rare earth supplies. In contrast, raw material extraction is generally more geographically diverse, reflecting the distribution of natural resource endowments. China is therefore not the leading producer for all raw materials required in these supply chains. Nonetheless, mining activities for some key minerals remain highly concentrated: around two-thirds of global cobalt output originates in the Democratic Republic of the Congo (DRC), while 85% of natural graphite production takes place in China (IEA, 2025c).

Market concentration in clean energy technology supply chains is also pronounced. Whereas traditional energy technologies are produced by companies based in multiple countries, clean energy manufacturing is disproportionately controlled by firms headquartered in a single country – predominantly China. For most of the key clean energy technologies and their components, Chinese firms collectively hold the majority of global manufacturing capacity; in the case of solar PV cells and battery anodes, the share exceeds 85% (Figure 6.2). Such concentrated ownership heightens the risk of supply disruptions, whether from a major producer halting operations due to financial difficulties or from sanctions targeting specific companies. An example of the latter is China's Huawei, whose operations in the United States have been restricted due to concerns about surveillance and espionage.

Figure 6.2 Production capacity of selected clean energy technologies and components by region of company headquarters, 2024



IEA. CC BY 4.0.

Notes: The name and market share of the largest manufacturer is shown on the right side of each bar. Batteries refers to lithium-ion battery cells. HYNEBM refers to Hunan Yuneng New Energy Battery Material Co Ltd.,

Sources: IEA analysis based on BNEF (2025a), Benchmark Minerals Intelligence (2024), WindEurope (2023), GWEC (2024), GWEC (2022), InfoLink (2025), S&P Global (2025) and ChinaIOL (2025).

Almost all the leading clean energy technology manufacturing companies are headquartered in China, often holding a global market share exceeding that of entire regions.

Implications for security and resilience

Secure and resilient supply chains are needed to ensure adequate and uninterrupted supplies of raw and intermediate materials, components and equipment at every stage of production, as well as the timely delivery of finished products to end users (IEA, 2024a). In IEA parlance, energy security refers to adequate and timely investments to ensure supply stays in line with demand, while resilience refers to the ability of energy systems to handle physical disruptions along supply chains. A high degree of geographic and market concentration threatens both the security and resilience of supply chains.

Secure supply chains are supported by diversity in both suppliers and technologies, which fosters competition, provides flexibility and maintains efficient spare capacity. Such diversity helps stabilise prices and ensures price formation is transparent, providing clear investment signals and effective hedging opportunities for market participants. Threats to security often arise from under-investment in specific supply chain segments, leading to global supply-demand imbalances. Resilient systems must be able to respond and adapt rapidly to sudden market shocks – whether related to supply, demand or price – by co-ordinating with alternative supply chains capable of delivering equivalent technologies or services. Diversity of supply can also help mitigate the impact of such shocks.

In practice, there are significant risks to the security and resilience of energy supply chains, mainly due to a lack of supply diversity, with the potential to severely disrupt energy markets. For example, the surge in critical mineral prices in 2022, driven by rapidly rising demand and pandemic-related supply disruptions, triggered the first-ever increase in electric vehicle (EV) battery prices. Likewise, China’s introduction of export restrictions on magnets containing rare earth elements in early 2025 forced several non-Chinese manufacturers of electric motors and other machinery to halt production (Reuters, 2025). China announced additional export controls on supply chain components used to make EVs in the second half of 2025 (see Chapters 4 and 5). In both cases, the high degree of geographic and market concentration of certain supply chain segments exacerbated the impact of these market shocks. Energy supply chains – both for fossil fuels and clean energy technologies – must be robust enough to withstand such disruptions.

Box 6.1 The increasing importance of cyber security

Energy security considerations related to clean energy technologies go beyond the risks to supply of physical assets. Increased electrification brings with it new security challenges related to the IT systems required to manage the generation, transmission, distribution and use of electricity.

Electricity networks are the backbone of clean energy transitions. As digital controls, sensors and connected devices proliferate in order to integrate renewables and operate systems closer to their limits, exposure to cyber risk is growing in scale and complexity. The true picture is likely under-reported, yet available evidence shows a sharp increase: estimated attacks on critical infrastructure jumped 30% in 2023 to 420 million worldwide, and the average number of attacks on energy utilities has quadrupled since 2020 (IEA, 2023; Checkpoint, 2026). In the United States, the grid's "vulnerable points" are estimated to be increasing by 60 per day, from 21 000 in 2022 to 24 000 today (knowbe4, 2024). The economic toll is also rising, with average breach costs at USD 4.83 million in 2025 (IBM, 2025).

In power generation, landmark incidents include the sabotage of enrichment centrifuges in Iran in 2010; the Aurora generator test, a live demonstration carried out in 2007 by the US government of a destructive, cyber-induced operation against a power plant; and a 2022 outage of satellite modems that cut remote monitoring and control for around 5 800 wind turbines in Germany (PV Magazine, 2022). Though less visible to the public, 22 Danish energy companies were breached over a few days in May 2023, prompting targeted disconnections and islanding to limit spread and avert wider consequences (cybernews, 2023).

At transmission level, a notable increase in the number and variety of attacks has been seen globally since Russia's full-scale invasion of Ukraine. Nevertheless, Ukraine's experience shows defence is improving: while malware-driven operations cut power in 2015–16, attempts against nine high-voltage substations in 2022 were ultimately contained (US Congress, 2024). Campaigns against North American utilities in 2017-18 demonstrated how stolen credentials and compromised vendor access can reach the transmission grid control-room (AP News, 2018) (CSIS, 2025).

Risks are broadening with digitalisation and decentralisation

Distribution networks now rely on advanced distribution management systems, automated switches and millions of smart meters. Even when power flows remain stable, ransomware can disrupt customer-facing services: in Johannesburg (2019) (Help Net Security, 2019), billing systems and the pre-paid vending platform were knocked offline; in Colombia (2022) (Finance Colombia, 2022), ransomware crippled customer systems, affecting over 300 000 customers.

As connected devices spread "behind the meter," small vulnerabilities can add up to system effects. Research indicates that hijacking less than 2% of system load (American Public Power Association, 2023), for example via compromised smart meters, can destabilise frequency if they are then switched in unison.

Supply-chain cyber risk is now an evolving system issue

Global supply chains introduce dependencies in hardware, firmware and cloud services, as well as pathways to access critical functions through compromised vendor equipment. This risk is no longer theoretical. In 2025, authorities in the United States and European Union examined communications modules in imported inverters and batteries, warning about the potential for large-scale remote manipulation (Engineering, 2025) (MAYA, 2025). In 2024, Lithuania blocked remote access by Chinese suppliers to solar, wind and storage control systems, citing national security concerns (PV Magazine, 2024).

In Europe, some 200 GW of installed PV capacity is linked to Chinese-manufactured inverters, and about 75% of new inverters originate from China, making firmware assurance and authenticated updates a priority. In the United States, a 2019 seizure and inspection of a Chinese-made large power transformer shipment, whose findings were not disclosed, reflected concerns about the approximately 500 large power transformers from China operating in the United States (knowbe4, 2025) (SecuretheGrid, 2023).

Raising the floor on cyber risk in modern power systems

As grids digitalise and decentralise, exposure grows in ways that are often invisible to consumers: attacks may not always cut power, but they can degrade operations, disrupt services and undermine confidence. Evidence from multiple jurisdictions shows that despite adversaries becoming more capable and opportunistic, day-to-day operational discipline can stop most incidents from cascading. Sustaining trust therefore means treating cybersecurity as integral to reliability, adequacy and flexibility, on par with physical assets and markets.

Policy is catching up: new US regulation now requires supply-chain risk management and patch authenticity verification as part of energy-sector cyber measures. Australia now empowers authorities to set conditions, mandate incident reporting and block high-risk equipment in critical systems. India issued guidelines in 2025 requiring that rooftop solar PV inverters only transmit data to servers hosted in India. Japan’s 2024 regime allows authorities to intervene when “specified critical facilities” rely on high-risk technologies or service arrangements. In parallel, utilities are embedding these expectations in procurement, so that supply-chain governance becomes part of day-to-day operations.

Investing in people and TSO-DSO co-ordination matters as much as technology, and international alignment can improve performance faster given shared suppliers and cross-border power flows (IEA, 2023). Progress can be tracked with a small set of indicators, such as the share of critical assets meeting operational security baselines, the proportion of distributed energy resources connected under assured firmware, time to detect and recover, and the coverage of enhanced supplier assurance. This can help to ensure that grids remain secure, reliable and affordable as digitalisation expands.

Assessing dependencies in the supply chain

As noted, the degree of geographic concentration of production differs widely across clean energy technology supply chains and among different stages of those chains. However, concentration alone does not determine vulnerability: in some segments, substantial spare production capacity exists. This means that, in some cases, even the loss of a major supplier could be offset quickly by ramping up output in other countries with unused capacity.

To assess overall supply security and resilience, we conducted an “N-1 analysis” of the leading clean energy technology supply chains. Commonly used in power system studies, this method evaluates the consequences of losing the largest asset – in this case, the largest exporter of a given technology or component – regardless of the cause. Using 2024 data and assuming that all other plants produce at 85% of their nameplate capacity, we estimate the share of global demand that could still be met without the largest exporter.[1] In 2024, China was both the largest producer and exporter for most manufacturing steps of clean energy technologies except for the mining of certain critical minerals, therefore in this analysis Chinese supply is excluded from all steps of the supply chain. The resulting share of global demand – excluding China – that could have been met provides an indication of the security and resilience of each supply chain. This exercise is not intended as a full simulation of the impact of potential disruptions, but rather as a way of highlighting where global supply chains are most dependent on a single source.

Results from this analysis vary sharply across and along supply chains. For the final downstream stages of most of the four technologies examined – solar PV, wind, batteries and heat pumps – capacity outside China could, in theory, have met most non-Chinese demand in 2024 (Figure 6.3). However, each of these supply chains contains several steps where production outside the largest exporter is insufficient to meet demand, and at least one step where it covers less than one-quarter of demand. The lack of availability of supply of a single step could affect the entire supply chain, making it less secure.

In metals and minerals processing, capacity outside the leading producer is generally adequate for bulk materials such as steel and copper, but falls well short for most critical minerals. This is particularly the case for magnet rare earth elements and graphite, as refining capacity is overwhelmingly concentrated in China. At the extraction stage, the leading producer for each mineral often differs from that for clean energy technologies, and mined ores serve a wide range of industries beyond clean energy applications. As a result, global mining output excluding China would still exceed non-Chinese demand for most minerals, except for rare earths and to a larger extent graphite.

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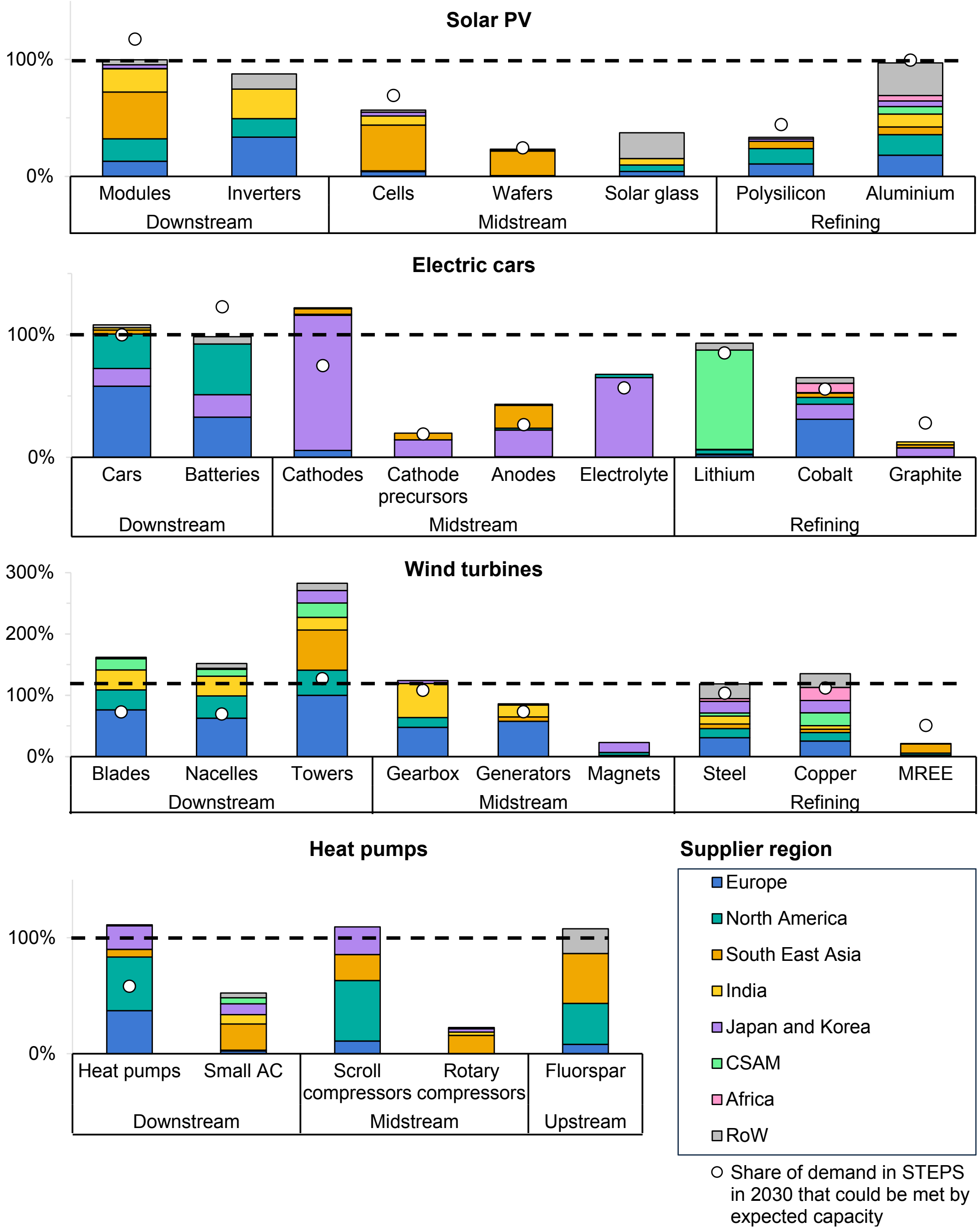
[1] In this analysis, the global demand without the largest exporter is considered to be the demand for the final technology and all the intermediate steps that would be needed to satisfy it.

Figure 6.3 Share of global demand excluding China for selected clean energy technologies and components that could have been met without China, 2024



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Notes: MREE = Magnet rare earth elements (neodymium, dysprosium, terbium and praseodymium); CSAM = Central and South America; STEPS = Stated Policies Scenario; AC = air conditioner; RoW = Rest of World. Aluminium, cobalt, copper, fluorspar, graphite, lithium, MREE and steel refer to total production capacity and demand across all sectors, and not specifically to demand from any single supply chain. Cathode and anode refer to active materials. All facilities able to produce graphite anodes suitable for battery applications are included in global anode manufacturing capacity. Battery refers to lithium-ion battery cells. For the midstream and downstream, manufacturing capacities are used, while for critical minerals and materials, production is used. Assumes production outside of China is set to 85% of nameplate capacity. For inverters and solar glass, production from Asian countries outside of China is classified as RoW.

Sources: IEA analysis based on IEA (2025b), IEA (2025c), Benchmark Minerals Intelligence (2024), BNEF (2025a), EV Volumes (2025), WindEurope (2023), InfoLink (2025), S&P Global (2025) and ChinaIOL (2025).

All clean energy technology supply chains have at least one step where only one-quarter of global demand could be met by suppliers outside China.

The results of this analysis can be interpreted as an upper bound on the production capacity available outside China for two main reasons. First, a portion of intermediate production located outside China currently supplies downstream manufacturers within China. For example, an estimated USD 28 million – equivalent to around 12% of European polysilicon output – is exported to China for wafer production. In the event of a supply disruption, new logistical and commercial linkages would need to be established, a process that could take time. Second, manufacturing facilities outside China are currently operating at relatively low utilisation rates. Increasing output to 85% of nameplate capacity would therefore require both time and additional investment.

No major change in the security of clean energy technology supply chains is likely before the end of the current decade, taking account of committed[2] manufacturing and mining projects and projected market trends based on today's stated policy settings. In the Stated Policies Scenario (STEPS), the share of demand that could be met with production outside China in 2030 increases slightly for rare earth element refining but falls for cathodes and wind turbine components. It remains largely unchanged for the other components and final technologies. In the longer term, more investment outside China, particularly in upstream segments and component manufacturing, would be needed in order to have any significant impact on the overall security of those supply chains.

The influence of Chinese clean energy technology manufacturing companies extends beyond China's borders. The "extraterritorial" elements of China's export controls on certain battery and permanent magnet supply chains highlight the importance of understanding Chinese ownership of productive assets located abroad (China, Ministry of Commerce, 2025). This is particularly evident in the refining of critical minerals and in the solar PV industry.

For nickel, while only about 30% of global supply is refined in China, Chinese companies control almost half of supply outside of China – primarily through operations in Indonesia. For graphite, Chinese companies hold nearly 30% of production capacity outside of China. For other critical minerals, Chinese ownership of overseas assets remains more limited, though new investments, especially in lithium, could significantly expand China's global footprint in the coming years.

In the solar PV sector, around 85% of wafer production capacity outside China is controlled by Chinese firms. By contrast, Chinese ownership of battery manufacturing capacity abroad (apart from for anode active materials) remains

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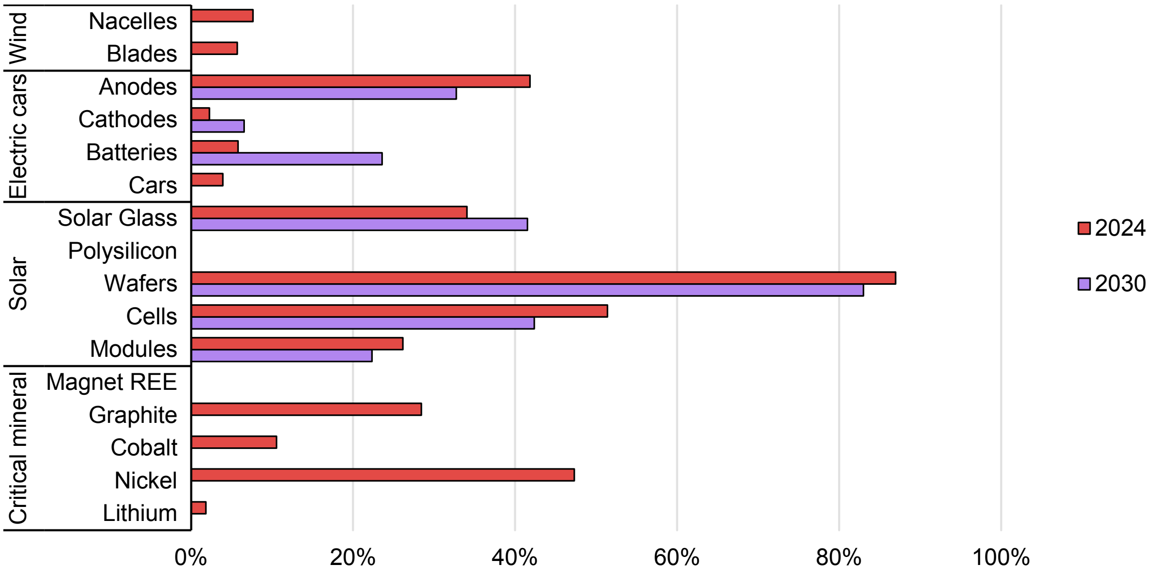
[2] "Committed" refers to plants that have reached a final investment decision or are under construction.

modest, though it is expected to grow rapidly. Based on currently committed projects, by 2030, the share of battery production capacity outside China owned by Chinese firms could rise from around 6% in 2024 to around one-quarter by 2030. This expansion reflects growing outward foreign direct investment, as Chinese companies seek access to international markets while mitigating the impact of trade restrictions.

As a result, in many clean energy technologies supply chain steps, operational know-how and technical expertise are increasingly concentrated within Chinese firms. This concentration adds a further layer of complexity to diversification efforts, even when production assets are geographically distributed.

Figure 6.4 Share of committed global production capacity located outside China owned by China-headquartered companies for selected technologies and minerals, 2024 and 2030



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Notes: REE = rare earth elements. No projections are available for wind turbines, critical minerals and electric cars. For polysilicon, no production capacity outside of China is owned by Chinese companies.

Sources: IEA analysis based on BNEF (2025a), Benchmark Minerals Intelligence (2024), WindEurope (2023), InfoLink (2025), S&P Global (2025) and ChinaIOL (2025).

Chinese firms account for large shares of solar PV production and minerals refining capacity located outside China, and their share of the battery supply chain is set to jump by 2030.

Accidents or natural hazards can pose significant risks to the security and resilience of supply chains, potentially taking facilities offline for extended periods. Supply chains that depend heavily on a small number of production facilities are particularly vulnerable. For example, fires at Chinese polysilicon plants in 2020 and 2022 had major repercussions for the global solar PV supply chain, sharply pushing up prices. When disruption persists for more than a few days or weeks, its effects can extend beyond prices, resulting in reduced demand and delays in technology deployment.

We have applied the N-1 analysis to the largest facility for each of the clean energy technology supply chains reviewed above. The results show that in 2024, the single largest operating factory in each segment had the capacity to supply between 2% and 17% of global demand (Table 6.1). Solar PV wafer manufacturing sits towards the top of this range, with one facility in China's Inner Mongolia province capable of producing the equivalent of the solar PV demand of the European Union and India combined, or twice that of the United States. However, the loss of output from this plant could be offset relatively easily, as total wafer manufacturing capacity at the end of 2024 was more than one and a half times global demand due to underutilised capacity both in China and elsewhere.

The least concentrated segment in this analysis is module assembly, where the largest facility – the Jinko Solar plant in Zhejiang, China – accounted for around 2% of global production. Here too, spare capacity was substantial, exceeding actual production by around 75% in 2024.

While individual factories generally represent only a small share of global output, any disruption to them could have significant regional impacts. For instance, Europe's biggest battery factory – LGES's 86 GWh plant near Wroclaw, Poland – accounts for around half of the continent's battery manufacturing capacity. In the case of wind turbine manufacturing, the biggest factories in the United States and Korea account for half of total manufacturing capacity for nacelles in those countries. In China, the large number of individual factories means that no single factory has capacity exceeding 5% of the total for the country.

Very high market concentration can also create significant risks, particularly in the event of major firms facing financial difficulties, labour disputes or being targeted by sanctions. For most technologies, the largest company holds between 10% and 20% of global production capacity. There are some notable exceptions: compressors for heat pumps, polysilicon manufacturing and wind turbine gearbox production, where the largest company – in the latter two cases headquartered in China – accounts for around 30% of total capacity. Even a temporary halt to production by these companies could create major bottlenecks in the global solar PV and wind turbine supply chains.

Table 6.1 Largest individual company and production facility for selected clean energy technology supply chain by segment, 2024

Technology	Step	Largest company		Largest factory	
		Share	Name	Share	Location
Batteries	Cells	19%	CATL	4%	Yibin (China)
	Cathodes	16%	Hunan Yuneng New Energy Battery Material	2%	Yulin (China)
	Anodes	8%	Shanghai Shanshan Lithium Battery Material Technology	5%	Jilin (China)
Solar PV	Modules	9%	Jinko Solar	2%	Haining (China)
	Cells	12%	Tongwei	3%	Yiwu (China)
	Wafer	17%	LONGi	9%	Baotou (China)
	Polysilicon	27%	Tongwei	6%	Baotou (China)
Wind turbines	Nacelles assembly	14%	Envision Energy	3%	Pensacola (United States)
	Blades	17%	China National Building Material	5%	Sheyang (China)
	Towers	19%	CS Wind Corp.	12%	Tan Thanh (Viet Nam)
	Generators	22%	CRRC Zhuzhou	5%	Dafeng (China)
	Gearboxes	31%	NGC	17%	Jinhu (China)
Heat pumps	Assembly	15%	Daikin	4%	Foshan (China)
	Rotary compressors	35%	GMCC	12%	Hefei (China)
	Scroll compressors	51%	Copeland	10%	Lebanon, Missouri (United States)
Electrolysers	Assembly	9%	Sungrow	5%	Shenzhen (China)

Notes: Batteries refers to lithium-ion batteries. Cathodes and anodes refer to cathode and anode active materials. All facilities able to produce graphite suitable for battery applications are included in global anode manufacturing capacity. The largest factory does not always belong to the largest producing company. In this table, heat pumps refer to reversible units without distinction as to their application.

Sources: IEA analysis based on BNEF (2025a), Benchmark Minerals Intelligence (2024), WindEurope (2023), InfoLink (2025), S&P Global (2025) GWEC (2025) and ChinaIOL (2025).

Technology-specific security considerations

Solar PV

China is the largest producer across all major segments of the solar PV supply chain, but significant capacity also exists in other regions – much of it currently underutilised. At present, production outside of China could mostly meet the rest of the world’s needs for solar PV modules and inverters. For modules, much of this capacity stems from recent investments in Southeast Asia (with almost 60% owned by Chinese companies), India and North America, while for inverters legacy facilities in Europe account for a large share. However, a significant share of this non-Chinese capacity is less competitive, as it is geared towards manufacturing older, less-efficient modules, which is one reason for low utilisation rates. This mostly concerns facilities that have existed for several years, whereas more recent capacity expansion is oriented to produce modern, high-efficiency models.

Further upstream in the supply chain, the picture is very different. Only just over half of global cell demand (excluding China) could be met by factories outside China, and just one-quarter for wafer manufacturing. In these segments, most non-Chinese production capacity is located in Southeast Asia, with 70% or more owned by companies headquartered in China and primarily serving export markets. For solar glass and polysilicon, less than half of demand outside China (excluding China) could be met without Chinese production.

In the STEPS, supply diversity improves somewhat in the downstream solar PV sector to 2030, on the assumption that committed manufacturing projects go ahead. Upstream, however, change is limited, except for cell manufacturing, where new capacity in India and the United States increases diversity. Achieving a meaningful improvement in the security and resilience of the solar PV supply chain would require major new investments in upstream segments outside China.

Wind

China is the largest producer of all major wind power components (nacelles, blades, towers, gearboxes and generators), as well as the refined metals used to manufacture them. In 2024, global production capacity for the main downstream turbine components – nacelles, blades and towers – exceeded demand outside China, largely thanks to substantial capacity in Europe. However, most of the key components for nacelles are produced in China, with limited manufacturing capabilities elsewhere. Capacity for the assembly of gearboxes outside China could meet all demand beyond China’s borders, thanks to Indian and European production capacity.

Further upstream, supply chain vulnerabilities are more pronounced. Copper – essential for generators and cabling (and used in several industrial applications outside the energy sector) – is mainly mined in Chile and refined in China. The most critical potential bottleneck lies in permanent magnets and the rare earth elements required to produce them. Permanent magnets are used almost exclusively for offshore wind turbines, which accounted for 8% of global wind capacity additions in 2024 and are projected to make up 20% of capacity additions to 2030 in the STEPS. Less than 10% of rare earth refining capacity is located outside China, though mining and magnet manufacturing shares are somewhat higher thanks to recent investments in Europe and the United States. Given the recent Chinese export control announcements on these minerals, this remains the most acute supply security risk for the wind turbine industry.

These vulnerabilities are set to worsen under today's stated policy settings. In the STEPS, demand outside China is projected to rise, yet planned capacity expansions are minimal, held back by the perception of uncertain demand among manufacturers headquartered outside China. Most new turbine manufacturing capacity is expected to be built in China. As a result, dependency on China – currently concentrated in midstream and upstream components – will extend to downstream segments in the future as well.

Electric vehicles and batteries

China is the largest producer and exporter across most of the EV supply chain stages, with the exception of lithium mining (led by Australia), cobalt mining (led by the DRC) and nickel mining and refining (led by Indonesia). In downstream segments, including EV assembly and battery cell manufacturing, production capacity outside China is sufficient to meet all non-Chinese demand, as cell factories are often located in the same regions as vehicle assembly.

Electric motor manufacturing appears to be in a similar position, though precise data are unavailable, as most motors are produced in-house by car manufacturers. However, nearly all EV motors contain permanent magnets, which require rare earth elements. For both rare earth refining and permanent magnet manufacturing, less than 25% of non-Chinese global demand could be met with capacity outside China, leaving motor supply chains as exposed as those for batteries.

With regards to battery components, capacity outside China is sufficient to meet demand for nickel manganese cobalt (NMC) battery active materials, supported by facilities in Korea and Japan, but largely insufficient for lithium iron phosphate (LFP) battery active materials, NMC and LFP precursors, and anode active material. Production capacity for electrolyte salts and solvents outside China could cover about two-thirds of demand. While electrolyte solvent production could, in principle, be expanded in regions with a developed chemicals industry, capacity remains limited today.

For critical minerals, the picture is mixed. In the case of lithium – the most important mineral for lithium-ion batteries – around 65% of mining and nearly 95% of processing demand could be met without relying on the largest producer. By contrast, cobalt remains heavily dependent on the largest producer for mining and, albeit to a lesser extent, for refining. Graphite refining for lithium-ion batteries – today mostly focused on synthetic graphite – is even more concentrated, with only minimal capacity outside China, as few countries have been willing or able to develop this highly energy-intensive industry.

There is little prospect of any significant change in the security and resilience of EV supply chains over the rest of this decade, given current investment plans. In the STEPS, committed investments in cell and graphite production outside China improve diversity slightly, but in most other stages the situation either worsens or remains stable. As a result, the risk profile for EV supply chains is likely to remain high, with upstream stages remaining highly exposed.

Heat pumps

China is the largest producer and exporter of assembled heat pumps.[3] However, international trade in heat pumps is limited because units are often tailored to local market requirements, meaning reliance on Chinese imports is currently modest in most heating regions. Overall, for heat pumps used as primary heating equipment, manufacturing capacity outside China is more than sufficient to meet demand, moderating concerns about supply security.

The situation is very different for small air conditioning (AC) units, which – in the case of reversible models – can also be used for heating (i.e. functioning as conventional space-heating heat pumps). Reversible units are common in countries with a temperate climate, where both heating and cooling are needed seasonally. These units are estimated to account for around 30% of heat pump capacity sold as primary heating equipment. Small AC units are more easily traded internationally, and their production is far more concentrated in China, which dominates manufacturing and exports. Outside China, production capacity could only meet over half of global demand.

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[3] In this report, "heat pumps" refers to units that deliver heat directly to households and residential or commercial buildings for space heating and/or domestic hot water provision. 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.

Across the heat pump sector, the main supply security risk lies in rotary compressor manufacturing. Such compressors – used in both small heat pumps and AC units – are also produced predominantly in China, where many manufacturers either make their own or source them from a well-developed local supply chain. Chinese producers benefit from economies of scale, and compressors are easy to transport and trade. At present, rotary compressor production capacity outside China can cover about one-quarter of global demand for use in heat pumps. The production of scroll compressors, used in larger residential and commercial units, is less concentrated geographically. Fluorspar, the key feedstock for current F-gas refrigerants, is produced mainly in China, but non-Chinese production is thought to be sufficient to meet remaining global demand.

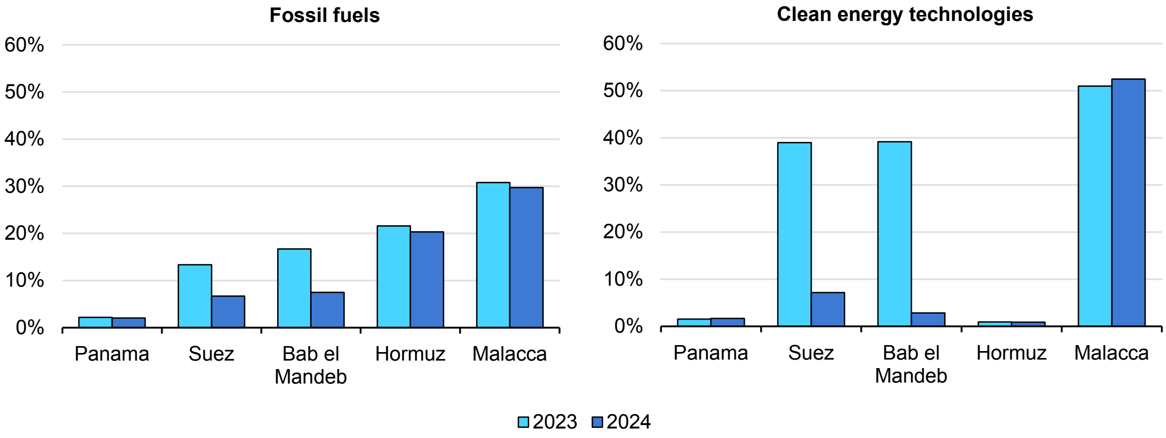
New project announcements for heat pump manufacturing are not common in most parts of the world, so it is hard to assess the medium-term prospects for supply diversity. In Europe, where announcements are more commonplace, new project plans since 2022 point to rising domestic production capacity through to 2030. In all regions, without fresh investment, production capacity for heat pump assembly could begin to lag behind demand in the coming years. In the STEPS, production outside China would not be enough to cover global demand in 2030 – a reversal of the current situation.

Maritime chokepoints

The supply chains for most clean energy technologies – along with their components and material inputs – rely heavily on maritime shipping. As global trade volumes continue to grow, the risk of severe congestion or physical disruption at key maritime chokepoints could rise. Such disruptions may be triggered by geopolitical tensions, extreme weather events, piracy or accidents.

In 2023, 60% of global trade by value passed through at least one maritime chokepoint; the share was 70% for fossil fuels and 65% for clean energy technologies. For fossil fuels, the most critical passages are the Strait of Hormuz and the Strait of Malacca: typically, around one-fifth of global oil and liquefied natural gas (LNG) trade flows through the Strait of Hormuz (Figure 6.5). For clean energy technologies, Malacca and the Suez Canal are the most important routes, with the Panama Canal playing a key role in trade between the United States and South America or Asia, though its overall volumes are smaller.

Figure 6.5 Global clean energy technologies and fossil fuels passing through selected chokepoints by share of value, 2023-2024



Notes: Trade passing through each chokepoint is calculated by combining global trade data with shortest shipping routes between ports. 2023 values are estimated by the IEA based on modelled shipping routes and trade values, while 2024 values are adjusted based on data for tankers and container carriers.
Sources: IEA analysis adapted from IEA (2024b) and International Monetary Fund (2024).

Recent disruptions at the Bab el Mandeb Strait and the Suez Canal have had a significant impact on maritime energy trade routes.

Since November 2023, Houthi attacks on shipping have significantly disrupted shipping through the Bab el Mandeb Strait and the Suez Canal, driving up freight and insurance costs and forcing the re-routing of traffic via the Cape of Good Hope. Shipping along that route has fallen by about 90% for container carriers and 50% for oil tankers, with the containerised freight index more than doubling between 2023 and 2024.

Around half of all clean energy technology trade today transits the Strait of Malacca, making it the single most important chokepoint for the sector. This reflects the gap between European demand for clean energy technologies and its domestic manufacturing capacity. Across the leading clean energy technologies, at least half of global supply is located in Asia, east of Malacca.

A blockage at any of these chokepoints – whatever the cause – could disrupt both clean energy and fossil fuel supply chains, posing a threat to energy security. The scale of the impact would vary by commodity and by country, depending on the location of supply and demand. Disruptions would generally be far more severe for fossil fuels, as they are primary energy sources: the loss of a significant share of global oil supply, for example, has historically triggered rapid spikes in international prices and far-reaching economic consequences worldwide. By contrast, delays in the delivery of clean energy technologies could severely disrupt supply chains but are unlikely to cause such acute economic shocks, as these technologies are assets used to produce, transform or consume energy, rather than being energy sources themselves.

Box 6.2 Low-emissions fuel bunkering: an opportunity for diversification or further concentration of supply?

Fuel is a significant and volatile cost component in maritime shipping, making the distribution and concentration of bunkering supply key determinants of freight costs. Bunkering today is highly concentrated: the Port of Singapore alone meets around one-fifth of global demand – with nearly 55 Mt delivered in 2024 – and the top 17 ports account for more than 60%. Located along main trade routes, these hubs benefit from economies of scale and proximity to refineries, reducing costs. However, maritime instability from conflict, piracy or environmental hazards can cause delays and re-routing, raising freight costs and emissions. With demand for low-emissions marine fuel set to grow, an important question is whether today's bunkering hubs will retain their dominance or give way to a more diversified supply landscape.

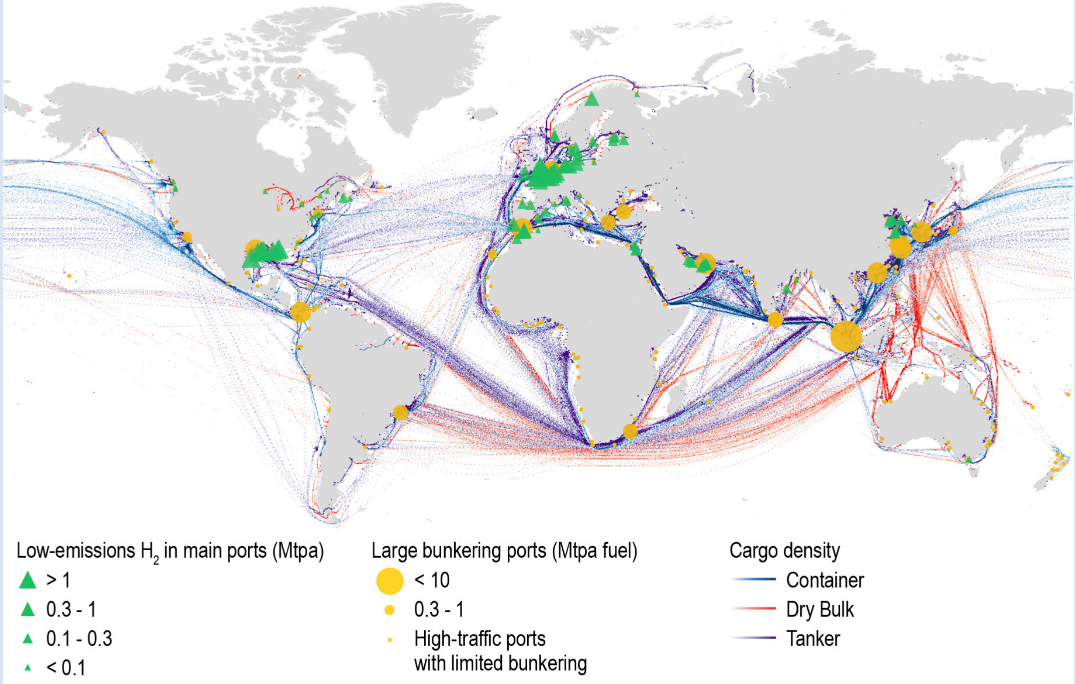
Alternative marine fuels include biofuels, hydrogen and hydrogen-based fuels. Certain biofuels, such as biodiesel and biomethane, can be used as "drop-in" fuels with limited modification to existing vessels, but their scalability is constrained by the availability of sustainable biomass and competing demand from other sectors, particularly aviation. Hydrogen-based fuels, while currently more costly, offer greater long-term potential. In 2025, over 100 methanol-powered vessels were in service and around 360 were on order, while over 40 ammonia-powered vessels were on order books. Most are equipped with a dual-fuel engine that can operate on both the alternative fuel and conventional oil, improving operational flexibility, compliance with regional fuel standards and resilience to oil price spikes.

Low-emissions fuels are not yet traded as readily as conventional heavy fuel oil. The scale and geography of their supply will strongly influence future freight costs and resilience. If bunkering remains concentrated in a few ports, ships may face longer diversions and higher prices when alternative fuels are unavailable. However, if supply expands along main routes and re-routing corridors, bunkering would become more diversified and less vulnerable to disruption.

Announced projects suggest about 10 Mt per annum (Mtpa) of low-emissions hydrogen has strong potential to be operational* by 2030, covering roughly 10% of 2024's marine fuel demand with hydrogen-based fuels. This is contingent on demand-side policies, including for shipping, and measures to narrow the cost gap with fossil-based pathways. About three-quarters of this capacity lies within 500 km of a major port (falling to 60% within 250 km) giving more than 70 of the world's 242 main cargo and bunkering ports access to at least 0.1 Mtpa of hydrogen

(44 ports are within 250 km). Supply would remain uneven, concentrated in Europe, the US East Coast, the Middle East and northern China, though this aligns with today's major bunkering hubs, giving them an early-mover advantage.

Figure 6.6 Major current shipping routes and ports, and low-emissions hydrogen supply from announced projects, 2030



Notes: H_2 = hydrogen. Hydrogen supply is based on announced projects with a strong potential to be operational by 2030 within a 500 km radius of each port, regardless of announced end-use. The methodology used to assess the likelihood of hydrogen projects with an announced operational date between 2026 and 2030 becoming operational by 2030 is described in the IEA´s *Global Hydrogen Review 2025*. The map shows the potential hydrogen supply available to each port individually, but does not account for competition, so the actual volumes available may be lower if multiple ports draw from the same project.

Sources: Adapted from IEA (2024b) and IEA (2025e).

Only about 2.4 Mtpa – less than one-quarter of the total – is within 500 km of major maritime chokepoints. Several major ports in the Asia Pacific, sub-Saharan Africa and Latin America may therefore need to import hydrogen-based fuels from distant sources, even where local production costs are relatively low. An additional 27 Mtpa of projects have been announced for 2030 or earlier but remain uncertain. If they are realised later in the 2030s, these projects could transform prospects, enabling new hubs to emerge near major dry-bulk ports in Australia and along alternative routes such as in Namibia (via the Cape of Good Hope) and the Strait of Magellan.

* Calculated based on a methodology developed to assess the likelihood of hydrogen projects with an announced operational date between 2026 and 2030 becoming operational by 2030, described at IEA´s *Global Hydrogen Review 2025* (IEA, 2025d).

We have analysed the potential impact of a blockage at the main maritime chokepoints by estimating deviations in route distance and time, and the resulting changes in energy consumption, using the shipping route modelling tool developed for *ETP-2024* (IEA, 2024b). This analysis focused on two major origin-destination pairs: Shanghai (China) – Rotterdam (Netherlands), for clean energy technology trade, and Corpus Christi (United States) – Chiba (Japan), for oil and gas. For each pair, alternative routes were considered depending on which chokepoints were affected. The results are summarised in Table 6.2. In the case of Shanghai (China) – Rotterdam (the Netherlands), the shortest, most convenient route is eastbound via the Suez Canal, transiting other chokepoints such as the Taiwan Strait, the Strait of Malacca and the Bab el Mandeb Strait.

In the event of a blockage at the **Strait of Malacca**, ships would be forced to divert via the Sunda or Lombok Straits, adding roughly 2 000 km to the route from Shanghai to reach Colombo (Table 6.2), assuming navigation through Sunda is not possible. Although Malacca handles very high traffic volumes, a closure would be disruptive but not crippling. On the Shanghai – Rotterdam route via the Suez Canal, such a diversion would add about 74 hours of sailing time and require 10% more fuel, though delays could be longer due to limited capacity and congestion in the alternative straits. Fuel can account for roughly 30% of operational shipping costs, but transport generally represents a small share of total clean energy technology costs, ranging from 1% for solar PV polysilicon to 15% for wind blades (IEA, 2024b). Longer voyages would therefore have only a minor impact on the final price of the technology. However, extended transit times could create temporary shortages in shipping capacity, pushing freight rates sharply higher,

A blockage at the **Suez Canal** or **Bab el Mandeb Strait** would be more disruptive, as demonstrated by recent disruptions. Ships leaving from Shanghai can reroute either around the Cape of Good Hope, increasing distance by 35%, or across the Pacific and through the Panama Canal to Europe, adding 27%. Despite being shorter, the Panama route is less favoured due to congestion, vessel size limitations and high tolls. Since early 2024, geopolitical instability in the Red Sea has reduced Suez traffic by roughly 60%, with a comparable rise in traffic via the Cape of Good Hope but little change through the Panama Canal. The Red Sea remains a critical corridor for both clean energy and fossil fuel shipments; its complete closure would cause severe disruption, even though the shipping industry can adapt at the cost of longer transit times and higher freight rates.

For the Corpus Christi (United States) – Chiba (Japan) route, the shortest passage is via the **Panama Canal**, which is also vulnerable to weather-related constraints. Severe drought in late 2023 and early 2024 reduced traffic by almost 50% year-on-year. A closure would leave three options: east via the Suez Canal (increasing distance by 60%), east via the Cape of Good Hope (75%) or around South America via the Strait of Magellan. The latter is rarely used and traffic data from

2023-24 show no notable increase consistent with diversions from the Panama Canal. Although the Panama Canal is less relevant for clean energy technology trade, it plays a major role in other energy commodity transport, meaning closures would significantly affect transit times and costs.

Beyond these two cases, the **Strait of Hormuz** remains the most critical chokepoint for fossil fuels: roughly 25% of the world’s seaborne oil trade and almost one-fifth of global LNG trade passed through it in 2025. Unlike other passages, there is no alternative route for ships entering or leaving the Persian Gulf, so any disruption would halt maritime trade entirely. This makes Hormuz’s risk profile fundamentally different – and potentially far more severe – than for all other chokepoints.

In addition to the direct rise in fuel consumption and operational expenses, such as additional staffing costs from longer distances and increased insurance premium, chokepoint blockages would also have wider indirect impacts. Longer voyage durations reduce effective global shipping capacity, pushing up freight rates and heightening inflationary pressures. They also increase emissions from the shipping sector and force customers to hold more working capital to absorb potential delivery delays.

Table 6.2 Potential impact of a blockage of maritime shipping at selected chokepoints

Origin-destination pair	Blocked chokepoint	Alternative route	Share of global trade (%), 2023		Impact			Risk profile
			Clean energy technologies	**Fossil fuels**	**Extra distance (km)**	**Extra hours of navigation**	**Extra fuel consumption**	
Shanghai (CHN) to Rotterdam (NDL)	Strait of Malacca	Via Sunda or Lombok Straits	51%	31%	2000	74 hours	+10%	Disruptive but manageable; congestion risks on alternative routes
	Suez Canal/Bab el Mandeb	Via Panama	40%	16%	5300	193 hours	+27%	Severe disruption; industry could adapt but with higher costs and delays
		Via Cape of Good Hope	40%	16%	6700	243 hours	+35%	
Corpus Christi (USA) to Chiba (JPN)	Panama Canal	Via Suez Canal	1.5%	2%	10000	502 hours	+60%	Significant cost and delay impact; drought risk
		Via Cape of Good Hope	1.5%	2%	13000	639 hours	+75%	
	Strait of Hormuz*	N/A	1%	22%	N/A	N/A	-	Extremely high for oil and gas – closure halts all maritime trade from the Persian Gulf

* All routes leaving and entering Persian Gulf.

Notes: N/A = not applicable. Extra hours are considered at the same speed as the base case, which is 11 knots for tanker, used for the Corpus Christi to Chiba case, and 15 knots for container carrier, used for the Shanghai to Rotterdam case. Extra fuel consumption is assumed to be proportional to the extra distance.

References

American Public Power Association. (2023). *Study Highlights Hacker Vulnerabilities Created by Smart Meters*. Retrieved from https://www.publicpower.org/periodical/article/study-highlights-hacker-vulnerabilities-created-smart-meters

AP News. (2018). *Russian hackers used phishing tools in 2017 attack on grid*. Retrieved from https://apnews.com/article/2c17bda4ac704df6be66018197f29912

BCG-SIA. (2024). *Emerging Resilience in the Semiconductor Supply Chain*. Retrieved from https://www.semiconductors.org/wp-content/uploads/2024/05/Report_Emerging-Resilience-in-the-Semiconductor-Supply-Chain.pdf

Benchmark Minerals Intelligence. (2024). *Benchmark Minerals Lithium Ion Battery Gigafactory Assessment*. Retrieved from https://www.benchmarkminerals.com/

BNEF. (2025a). *Data service*. Retrieved from https://about.bnef.com/

Checkpoint. (2026). Cyber Security Report 2026. Retrieved from https://www.checkpoint.com/resources/report/report-cyber-security-report-2026

China, Ministry of Commerce. (2025). *The Ministry of Commerce spokesperson answered reporters' questions regarding adjustments to the Catalogue of Technologies Prohibited and Restricted for Export from China*. Retrieved from https://www.mofcom.gov.cn/syxwfb/art/2025/art_072f1b88bcb4415fae1f05bbd569fd50.html

ChinaIOL. (2025). *Annual ChinaIOL Database on HVAC, Heating, Compressors and Refrigerants*. Retrieved from data.chinaiol.com

CSIS. (2025). *Significant Cyber Incidents Since 2006*. Retrieved from https://csis-website-prod.s3.amazonaws.com/s3fs-public/2025-11/251114_Significant_Cyber_Incidents.pdf?VersionId=GZ0fl_iuR1WJplsXUf9NzVAHHP7KspWy

cybernews. (2023). *Denmark hit with largest cyberattack on record*. Retrieved from https://cybernews.com/news/denmark-cyberattack-energy-infrastructure-sandworm/

Engineering, I. (2025). *Rogue hardware in Chinese inverters could trigger worst blackout threat to date*. Retrieved from https://interestingengineering.com/energy/rogue-hardware-in-chinese-inverters-could-trigger-blackout-threat

EV Volumes. (2025). *Global Electric Vehicle Sales Data, Market Trends & Forecasts You Can Trust*. Retrieved from https://ev-volumes.com/

Finance Colombia. (2022). Retrieved from https://www.financecolombia.com/epm-falls-victim-to-ransomware-attack/

GWEC. (2022). *Global wind gearbox supply chain update.* Brussels: GWEC Market Intelligence.

GWEC. (2024). *Global wind turbine generator supply chain update.* GWEC Market Intelligence.

GWEC. (2025). Generators and gearboxes largest facilities globally.

Help Net Security. (2019). *Ransomware attack leaves Johannesburg residents without electricity*. Retrieved from https://www.helpnetsecurity.com/2019/07/26/ransomware-johannesburg/

IBM. (2025). *Cost of a Data Breach Report 2025: The AI Oversight Gap.* Retrieved from https://www.ibm.com/think/x-force/2025-cost-of-a-data-breach-navigating-ai

IEA. (2023). *Cybersecurity – is the power system lagging behind?* Retrieved from https://www.iea.org/commentaries/cybersecurity-is-the-power-system-lagging-behind

IEA. (2024a). *Advancing Clean Technology Manufacturing*. Retrieved from https://www.iea.org/reports/advancing-clean-technology-manufacturing

IEA. (2024b). *Energy Technology Perspectives 2024.* Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2024

IEA. (2025b). *World Energy Outlook 2025*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2025

IEA. (2025c). *Global Critical Minerals Outlook 2025*. Retrieved from https://www.iea.org/reports/global-critical-minerals-outlook-2025

IEA. (2025d). *Global Hydrogen Review 2025.* Retrieved from https://www.iea.org/reports/global-hydrogen-review-2025

IEA. (2025e). *Hydrogen Production and Infrastructure Projects Database*. Retrieved from https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database

IFR. (2024). *Record 435,000 robots now working in Japan's factories*. Retrieved from https://ifr.org/downloads/press2018/2024-SEP-24_IFR_press_release_World_Robotics_2024_-_Japan.pdf

InfoLink. (2025). *InfoLink Consulting*. Retrieved from https://www.infolink-group.com/

International Monetary Fund. (2024). *IMF PortWatch*. Retrieved from IMF PortWatch: https://portwatch.imf.org/

knowbe4. (2024). *KnowBe4 Report Reveals Critical Infrastructure Under Siege with Cyber Attacks Increasing 30 Percent in One Year*. Retrieved from https://www.knowbe4.com/press/knowbe4-report-reveals-critical-infrastructure-under-siege-with-cyber-attacks-increasing-30-percent-in-one-year

knowbe4. (2025). *Hidden Threats in Our Power Grid: The Chinese Transformer Backdoor Scandal*. Retrieved from https://blog.knowbe4.com/hidden-threats-in-our-power-grid-the-chinese-transformer-backdoor-scandal

MAYA. (2025). *Chinese Inverter Backdoors: A Renewable Energy Cybersecurity Wake-Up Call*. Retrieved from https://www.maya-security.com/post/chinese-inverter-backdoors-a-renewable-energy-cybersecurity-wake-up-call

Meier, R. (2025). COMAC delivers more aircraft and gets closer to Embraer. *ADN*. Retrieved from https://www.airdatanews.com/comac-delivers-more-aircraft-and-gets-closer-to-embraer/

PV Magazine. (2022). *Satellite cyber attack paralyzes 11 GW of German wind turbines*. Retrieved from https://www.pv-magazine.com/2022/03/01/satellite-cyber-attack-paralyzes-11gw-of-german-wind-turbines/

PV Magazine. (2024). *Lithuania bans remote Chinese access to solar, wind, storage devices*. Retrieved from https://www.pv-magazine.com/2024/11/18/lithuania-bans-remote-chinese-access-to-solar-wind-storage-devices/

Reuters. (2025). *Auto companies face shortages due to China's rare earth restrictions*. Retrieved from https://www.reuters.com/business/autos-transportation/auto-companies-face-shortages-due-chinas-rare-earth-restrictions-2025-06-05/

S&P Global. (2025). *Commodity Insights*. Retrieved from https://www.spglobal.com/commodity-insights/en

SecuretheGrid. (2023). Retrieved from U.S. Continues to Import Large Transformers from China in 2023: https://securethegrid.com/u-s-continues-to-import-large-transformers-from-china-in-2023/

US Congress. (2024). Retrieved from Attacks on Ukraine's Electric Grid: Insights for U.S. Infrastructure Security and Resilience: https://www.congress.gov/crs-product/R48067

WindEurope. (2023). *The State of the European Wind Energy Supply Chain*. Retrieved from https://windeurope.org/data/products/the-state-of-the-european-wind-energy-supply-chain/

Chapter 7. Industrial competitiveness

Highlights

- Industrial competitiveness is shaped by a wide set of structural drivers, including the price of labour, energy, capital and raw materials, but also productivity, manufacturing efficiency, infrastructure quality, digitalisation, access to skilled labour and the strength of innovation ecosystems. Stable policies and secure energy systems also underpin competitiveness, by helping firms to commit capital at scale to better technologies and manufacturing plants.
- Energy-intensive industries account for 30% of global manufacturing value added, 70% of industrial energy use and 20% of manufacturing employment. They play a strategic role in providing the inputs for downstream industries, with implications for economic and national security. Yet they are highly vulnerable to volatile energy prices: energy can represent over two-thirds of total production costs.
- Decarbonisation reinforces the importance of access to low-cost clean energy in industry. As industry shifts towards electricity and hydrogen, regions with abundant renewable resources gain competitive advantage. For example, offshoring ironmaking to regions with low-cost renewables – such as Brazil – could significantly narrow cost gaps with conventional production routes, with limited impacts on jobs.
- Input costs vary considerably across countries and regions. Labour costs tend to be lower in emerging economies; in China, labour costs can be five times lower than in Europe or in the United States. Capital costs are typically lower in advanced economies. Regional energy prices also vary substantially, with electricity prices varying by up to a factor of seven across regions, and natural gas varying even more.
- In clean energy technology manufacturing, there is no single factor that explains China’s cost advantage and central position. Structural cost differences, such as energy and labour, account for over two-thirds of the cost gap with Europe in manufacturing steps that are particularly energy- or labour-intensive, such as upstream solar PV manufacturing and wind turbine blade production. Economies of scale are especially important for heat pumps and solar PV, while for batteries over 40% of the cost gap reflects higher manufacturing efficiency in China.
- Countries will need to identify and play to their strengths while establishing strategic partnerships to offset weaknesses in competitiveness. For example, producing solar PV modules in the European Union with imported wafers from North Africa would cost almost 20% less than producing a fully EU-made module.

Drivers of competitiveness

Industrial competitiveness refers to how well a country's industries can produce goods and services that succeed in global and domestic markets. This can be achieved through a superior design, either of a product or a (manufacturing) process, or by producing at lower cost. For standardised products and commodities, competitiveness is largely determined by relative production costs across countries (OECD, 2022a). In open and competitive markets, lower prices of labour, capital, energy and raw materials typically translate into lower costs of production, larger market shares and potentially higher revenues or profits. Productivity and efficiency – that is, how effectively industries convert inputs into outputs – are also central drivers of relative cost performance.

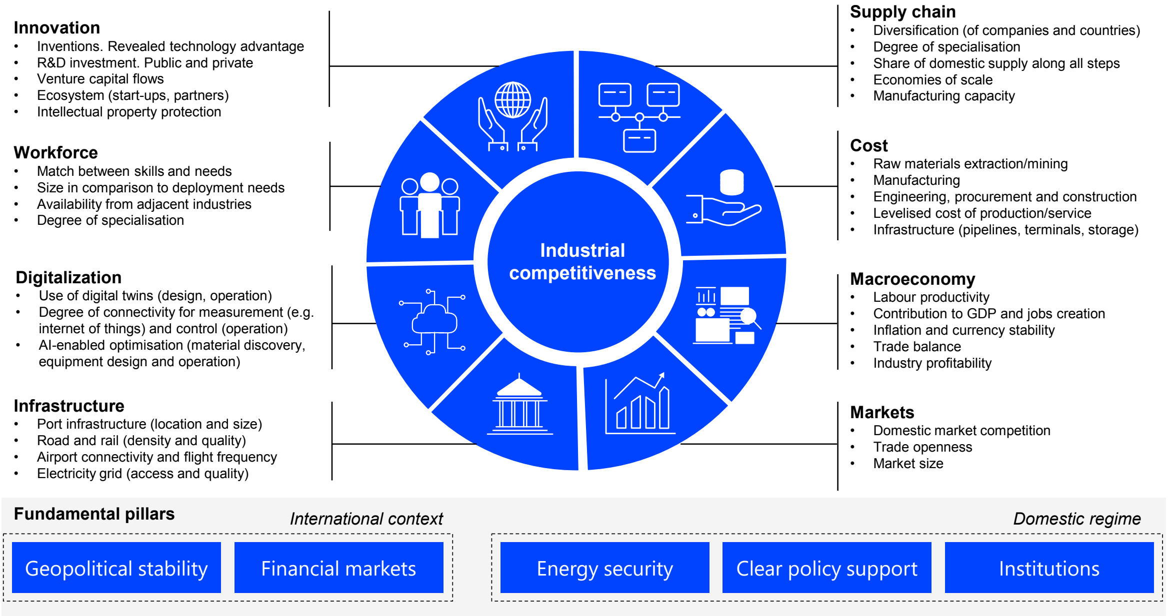
A wide range of other conditions directly or indirectly influence both the cost base and the quality or attractiveness of manufactured goods. These include access to a skilled workforce, adequate and reliable infrastructure, the degree of digitalisation and the presence of an ecosystem that supports incremental and disruptive innovation. Enabling factors such as integrated networks of stakeholders along supply chains, with close interactions to build new capabilities and know-how, as well as access to well-developed and sizeable markets also play a role (Figure 7.1). In addition, collaboration to integrate diverse expertise and functions within and across industries is essential for global competitiveness. Other enabling factors that do not affect cost or quality directly, including public and corporate governance, transparency, institutional quality and political, economic and social stability, also shape the broader environment for industrial competitiveness.

Policy predictability is particularly important; by reducing uncertainty over future cash flows and project risks, a stable and transparent policy environment helps private investors to commit capital at scale. Likewise, a secure energy system – one that provides affordable, stable prices and can withstand unexpected shocks – enhances competitiveness across all sectors. These conditions reflect long-term choices made by governments and industry, and their interplay ultimately determines both national industrial performance and investment decisions.

These factors mean that cost advantages alone are not always sufficient to sustain competitiveness. The evolution of the semiconductor industry provides a clear illustration. North America dominated the sector from the 1950s through the 1970s, while Japan built strong positions in specific components in the early 1980s. At that time, Chinese Taipei had only a nascent industry with limited global presence. In response, its government established the Industrial Technology Research Institute in the 1970s, expanded R&D funding, developed science and software parks and introduced targeted tax incentives and financing mechanisms. These measures supported the creation in the late 1980s of TSMC – the world's leading semiconductor foundry today.

The subsequent expansion of the industry was underpinned by several mutually reinforcing factors: a highly skilled workforce; a tightly integrated network linking universities, research institutes and industry to accelerate innovation, knowledge-sharing and rapid prototyping; strong co-ordination between suppliers and manufacturers supported by a resilient supply chain; and strategic specialisation in specific stages of the manufacturing process. Together, these elements demonstrate how long-term policy consistency, institutional capacity and ecosystem development can secure global competitiveness even in highly capital-intensive, technologically demanding sectors.

Figure 7.1 Factors influencing industrial competitiveness



IEA. CC BY 4.0.

Sources: IEA analysis based on inputs from World Economic Forum (2018); European Commission (2025b); World Bank (2017); and OECD (2022b).

Competitiveness is largely determined by relative prices of inputs to production, but other factors can also have a major impact on the development of a domestic industry.

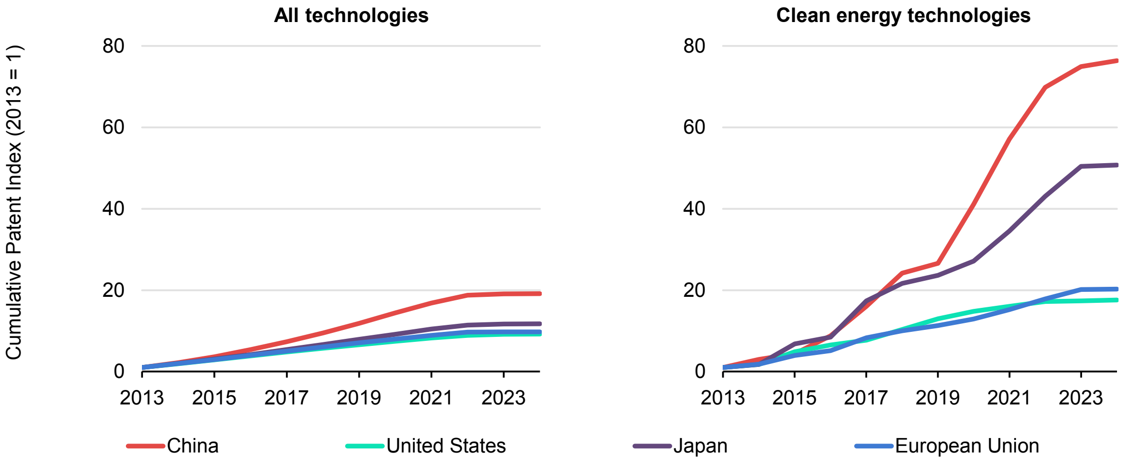
Governments can counter unfavourable competitiveness conditions and encourage firms to locate production facilities within their borders by offering targeted incentives. For example, all OECD member countries employ at least one instrument aimed at attracting or retaining foreign investment. Tax incentives and financial measures remain the most widespread tools, with around three-quarters of OECD countries citing productivity and innovation as the primary objectives of these schemes (OECD, 2024a). The People's Republic of China (hereafter, "China") has likewise drawn on a broad suite of economic incentives to strengthen the competitiveness of its domestic industrial base, including preferential borrowing through state-owned enterprises (OECD, 2024b).

These incentives take a variety of forms. Direct financial support may include capital grants, production-linked subsidies, or temporary assistance with energy and operating costs. Tax measures range from preferential rates to exemptions and credits. Governments also provide support through land, infrastructure and utilities – for example, by offering low-cost industrial sites, building transport and grid connections, or guaranteeing long-term utility contracts at stable prices (OECD, 2019).

Public financing instruments, such as loans, guarantees and co-investment vehicles, can lower investor risk and improve access to capital. Meanwhile, workforce training subsidies, R&D grants and integration into regional innovation ecosystems strengthen the long-term competitiveness of industrial facilities.

Technological innovation also shapes industrial competitiveness. Alongside efficiency gains and economies of scale, innovation remains an important lever for improving product quality and performance, maintaining cost leadership and reducing emissions. Over time, these advantages lead to strong competitive positions. Patent activity provides one tangible measure of an economy's capacity to generate, protect and commercialise intellectual property. Over the past decade, China's share of global patents has increased rapidly, with the number of patents for clean energy rising four times faster than for all technologies combined (Figure 7.2). By contrast, patent growth in the European Union, Japan, and the United States has been slower. Yet, when assessed using metrics that include patent quality characteristics such as originality and scope rather than volume these economies continue to exhibit strong specialisation in several key enabling technologies, including smart grids, that support multiple value chains (IEA, 2024a).

Figure 7.2 Cumulative patents in selected countries and regions, 2013-2024



Note: Index 2013 = 1.
Source: IEA analysis based on European Patent Office's Worldwide Statistical Patent (PATSTAT) database.

China's share of global patents has increased rapidly over the last decade, with the number of patents for clean energy rising four times faster than for all technologies combined.

Variations in input costs

The two primary factors of production in any industry – labour and capital – vary considerably across countries and regions, reflecting differences in economic structure, institutional frameworks and risk profiles. Labour costs refer to the expense of hiring a workforce to operate machines and equipment, while capital costs relate to the expense of raising funds to acquire land, buildings and machinery. Broadly, labour costs tend to be lower in emerging economies, while capital costs are typically lower in advanced economies.

Labour costs in advanced economies are generally much higher – sometimes by a wide margin. Manufacturing workers in Europe or the United States cost roughly 5 times more than their counterparts in China and up to 30 times more than in some emerging markets and developing economies (EMDEs). However, high wages are partly offset by higher productivity. Workers in regions with higher labour costs tend to generate more output, either through better organisation of labour or greater access to capital (i.e. more machinery and equipment per worker). In addition, regions with higher labour costs often employ a greater share of skilled labour, with lower-skill tasks more likely to be automated.

The balance of wages and productivity varies by sector and by region. For example, labour productivity[1] in car manufacturing in 2024 was higher in both the European Union and the United States than in China. By this measure, these regions held a competitive advantage. Yet when labour costs are factored in, the advantage shifts in the opposite direction, illustrating how competitiveness depends on the combined effect of multiple drivers.[2]

The availability of specific skill sets is also a critical factor. While many EMDEs have sufficient machine operators or production engineers for generic manufacturing, they may lack the specialised workforce needed to scale innovative or complex production processes. Countries with diverse industrial bases, producing a wide range of goods, including those not readily available elsewhere, are more likely to cultivate a workforce capable of supporting emerging industries such as clean energy technology manufacturing. In this respect, advanced economies and China retain a notable advantage over most EMDEs.

Capital costs likewise show marked regional differences, though these are less pronounced than labour costs. These differences largely reflect the real or perceived risks of investment: the higher the risk, the higher the rate of return

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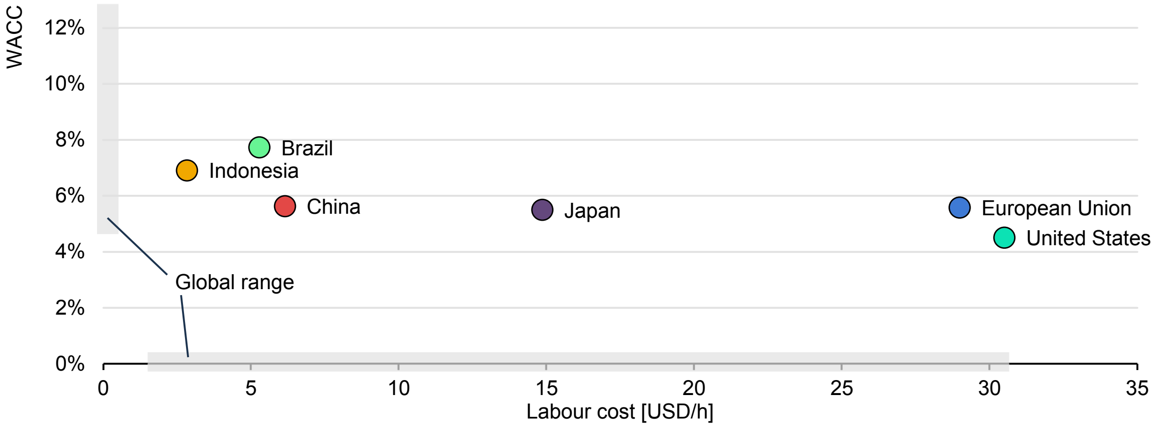
[1] Defined as gross value added (the value of output minus the value of intermediate inputs to production) per worker.

[2] Lower labour costs can be associated with forced labour or other unethical practices; for example, specific forced labour incidents have been reported in China (International Labour Organization, 2025).

demanded by investors. This again gives an advantage to advanced economies and China, where risk perceptions – and, thus, capital costs – are generally lower.

A common metric for comparing capital costs is the weighted average cost of capital (WACC), which reflects the cost of debt and equity financing as well as their relative shares. Together with asset depreciation periods, WACC directly determines the annual contribution of capital costs to levelised production costs. In China, WACC typically ranges between 5% and 6%, compared with above 6% in many EMDEs and sometimes more than 10%.

Figure 7.3 Labour costs and weighted average cost of capital in manufacturing industry for selected regions, 2024



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Note: WACC = weighted average cost of capital.
Source: IEA analysis based on IEA (2025b).

Labour costs vary more across countries and regions than capital costs, with the former generally lower in emerging economies, and the latter lower in advanced economies.

Even small changes in WACC can have a large effect on annualised capital costs. For example, a USD 1 billion investment with a WACC of 5% and a 25-year depreciation period results in annualised capital costs of around USD 70 million. Raising the WACC to 15% more than doubles this figure, to around USD 155 million.

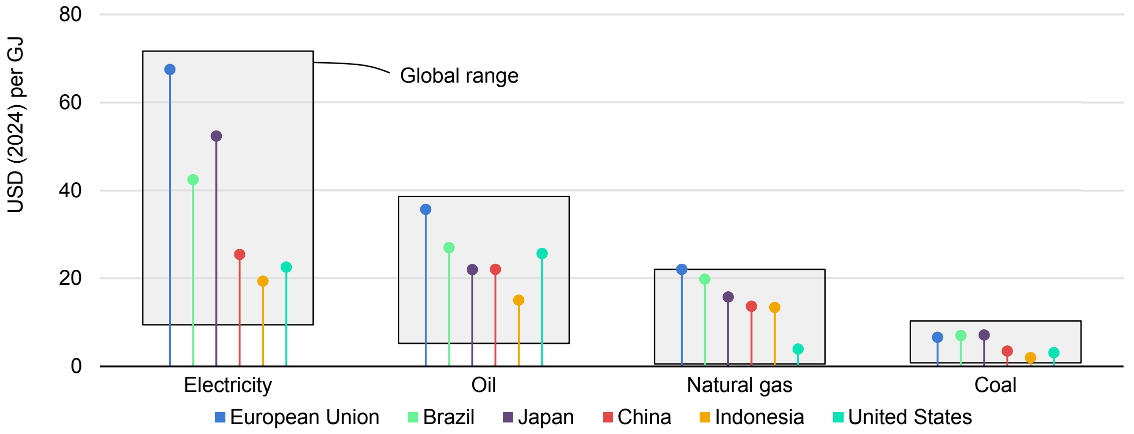
Energy – another important production input – is a major determinant of regional differences in industrial competitiveness. Its significance varies widely by sector. In light industries, energy typically represents only a small share of total production costs. By contrast, in energy-intensive industries, it can dominate: energy accounts for 20-40% of costs in metals production and more than 50% in upstream materials such as polysilicon.

Regional energy prices vary substantially, with little commonality across advanced economies, nor across EMDEs. This reflects the influence of local market conditions and individual government policies. Natural gas and electricity prices show the widest regional variation, as they are strongly shaped by domestic supply and demand. Regions with abundant local gas resources or easy access to pipeline networks generally enjoy lower prices than those reliant on imported liquefied natural gas (LNG). Some of the lowest natural gas prices are found in the United States and the Middle East, while in regions such as the European Union and Brazil prices can be more than five times higher (Figure 7.4).

Electricity prices broadly track natural gas prices, since gas is often the marginal fuel in liberalised power markets. As a result, electricity prices in the highest-cost regions can be up to seven times those in the lowest-cost regions.

Oil and coal prices show less regional variation because they are globally traded commodities. Significant differences can nonetheless arise due to taxation or subsidies. For example, many European countries and India apply excise duties on oil products used in combustion, while such duties are absent in the United States. Conversely, fossil fuel subsidies in many producing countries can make end-user prices significantly lower (OECD, 2024c).

Figure 7.4 Average industrial user energy prices by selected country or region and by fuel, 2024



IEA. CC BY 4.0.

Note: End-user prices include all taxes, subsidies and tariffs.
Source: IEA analysis based on IEA (2025c).

Regional energy prices vary substantially, with gas and electricity prices showing the widest variation, as they are strongly shaped by domestic supply and demand.

Taxes, duties and levies also play a major role in determining the electricity prices faced by industry. In some countries, network charges or the costs of renewable support schemes are directly incorporated into electricity bills, while in others they are funded through general government budgets. These policy choices significantly affect industrial energy costs and therefore competitiveness. For example, in Germany, taxes accounted for 14% of industrial electricity prices in 2024, compared with 1% in Japan.

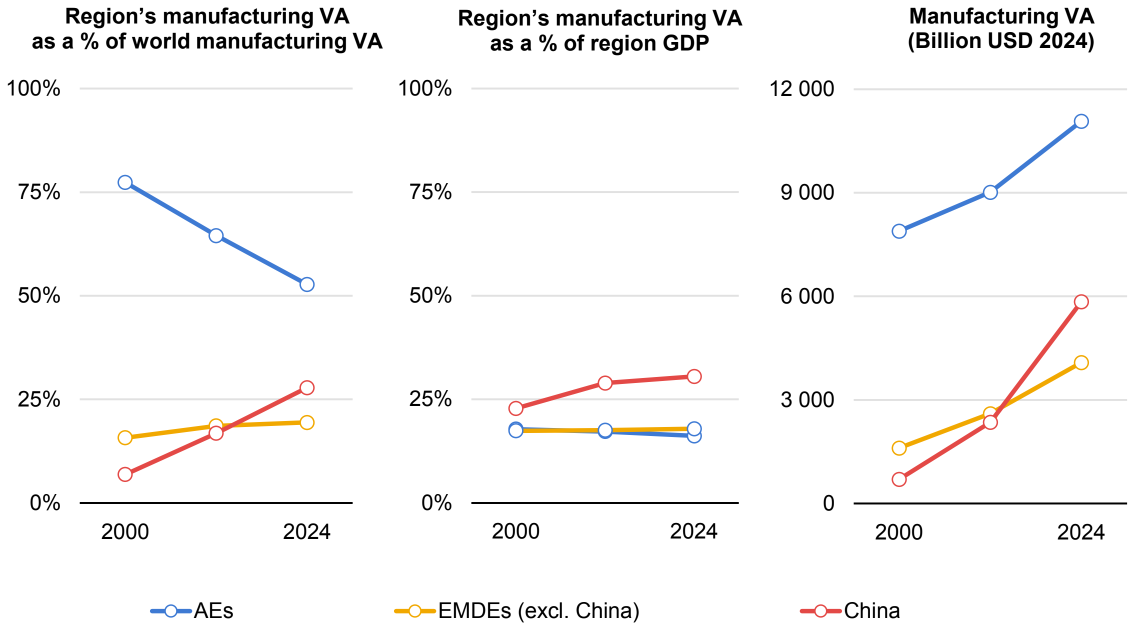
Regional trends in the manufacturing industry

The importance and structure of manufacturing

Manufacturing remains a central pillar of the global economy, and its share of global GDP remained broadly constant from 18% in 2000 to 19% in 2024. Global manufacturing value added doubled in real terms over this period, with more than 70% of the growth coming from China and other EMDEs.

China alone increased its share of global manufacturing value added by around 20 percentage points since 2000, underpinned by rapid industrialisation, large-scale infrastructure investment and technological catch-up. Manufacturing value added as a share of China's own economy also rose, supported more recently by growth in higher-value manufacturing segments. Beyond China, other EMDEs increased their share of global manufacturing value added by around 4 percentage points, benefiting from improvements in technological complexity and sectoral diversification (Figure 7.5).

Figure 7.5 Manufacturing value added by country or country grouping, 2000-2024



Notes: AEs = advanced economies; EMDEs = emerging market and developing economies; VA = value added. Manufacturing VA is based on International Standard Industrial Classification (ISIC) Rev.4 classification. All values are calculated based on constant 2024 dollars.

Source: IEA analysis based on Oxford Economics Limited (2025).

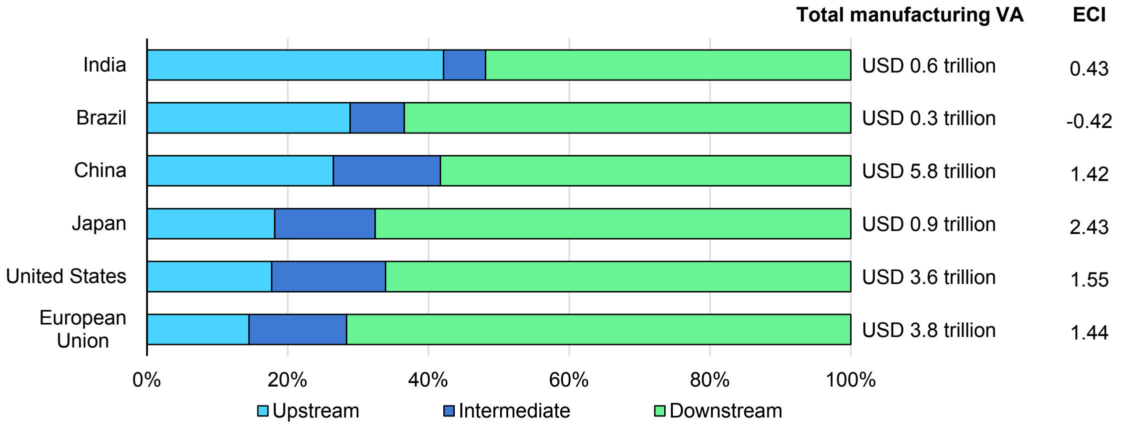
Manufacturing's centre of gravity has been shifting from advanced economies to China since the turn of the century.

In contrast, advanced economies saw their share of global manufacturing value added decline by about 25 percentage points, with manufacturing value added as a share of their total value added falling slightly. This does not necessarily reflect rapid deindustrialisation: on average, their per-capita value added has actually increased, amid a structural shift towards higher-value products.

The structure of manufacturing varies significantly across regions, shaped by the maturity of economies, relative production costs and strategic priorities. Globally, downstream industries account for the bulk of manufacturing value added. This is particularly the case in advanced economies, including Europe, Japan and the United States (Figure 7.6). These regions leverage their established industrial bases and technological capabilities to drive innovation and raise value added. Downstream industries – including electronics, pharmaceuticals and transport equipment – represent more than two-thirds of manufacturing value added.

In China, upstream industrial activities, including steel, cement and aluminium production, and intermediate activities, like metal and plastic manufacturing, remain more prominent, accounting for over 40% of manufacturing value added. While China initially concentrated on expanding capacity in these upstream segments, its industrial strategy has progressively shifted to encompass higher-value downstream sectors. This transition has been particularly notable in sectors with strong growth potential, like semiconductors, electronics and batteries.

Figure 7.6 Breakdown of manufacturing value added and economic complexity index for selected countries/regions, 2024



IEA. CC BY 4.0.

Notes: VA = value added; ECI = economic complexity index. This index ranks countries on a continuous scale based on how diversified and complex their exports are, with the highest ranked country currently at 2.52 and the lowest at -2.47. The ECI shown is an average of the values of each country over the 2021-2023 period. For the European Union, a weighted average was calculated based on the industrial VA of each member country. Upstream industry includes iron and steel, non-ferrous metals, non-metallic minerals, chemicals and paper. Intermediate industry includes wood, plastic, rubber and metal manufacturing. All other manufacturing industries, such as pharmaceuticals, food and beverages, transport equipment and high-tech goods, are included in downstream. The fossil fuel refining sector is excluded.

Sources: IEA analysis based on Oxford Economics Limited (2025) and Growth Lab (2025).

Manufacturing in advanced economies is concentrated in downstream sectors, while India and Brazil focus more on upstream products.

In several EMDEs, the share of upstream sectors in total manufacturing value added has increased significantly in recent years – by around 4-5% since 2010 in countries such as India and Brazil. This reflects ongoing infrastructure build-out, the scaling-up of domestic manufacturing capacity and relatively lower labour and production costs. Advanced economies retain an edge in producing more complex, high-value products. Indicators such as the economic complexity index (ECI), which ranks countries on a continuous scale based on how diversified and complex their exports are, show that countries like Korea, Germany and Japan specialise in sophisticated goods that few others can make (Growth Lab, 2025). China and Viet Nam have also moved rapidly up the complexity ladder: China rose from 30th to 16th in global ECI rankings between 2000 and 2023, while Viet Nam climbed from 86th to 48th, signalling growing productive capabilities and a shift towards more specialised manufacturing.

Industries positioned further down the value chain tend to generate higher value added. Sectors drawing on advanced technologies, strong innovation ecosystems and unique knowledge bases typically capture higher shares of value added because consumers pay a premium for specialised outputs. Upstream industries, by contrast, rely more on standardised technologies and process efficiencies, leading to more commodified products with lower direct value added.

Although upstream industries, which are often highly energy-intensive, generate less direct value added per unit of output, they play a strategic role by supporting activity and value creation in the rest of the economy. Input-output analysis[3] shows how their outputs become essential inputs for other industries: the iron and steel sector is a prime example, driving activity both upstream and downstream. On average, each USD 1 million of steel output enables between approximately USD 0.5 million and USD 1.9 million in total downstream domestic gross output in major economies (Figure 7.7). Multipliers are strongest where downstream industry is large, and supply chains are predominantly domestic — as in China. Most of the induced activity arises in metal fabrication, motor vehicles, and machinery and equipment, where steel is transformed into higher-value products.

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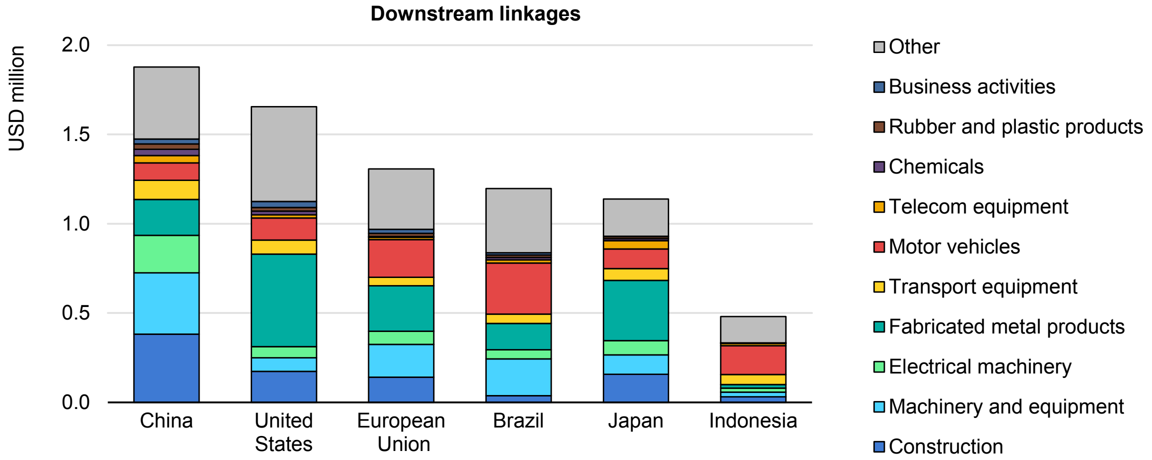
[3] See the Annex for a description of the methodology.

Figure 7.7 **Downstream domestic multipliers for the iron and steel sector in selected countries and regions, 2024**



Notes: The multipliers measure the average domestic output that is generated across downstream industries for each USD 1 million of iron and steel output, once all indirect effects are considered. Only domestic destinations (industries and final demand within the same region) are included. The European Union is treated as one single economy (i.e. any output used everywhere within the European Union is counted as domestic EU use).

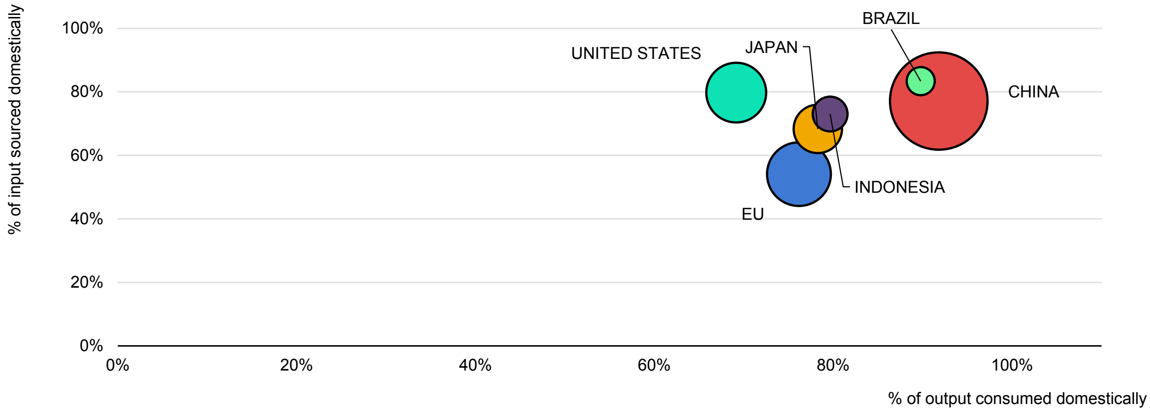
Source: IEA analysis based on EXIOBASE v3.9.4 (Stadler (2025)) – an environmentally extended multi-regional input-output (EE MRIO) table.

Every USD 1 million of iron and steel output produced in advanced economies enables between 1.1 and 1.7 times more domestic output through linkages with downstream sectors.

Differences in downstream linkages and, therefore, multipliers, reflect each country's domestic sourcing and patterns of consumption. They shape resilience, competitiveness and exposure to shocks. Stronger domestic linkages amplify the economic contribution of upstream industries but also mean that disruptions in these sectors can propagate quickly across the economy. This holds for chemicals, petrochemicals, cement, aluminium and pulp and paper, as well as iron and steel. Downstream sectors such as pharmaceuticals or electronics add more value within their own boundaries but have fewer spillovers.

Chemicals and petrochemicals highlight how sourcing structures influence competitiveness. For selected countries and regions, 55-85% of intermediate inputs for that sector are sourced domestically, even in energy-importing economies, partly because refineries supply key inputs despite relying on imported feedstocks. Downstream integration varies as well: in Europe and the United States, chemical products are more export-oriented, whereas in China and Brazil, around 90% of output is consumed locally. More self-contained systems, with strong internal supply chains and limited reliance on imported intermediates, offer insulation from global disruptions but also carry risks. Domestic slowdowns can intensify overcapacity pressures and squeeze margins during economic downturns.

Figure 7.8 Share of intermediate chemicals and petrochemicals sourced and used domestically in selected countries and regions, 2024



Notes: For the European Union, all 27 Member States are treated as a single internal market, with transactions between EU member states counted as 'domestic', with only flows between those countries and the rest of the world treated as external. The size of the bubble indicates the amount of domestic value added by the chemicals and petrochemicals industry in each country.

Source: IEA analysis based on EXIOBASE v3.9.4 (Stadler [2025]).

In most major economies, the bulk of chemical products are consumed domestically, while the extent to which inputs are sourced domestically is more varied.

Competitiveness of established industries

Industrial competitiveness has changed markedly since 2000. Competitiveness has always been a concern for manufacturers, and the growing interconnectedness of the global economy has increased its importance. On a macro level, the size and structure of a country's manufacturing sector provide important signals about its competitiveness. However, they can sometimes be misleading, as they may reflect domestic demand rather than international strength – as has often been the case for China in several sectors. Similarly, high levels of specialisation in niche manufacturing areas can be obscured within broader sectoral categories.[4]

To provide a clearer picture, industrial competitiveness can be assessed using the Revealed Comparative Advantage (RCA) index (United Nations Trade and Development, 2025). This measure evaluates whether a country is more or less specialised in a given sector compared with the world average, based on trade data. An RCA value above 1 indicates a comparative advantage, meaning the

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[4] For example, a broad category such as "machinery", covering diverse products, can potentially mask specific competitive strengths or weaknesses in sub-sectors such as "wind turbines or heat pumps".

sector is more significant in the country's export mix than in global trade overall.[5] Rising RCA values point to a deepening comparative advantage, whether from productivity gains, stronger global demand or successful trade strategies. Falling RCA values suggest relative decline, due to stronger foreign competition, weaker demand, or a deliberate shift towards other sectors. While insightful, RCA is not without limitations: trade data can be shaped by non-tariff barriers, policy distortions and other structural factors.

RCA analysis highlights significant shifts in manufacturing competitiveness across major economies since 2000 (Figure 7.9). The **European Union** retains a strong industrial base, but traditional heavy industries have lost relative ground as they adapt within an increasingly competitive global environment. At the same time, the European Union has preserved its comparative advantage in machinery, while policy initiatives – such as the Net-Zero Industry Act – are stimulating investment in manufacturing capacity for clean energy technologies and their key components. The chemicals sector has seen a relative decline in competitiveness, partly due to high energy costs. Nevertheless, innovation and specialisation have allowed European producers to maintain capacity in high-margin specialty chemicals and expand further in pharmaceuticals.

In the **United States**, industrial competitiveness has fluctuated in recent years, shaped by technological innovation, energy market dynamics and targeted industrial policies. RCA analysis shows that the country has retained a strong comparative advantage in chemicals, supported by sustained investment in petrochemicals and biopharmaceuticals. Innovation capacity, efficient logistics networks and access to affordable energy have reinforced this position.

The shale gas boom significantly reduced domestic energy costs, while infrastructure expansion – including the construction of LNG export terminals – and regulatory changes, such as the repeal of the crude oil export ban in 2015, positioned the United States as a leading exporter of oil and gas, with oil production nearly doubling between 2009 and 2015. This transformation has had far-reaching effects on global supply dynamics.

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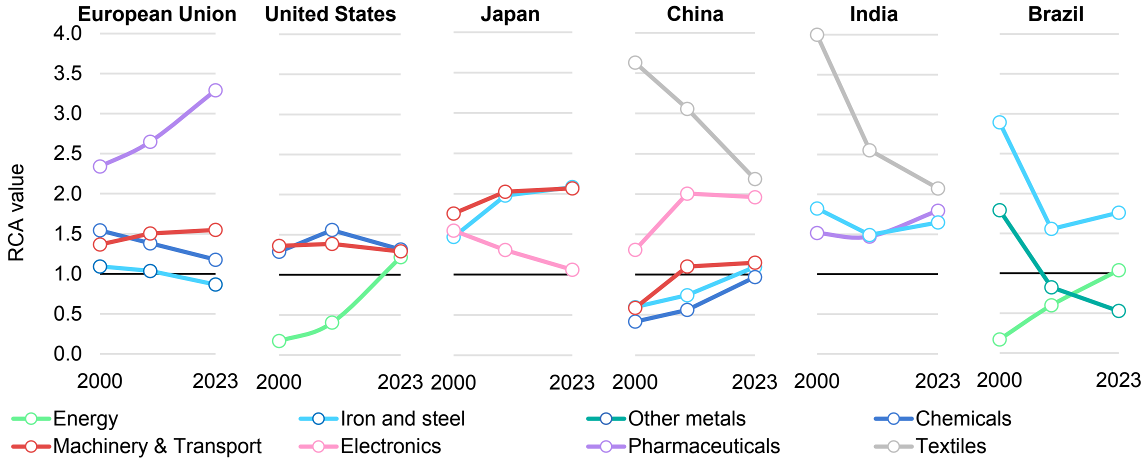
[5] $RCA_{i,j} = \frac{(X_{i,j}/X_{i,total})}{(X_{world,j}/X_{world,total})}$ where, $X_{i,j}$ = exports of product j by country i.

Figure 7.9 Revealed comparative advantage in selected industrial sectors and countries and regions, 2000-2023



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Notes: Revealed comparative advantage (RCA) is an index used to assess a country's relative advantage or disadvantage in exporting a particular good or sector, based on actual trade data. A high RCA means the sector is more important in the country's export mix compared with the global average. Energy includes both fossil and non-fossil fuels. Not all eight sectors are displayed for each region in order to highlight key trends.

Source: IEA analysis based on CEPII (2025).

Advanced economies tend to have a comparative advantage in high-tech products, though China is also becoming more competitive for these products.

In parallel, strong private investment and supportive policy measures have sustained competitiveness in high-value manufacturing. Companies such as Tesla and Boeing illustrate the depth of private-sector innovation, while initiatives such as the CHIPS and Science Act have channelled public resources into semiconductors, aerospace and defence supply chains. These combined efforts have helped the United States retain leadership in key segments of advanced manufacturing, including automotive and high-tech equipment.

Japan maintains industrial competitiveness by concentrating on a set of high-technology sectors – notably automotive manufacturing, robotics and high-precision industrial machinery. The electronics sector retains a comparative advantage despite declines in RCA, and for machinery and transport the indicator confirms a sustained comparative advantage, reflecting long-term specialisation. Co-ordinated policies, including the Green Innovation Fund, alongside instruments such as standards-setting and regional clustering, have enabled Japanese firms to steadily move up the value chain (New Energy and Industrial Technology Development Organization, 2024). The result is a durable edge in specialised segments where quality, precision and reliability underpin export demand.

China’s manufacturing competitiveness has undergone a marked transformation. Between 2000 and 2010, the country consolidated its role as the global hub for mass production, with a sharp rise in RCA in machinery and transport equipment exports, supported by heavy investment. At the same time, RCA in low-complexity sectors such as textiles declined, reflecting the evolution of a maturing economy. Today, China continues to strengthen its comparative advantage in machinery while low-value manufacturing, such as textiles, continues to lose ground. Strong RCA gains in electric vehicles (EVs) and exports of renewable energy technologies illustrate its shift towards high-value growth sectors.

Heavy industries, although vast in scale, are largely driven by domestic demand and less visible in RCA export metrics, particularly for industries with national production caps or capacity restrictions. Government policies reinforce this shift by encouraging downstream processing and domestic supply stability, for instance, through high export duties on unwrought aluminium and the removal of tax rebates on exports of semi-finished aluminium products. Together, these measures highlight China’s deliberate repositioning towards more complex, higher-value manufacturing.

India’s manufacturing competitiveness remains anchored in textiles and other light industries, which still dominate its export profile. RCA measures confirm these traditional strengths, but recent trends highlight gradual industrial upgrading. Growing capabilities in automobile assembly and pharmaceuticals are emerging as pillars of comparative advantage, supported by policy initiatives such as Make in India, which encourage dedicated investment in manufacturing. Structural barriers, including infrastructure bottlenecks and high logistics costs, continue to weigh on capital-intensive sectors, but the overall trajectory points to an incremental broadening of India’s industrial base.

Brazil is becoming increasingly competitive in energy and mining, with rising RCA driven by abundant natural resources, strategic investment and robust global demand. By contrast, its comparative advantage in heavy industry has declined, constrained by international competition, infrastructure gaps and limited technological progress. National policies now classify strategic minerals as a matter of “sovereignty”, aiming to limit raw material exports and promote greater domestic value addition. Its resource endowment positions Brazil as a highly competitive player in energy and resource-based industries, despite the recent weakening of traditional heavy industry.

Energy-intensive industries

Energy-intensive industries[6] matter far beyond their direct share of value added or jobs. They account for around 30% of global manufacturing value added and 20% of manufacturing employment, yet are seen as strategic by governments because they provide the foundational inputs for downstream manufacturing industries. Steel, cement, aluminium and primary chemicals are embedded in everything from cars and pharmaceuticals to aircraft and infrastructure. This creates highly interdependent ecosystems: for example, just-in-time vehicle production relies on stable supplies of steel and alloys, and secure food supply relies on fertiliser availability. However, these industries are particularly vulnerable to international competition as most of their products can be easily traded.

Losing domestic capacity in such sectors carries high risks. Once closed, facilities can be extremely difficult to bring back online or rebuild, making supply chains more fragile in times of crisis. Energy-intensive industries also underpin defence and critical infrastructure, making them important for national security. They account for about 70% of global industrial energy demand (and more than 80% of industrial CO_2 emissions), reflecting their bulk-material nature and the large weight of energy in their cost structure.

Energy costs are a major determinant of competitiveness in these industries. In some processes, such as ammonia production, energy can represent more than 60% of direct manufacturing costs. Methanol production is even more exposed, with energy accounting for roughly 90% of overall costs. As a result, these industries are structurally more exposed to energy price volatility than other sectors of the economy, for which direct energy inputs typically account for less than 3% of their total output value (Figure 7.10). A relatively small change in energy prices can wipe out already thin margins, particularly in globally traded commodities where prices are set by international benchmarks. For example, a primary aluminium producer with energy costs making up 30% of total production costs and operating at a 10% profit margin would lose all profitability if energy prices were to rise by around 35%.

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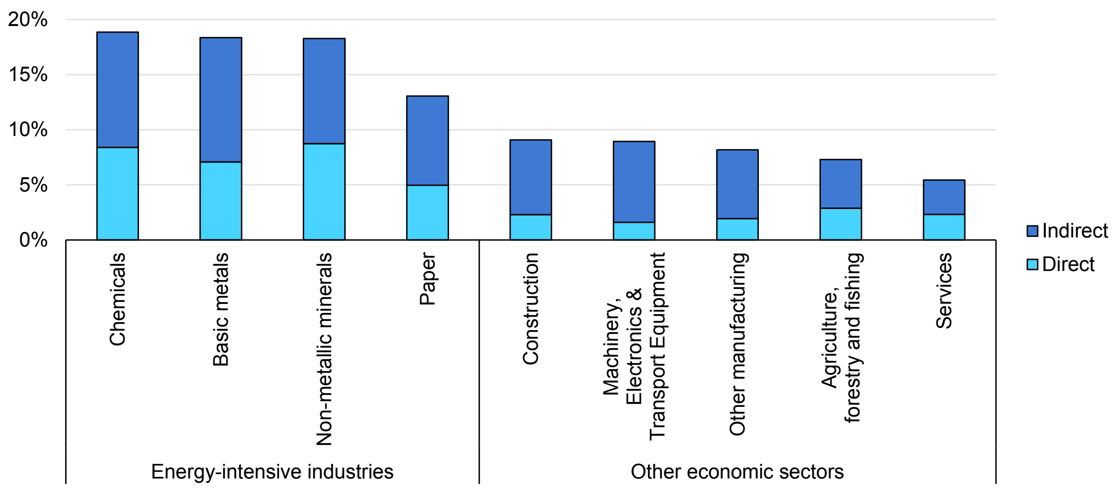
[6] Energy intensive industries refer to Iron and steel [ISIC Rev. 4 Group 241 and Class 2431], Chemicals and petrochemicals [ISIC Rev. 4 Divisions 20 and 21], Non-ferrous metals [ISIC Rev. 4 Group 242 and Class 2432], Non-metallic minerals [ISIC Rev. 4 Division 23] and Paper, pulp and print [ISIC Rev. 4 Divisions 17 and 18].

Figure 7.10 Cost of energy inputs as a share of the value of global industrial output by sector, 2022



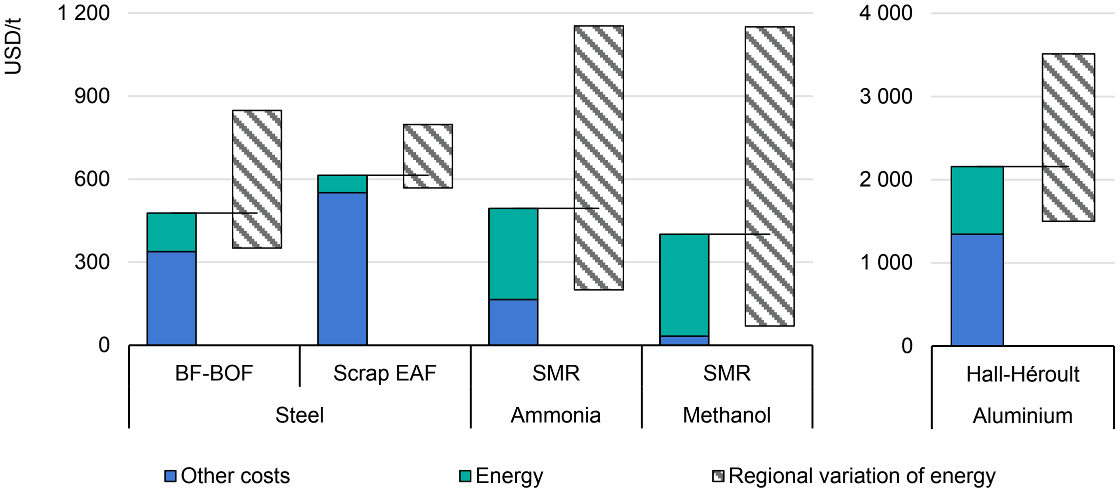
Notes: Direct refers to the cost of the energy directly used by companies in the sector; indirect refers to the cost of the energy used to manufacture non-energy intermediates which are inputs for companies in the sector. Energy refers to coke and refined petroleum products and electricity, gas, steam and air conditioning.

Source: IEA analysis based on European Commission (2025a).

Energy-intensive industries are structurally far more exposed to energy price volatility than other sectors of the economy.

Energy costs vary widely across regions once taxes, subsidies, transport and infrastructure are taken into account. In the global steel sector, coal prices can differ by a factor of around seven, electricity by a factor of eight and natural gas by as much as twenty (Figure 7.11). Price volatility also varies greatly: coal is generally the least volatile, while electricity prices fluctuate the most. As a result, coal-based production routes are relatively insulated from short-term energy price swings, whereas natural gas- and electricity-based routes face much higher exposure.

Figure 7.11 Average global levelised cost of selected materials and energy related regional variation, 2024



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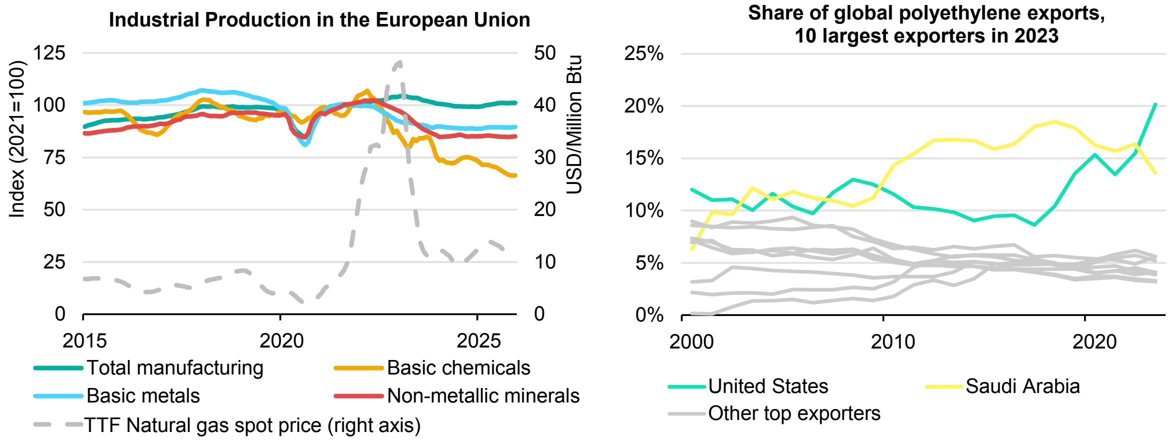
Notes: BF-BOF = blast furnace-basic oxygen furnace; EAF = electric arc furnace; SMR = steam methane reforming. Other costs include capital expenditure (CAPEX), operating expenditure (OPEX) and material costs. Energy includes fuels consumed for energy and feedstock purposes. Regional variation reflects only differences in fuel price and energy intensity. Fuel prices ranges are USD 1.5-10/GJ for coal, USD 1-20/GJ for natural gas and USD 35-260/MWh for electricity (USD 5-100/MWh for aluminium smelting). CO_2 pricing and subsidies are not considered. For steel, BF-BOF assumes no scrap input.

Regional differences in energy price play a key role in determining the cost-competitiveness of the leading bulk materials.

This exposure was laid bare during the 2022 energy crisis in Europe. While overall manufacturing held steady, energy-intensive industries contracted sharply (Figure 7.12). Basic chemicals output fell by more than 30%, ammonia production by one-third and in 2023 naphtha consumption dropped to its lowest level since 1975 (Bloomberg, 2023). Several steam crackers in the Netherlands (Argus, 2024b), France (ICIS, 2024), Italy (Tullo, 2024) and Germany (Argus, 2024a) have since closed or are set to close under pressure from both energy costs and competition from China and the United States, where large new capacity has come online. The European Union also lost almost 50% of its primary aluminium capacity due to the energy crisis (European Aluminium, 2025).

Figure 7.12 Industrial production indices and energy costs in the European Union, 2015-2025 and polyethylene export market shares by country, 2000-2025



Notes: TTF = Title Transfer Facility; Left-hand chart shows six-month rolling average.
Sources: European Commission (2025c); Argus (2025); and CEPII (2025).

EU energy-intensive manufacturing output slumped in the wake of the 2022 energy crisis, while US exports of polyethylene soared, thanks to its access to cheap ethane resources.

By contrast, US petrochemical producers have benefited from cheap shale gas. Abundant low-cost ethane, produced in association with shale gas, has led to a doubling of the US share of global polyethylene exports over the past decade. Ethane itself has become a major export, rising from less than 50 000 barrels per day (kb/d) in 2014 to 500 kb/d in 2024 (US Energy Information Administration, 2025), with China the leading buyer. Similar dynamics have played out in the Middle East. Strong aluminium export growth has been supported by limited domestic demand and substantial new capacity made viable by low-cost electricity, enabling producers in the region to compete effectively in global markets.

The link between energy prices and competitiveness is set to strengthen as decarbonisation efforts in different countries reshape industrial energy systems. Because electricity and emerging energy carriers such as hydrogen are harder and more expensive to transport than fossil fuels, the geography of energy-intensive production is likely to shift. Proximity to abundant, low-cost clean power will increasingly influence where industries choose to locate, as energy spending could be several times higher with near-zero emissions technologies.

Aluminium already shows how cheap electricity shapes global production patterns. Primary smelting – one of the most electricity-intensive industrial processes – has historically been concentrated in regions with inexpensive, often stranded hydropower, such as Iceland, Norway and Canada. These locations developed competitive smelting industries precisely because surplus power could not be easily moved to other demand centres. Although rapid growth in Chinese smelting based on captive coal-fired power loosened this relationship in the 2000s, the trend is now reversing: hydropower is regaining importance, and some producers are exploring solar and wind power for future operations (International Aluminium Institute, 2025) (Rio Tinto, 2024).

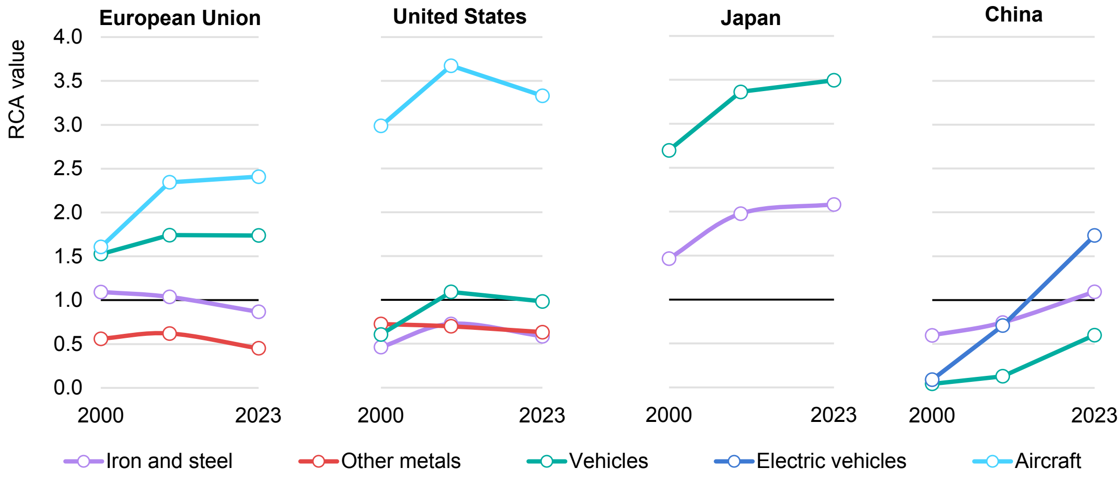
The shift to low-emissions production technologies will reinforce this clustering effect. As industries adopt electricity- or hydrogen-based processes, the share of energy in total production costs may rise, making access to cheap clean power even more critical. This could create patterns similar to those seen in aluminium, with competitive advantage concentrated in regions rich in solar, wind, hydropower or other low-emissions resources, potentially reshaping global supply chains.

Nevertheless, energy-intensive manufacturing can remain competitive even in countries with relatively high energy prices when it is anchored by strong downstream ecosystems, such as vehicle manufacturing and the aerospace sector. This helps explain why the European Union and Japan continue to play a significant role in global steel production despite elevated energy costs, accounting for 7% and 4% of world output respectively (Table 7.1). Japan, in particular, is a major exporter, accounting for about 10% of global steel exports.

Despite energy cost disadvantages, close integration with export-oriented end-use sectors provides important advantages for material producing industries. This is reflected in an RCA of about 3.5 for Japan’s vehicle industry and 1.7 for that of the European Union. The United States does not register a comparative advantage in steel, aluminium and other metal exports, but still produces 4% of global steel and 5% of global aluminium. This is sustained by efficient scrap usage, supportive trade policies and demand from competitive downstream sectors such as automotive and aerospace, where the United States has an RCA of 3.3 (Figure 7.13).

China is the key player in global steel, producing more than half of the world’s total, of which most is consumed domestically. As domestic demand has begun to ease, exports have risen sharply, reflecting China’s increasing comparative advantage. RCA analysis shows that its competitive position in steel has strengthened steadily, particularly in flat products, which generally carry higher value. More recently, China has built new strengths in EVs. What began as a domestic-oriented industry has now become a fast-growing source of exports, reshaping its industrial profile.

Figure 7.13 Revealed comparative advantage in selected industries and countries and regions, 2000-2023



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Notes: Revealed comparative advantage (RCA) is an index to assess a country's relative advantage or disadvantage in exporting a particular good or sector, based on actual trade data. A high RCA means the sector is more important in the country's export mix compared with the global average.

Source: IEA analysis based on CEPII (2025).

Even where heavy industry is becoming less competitive, supply chain integration with downstream sectors gives domestic production some important advantages.

Focus on the steel industry

Crude steel production remains one of the most energy-intensive industries, with energy and raw materials making up more than two-thirds of production costs. The availability and price of coal, natural gas, electricity, iron ore and scrap are therefore decisive for cost-competitiveness.

Today, around 90% of global ironmaking uses the blast furnace (BF) route, which mostly uses coal. This route dominates in most countries, including in China, which is by far the largest iron and steel producer (Table 7.1). Less than 10% of iron is made via the direct reduction process. Production of direct reduced iron (DRI) is concentrated where natural gas is abundant and cheap: the largest DRI producers are in the Middle East (36% of global production), North Africa (9%) and North America (9%). India (37%) is an exception, where most of the DRI production is based on cheap domestic coal.

Making iron is by far the most energy-intensive step in steel production. Steel scrap, when available, can substitute iron demand. Where end-of-life steel stocks are significant and electricity is affordable, scrap-based steelmaking in electric arc furnaces (EAFs) is highly competitive. The United States (64% scrap share in metallic inputs) and European Union (51%) rely far more on scrap-based production than China (24%) or India (20%), reflecting their mature economies with greater stocks of steel in use.

Table 7. 1 Steel production and trade by region and by route, 2024

Region	Share of global crude steel production	Share of DRI based iron	Share of scrap input	Share of global steel export
China	53%	0%	24%	28%
India	8%	37%	20%	3%
European Union	7%	0%	51%	14%
Japan	4%	0%	37%	10%
United States	4%	20%	64%	3%
Eurasia	4%	12%	33%	6%
Korea	3%	0%	39%	8%
Middle East	3%	93%	17%	4%
Central and South America	2%	9%	43%	2%

Notes: DRI = Direct Reduced Iron. The DRI share is calculated for total iron production. The share of scrap considers all inputs and not just for electric arc furnaces. The share of global exports is based on 2023 data and is calculated using data for semi-finished and finished steel products. Trade within each region is excluded.

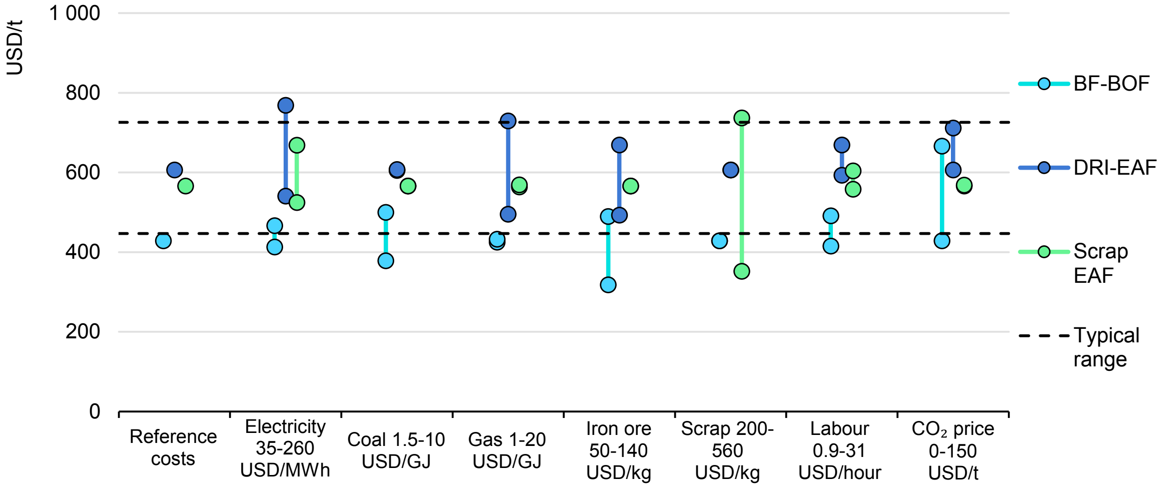
Sources: World Steel Association (2025); and CEPII (2025).

Labour costs vary as much as energy across regions, but this matters less because wages are a relatively small part of steel production costs. Raw material costs show smaller regional differences, though transport can be significant; for example, shipping iron ore from Australia to China can add up to 20% to delivered costs. Specialty alloys such as nickel in stainless steel can also heavily influence costs.

Energy efficiency is another critical factor affecting cost-competitiveness. Plant age, the extent of modernisation, the adoption of best operational practices and the quality of raw material inputs all influence overall performance. Given long investment cycles, major refurbishment projects provide key opportunities to raise efficiency levels.

The levelised cost of producing steel varies widely worldwide (Figure 7.14). Carbon pricing further impacts competitiveness. BF-BOF plants, with high coal reliance, are most exposed, while scrap-based production is largely unaffected. Higher-cost producers can compete in niche high-quality segments or regional markets, but fundamental energy economics remain hard to escape, especially in the context of global overcapacity.

Figure 7.14 Levelised cost of steel production for conventional production routes according to energy, labour, material and carbon prices, 2024



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Notes: BF-BOF = blast furnace-basic oxygen furnace; DRI = direct reduced iron; EAF = electric arc furnace. The levelised cost of production is the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Energy price ranges are based on those prevailing in 2024. Material input prices vary over time according to market conditions – the range represents price variations over the past decade. The typical cost range represents steel price variations over the past decade. Labour costs represent the range of typical hourly wage rates per tonne of steel in 2024. Input values to reference costs are approximations of global median values: USD 100/MWh for electricity, USD 5/GJ for coal, USD 10/GJ for natural gas, USD 108/t for iron ore, USD 400/t for scrap, USD 6/hour for labour and USD 0/t for CO_2.

Sources: IEA analysis based on World Steel Association (2025) and BNEF (2025b).

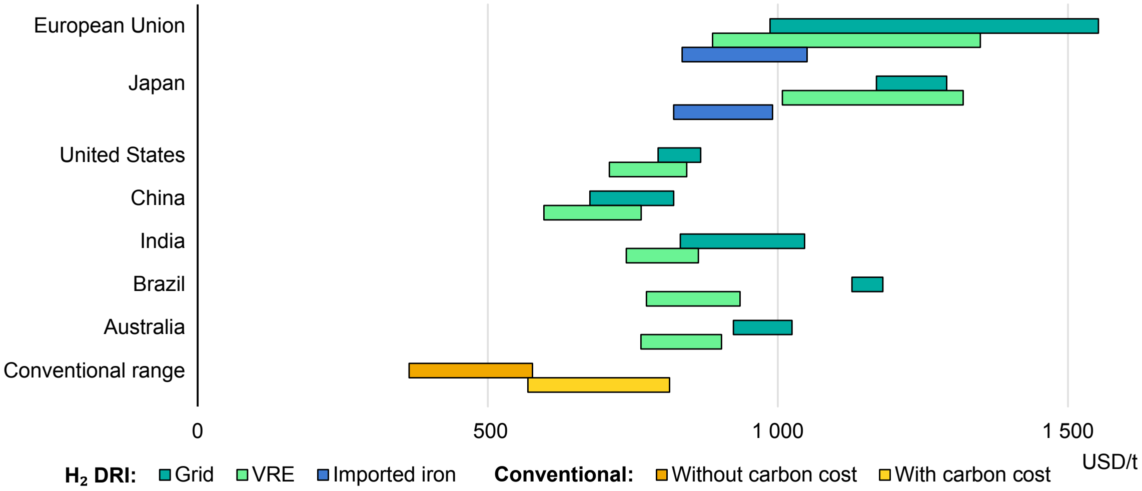
Steel production costs vary significantly across the world, mainly according to differences in production routes and energy input costs.

Among energy-intensive industries, the steel sector has become a decarbonisation focus in many countries, supported by recent progress in developing near-zero emissions technologies. Nonetheless, commercialisation of key near-zero emissions steelmaking routes remains at an early stage. Projects currently in the pipeline amount to around 10 Mt of capacity and an additional 105 Mt of *near-zero emissions capable* capacity. Competitiveness remains a critical concern; for near-zero emission routes, this depends even more heavily on access to cheap low-emissions electricity than for conventional steelmaking.

The most promising route – hydrogen-based DRI with EAFs – requires high-grade iron ore and very large supplies of affordable low-carbon electricity. Locations with abundant low-cost hydropower, solar, or wind could make hydrogen-based steelmaking cost-competitive with conventional technologies, especially under scenarios with higher carbon costs. Such favourable locations exist in countries including Australia, Brazil, China, India and the United States. By contrast, more limited renewable resources and high grid electricity prices in industrial areas in regions like Japan and the European Union mean that production costs for this route can be 50-80% higher than elsewhere, well above regional differences for conventional steel production today (around 25-50%). In fact, these higher costs have been cited as a major factor behind the recent delay, indefinite suspension, or cancellation of over 15 Mt of hydrogen-based DRI projects.

Governments can influence industrial electricity prices through taxation, levies, permitting and infrastructure planning. Yet closing the gap with regions rich in abundant high-quality renewable resources could require substantial public financial support. One possible solution is offshoring a portion of the ironmaking step to regions with competitive renewable energy resources like Africa, Latin America or Southeast Asia, and importing DRI for local steelmaking. This could narrow cost differences back down to 30-40% (Figure 7.15).

Figure 7.15 Levelised cost of steel production via hydrogen-based direct reduced iron in the Stated Policies Scenario, 2035



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Notes: H_2 DRI = hydrogen-based direct reduced iron; VRE = variable renewable electricity. The levelised cost of production is the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Grid uses the industrial end-user range of grid electricity for industry in 2024. VRE uses the price range of electricity produced from variable renewables plus the cost of hydrogen storage required to guarantee a minimum load of 80%. The range for imported iron assumes the iron is produced in a region with lower energy price (Brazil for the European Union and Australia for Japan) and imported to produce steel locally. The conventional range gives the cost of unabated conventional primary production of steel with unabated fossil fuels (blast furnace-basic oxygen furnace and DRI-electric arc furnace), with or without carbon pricing, at a value of USD 150/tonne of CO_2.

Dedicated renewable generation can considerably reduce hydrogen-based DRI production costs, while the European Union and Japan could import iron to improve competitiveness.

While offshoring ironmaking could shift part of the value chain abroad, it could help prevent the erosion of domestic steel production by addressing the problem of cost-competitiveness in the most energy-intensive steps. Early, proactive policy could safeguard the 75-90% of direct jobs in steelmaking and finishing (Bataille, et al., 2025) (RMI, 2024) (Agora Industry, 2023) and preserve the benefits that stem from close integration with downstream steel-consuming industries in the region (Agora Industry, 2025). Shifting from imports of iron ore to imports of iron would introduce new dependencies and potential risks, but precedents for such trade arrangements already exist. Notable examples include agreements between Namibia and Germany (Green Hydrogen Innovation Centre, 2024), Oman and Viet Nam (Hydrogen Europe, 2025), and Australia and China (Brown, 2025).

Carbon capture and storage could extend the competitiveness of existing BF-BOF and gas-DRI assets faced with the need to decarbonise, though it adds 30-55% to capital costs and remains dependent on low-cost energy. Proximity to CO_2 storage sites and clustering with other industries could make this option more viable. In the longer term, other more competitive technology options, such as molten oxide electrolysis, could emerge.

Demand for near-zero emissions steel remains modest but is growing, though greater certainty on climate policies is needed to build market confidence (see Chapter 2). Several major steel-consuming sectors – notably the automotive industry – are facing pressure from shareholders and consumers to decarbonise their value chains. This is creating early demand for near-zero emissions steel. High value-add sectors are among the most capable of absorbing the higher costs of steel in final products.

Voluntary labels for near-zero and low-emission steel are one option to stimulate demand. Certification and labelling initiatives are only just beginning to emerge (Responsible Steel, 2024) (LESS, 2025), yet their potential coverage could reach up to 72% of global production. In parallel, initiatives such as the First Mover Coalition (World Economic Forum, 2025), SteelZero (Climate Group, 2025) and the Industrial Deep Decarbonisation Initiative (IDDI, 2025) are helping to build a customer base. For example, GE Vernova has committed to purchasing near-zero emissions steel for its operations in the United States (SSAB, 2025).

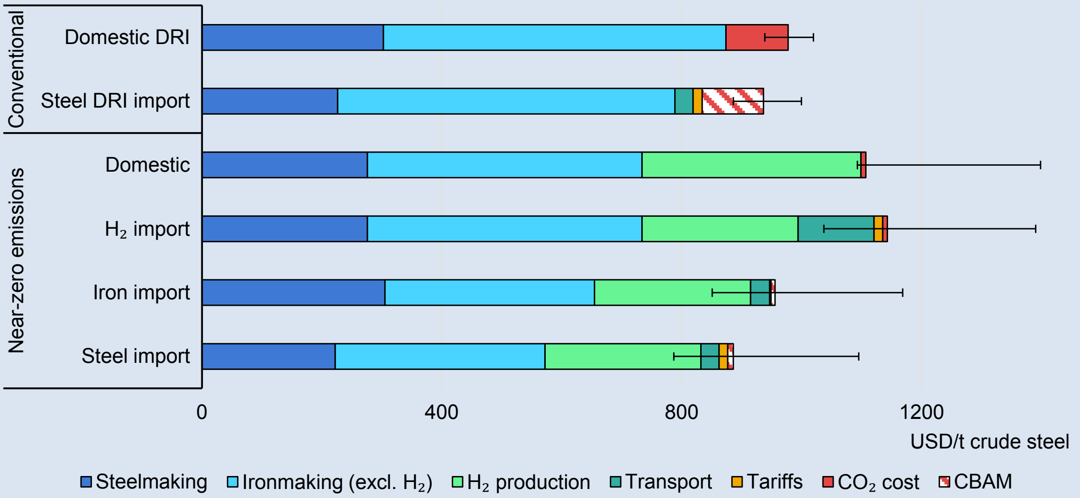
Companies able to move early may benefit from initial “green premiums” and secure strong positions in what could become a rapidly growing near-zero emissions steel market (see Chapter 2). Carbon border adjustments mechanisms, which aim to price the carbon embedded in imported goods, may also bolster the competitiveness of near-zero emissions steel (Box 7.1), though practical difficulties in implementing them might hinder their effectiveness.

Box 7.1 The EU Carbon Border Adjustment Mechanism (CBAM)

CBAMs add a cost to carbon-intensive imports, making lower-carbon domestic production more competitive and encouraging producers abroad to reduce emissions. The European Union became the first jurisdiction to establish a CBAM, which is scheduled to come into force in 2026, after a transitional phase from 2023. The mechanism seeks to confirm a price has been paid for the embedded carbon emissions generated in the production of imports into the region and to ensure the carbon price of imports is equivalent to that incurred by EU domestic production. It eventually aims to cover more than 50% of the emissions covered in the EU Emissions Trading Scheme (ETS).

This scheme is expected to have a significant impact on the cost-competitiveness of EU steel production. For example, conventional steel produced in the European Union is projected to cost around USD 980/t in 2035 in the Stated Policies Scenario (STEPS), compared with import costs of USD 940/t (Figure 7.16). The CBAM increases costs by USD 100/t, which – added to tariffs – would help EU steel producers to compete.

Figure 7.16 Levelised cost of production of steel in the European Union and cost of imports from Brazil in the Stated Policies Scenario, 2035



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Notes: H_2 = hydrogen; CBAM = Carbon Border Adjustment Mechanism. Direct policy costs outside of the EU Emissions Trading Scheme (ETS) and CBAM are excluded from this analysis but import tariffs are included. Domestic refers to production in western Europe. Imports are 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, 100% primary production is assumed. 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 hydrogen costs for different locations in each region for the near-zero emissions route (95%-175% for the European Union and 65%-175% for Brazil), and variations of natural gas and electricity prices over the period 2015-2020 (natural gas: 85%-120% for the European Union and 85%-125% for Brazil; electricity: 95%-105% for the European Union and 95%-105% for Brazil). The cost of CO_2 is assumed to be USD 150/t.

The CBAM and EU ETS are not expected to have a significant impact on near-zero emissions production. Costs for producers that move to hydrogen-based DRI remain high, at USD 1 100/t, in the same scenario, but importing DRI from low-cost producing regions (e.g. Brazil) and finishing it domestically could bring EU costs close to parity with conventional domestic production while preserving most jobs and value added in the sector. In contrast, importing hydrogen is not competitive. Near-zero emissions steel (imported or made domestically with imported iron) also achieves cost parity with conventional steel imports as a result of CBAM costs.

It is important to remember that steel production costs represent only a small share of most end-products. For example, using near-zero emissions steel and cement would increase the cost of building a house by around 2% and that of making a car by 1%. However, steel remains an important cost driver in some other sectors, such as wind turbines. As a result, any increase in the cost of steel associated with the transition to near-zero emissions production would likely have only a small impact on the final price of consumer products. For regions with limited access to low-cost clean energy, establishing a competitive near-zero emission steel sector will require governments to adopt targeted long-term policy support and the industry to build robust supply chains in partnership with other countries (see Chapter 8).

Competitiveness of clean energy technologies

Understanding the manufacturing cost gap

The rapid deployment of clean energy technologies worldwide is generating major economic opportunities in manufacturing them. Capturing these opportunities has become a strategic priority for many governments and industries. At the same time, the high level of concentration of clean energy technology supply chains is prompting governments to explore ways of mitigating associated risks. A growing number of countries have announced industrial strategies aimed at developing domestic manufacturing capacity for clean technologies and their components, though in several cases these plans remain aspirational and are not yet backed by firm policy commitments (See Table 4.1).

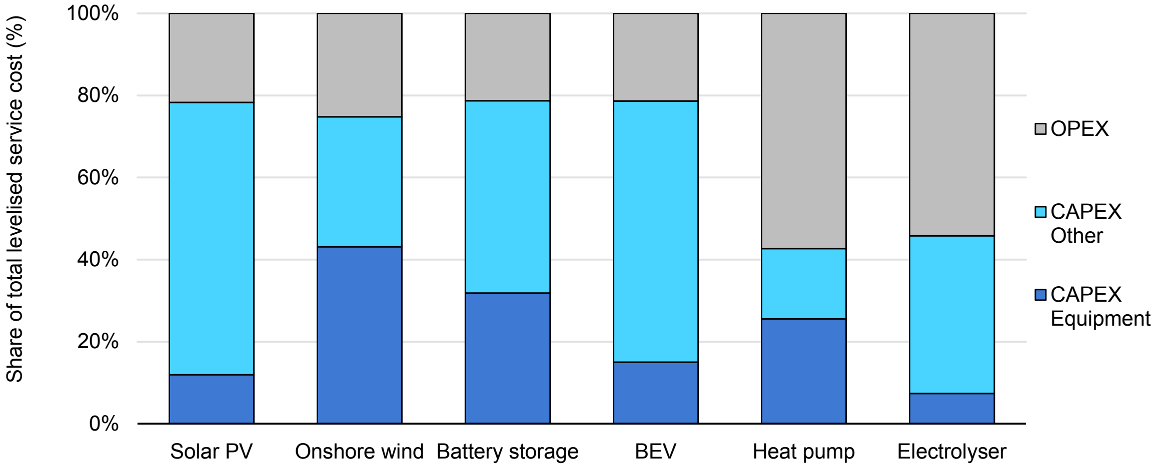
Competition is particularly intense with companies located in China – the global leader in clean energy technology manufacturing – and in a small number of other countries that have established strong positions in specific segments. Not all facilities in China are Chinese owned; some are operated by international companies with long-lasting experience in these industries. China's broader competitive position reflects sustained advantages built up over many years, including continuous technological innovation, large-scale investment, a skilled workforce, well-integrated supply chains and natural endowments such as resource availability and low-cost labour. Many of these strengths were achieved through a long-term industrial policy that combined direct government support with intense competition among domestic manufacturers, driving consolidation and the emergence of a small number of highly successful firms. Achieving success in other regions will depend on narrowing this competitiveness gap, both by reducing production costs and improving overall investment conditions for clean energy manufacturing.

As in other manufacturing sectors, competitiveness in clean energy technologies depends on several factors, including product quality, innovation capacity and supporting infrastructure. However, production costs are the most decisive factor in shaping the competitive advantage, since lower costs usually translate into lower prices and higher market share. This effect is especially pronounced for technologies that can be mass produced, are relatively standardised, and are inexpensive to transport. Production costs are influenced by familiar drivers such as energy prices, labour costs, access to the latest technologies and the cost of capital. However, clean energy technology manufacturing is still a relatively young industry, and additional factors – such as manufacturing efficiency, the availability of skilled workers and the scale of production facilities – are often critical determinants.

The implications of lower equipment prices in final installation costs vary significantly across technologies. For many traded clean technology components – such as PV modules, battery cells, heat pumps and electrolyser stacks – equipment accounts for a relatively small share of total installation costs. For example, PV modules make up just 15% of total capital expenditure (CAPEX) for utility-scale solar projects, with the remainder coming from mounting structures, cabling and power electronics. Similarly, for electrolysers, stacks account for only around 15% of total CAPEX, while the majority arises from the balance of plant, which includes complex chemical engineering systems (Figure 7.17).

The share of upfront capital costs associated with equipment in total lifetime costs also varies by technology. In power generation, CAPEX represents about three-quarters of the levelised cost of electricity (LCOE) for wind and solar. For batteries, the balance between CAPEX and operating expenditure (OPEX) is similar: in stationary storage systems and battery electric vehicles, OPEX represents just about 20% of total costs. Conversely, for heat pumps and electrolysers, OPEX is dominant, as energy consumption over their lifetime outweighs the initial investment. Regardless of the technology, even when equipment CAPEX represents a small share of total production costs, both private and public actors generally favour lower-cost options, since small cost differences can tip the balance between profitable and loss-making projects.

Figure 7.17 Breakdown of the levelised cost of energy service delivery for selected installed technologies, 2024



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Notes: OPEX = operating expenditure; CAPEX = capital expenditure; BEV = battery electric vehicle. CAPEX equipment refers to solar PV modules; wind turbine nacelles, blades and towers; battery cells; Heat pump external units and electrolyser stacks. Heat pump is air-to-water. Battery storage refers to a 2-hour system. Delivered energy service relates to the output of the technology, i.e. electricity for solar PV (utility-scale), wind and battery storage, distance driven for BEVs, heat for heat pumps and hydrogen for electrolysers.

The share of equipment capital costs in total lifetime costs is relatively low for solar PV, EVs and electrolysers, and highest for stationary battery storage and onshore wind.

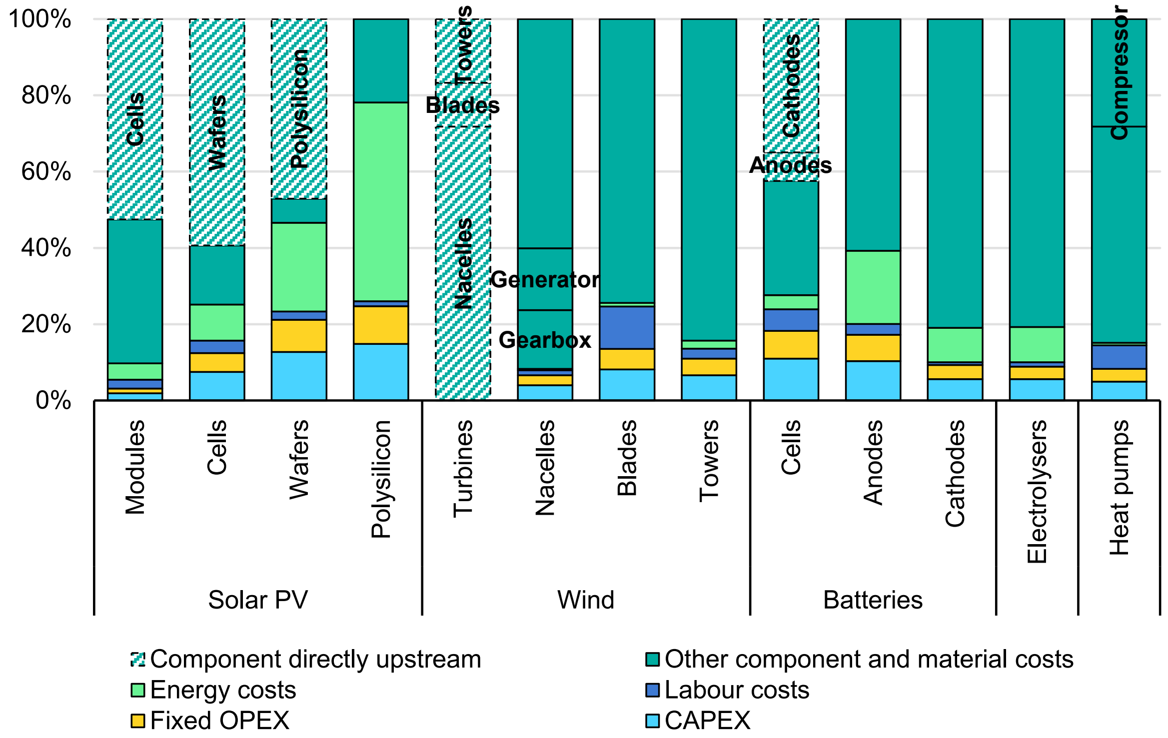
China holds advantages across most major cost drivers relative to advanced economies, while in comparison with other EMDEs its labour costs and, in some cases, energy costs, are higher. China has long been the world's largest producer of clean energy technologies, and this sustained leadership has given firms operating there a strong edge in technical know-how across almost all technologies. Electrolysers remain an exception, as large-scale mass manufacturing has yet to be established anywhere.

The relative importance of different manufacturing cost components varies by technology and by stage of the supply chain:

- **Labour costs:** Labour generally accounts for less than 5% of total production costs across most steps in China (Figure 7.18). A notable exception is wind turbine blade manufacturing, which has proven difficult to automate because of the scale of the products and the complexity of the operations involved.
- **Energy costs:** Direct energy use can be a major cost factor in upstream processes involving highly energy-intensive material transformation. For example, energy makes up about half of total costs in polysilicon production, compared with around 5% in solar PV module manufacturing. In batteries, energy accounts for around 20% of anode material production costs but closer to 5% for cell manufacturing.

- **CAPEX:** CAPEX contributes between 2% and 15% of the levelised cost of production (LCOP) for clean energy technology manufacturing, though this varies by process. Assembly-oriented steps such as solar PV module production, nacelle assembly or heat pump manufacturing require relatively simple equipment, so CAPEX accounts for less than 5% of total costs. By contrast, battery cell manufacturing relies on highly complex, fast and precise processes, pushing the CAPEX share closer to 10%.
- **Materials and components:** The bulk of costs across all clean energy technologies are associated with inputs of materials and components. Material inputs are typically semi-finished steel and aluminium products, plastics and fibres. Components vary widely, ranging from fully assembled items, such as printed circuit boards, compressors or gearboxes, to semi-finished components like solar glass or separator membranes. The further downstream a production step, the higher the share of costs accounted for by fully assembled components, while upstream stages rely more heavily on raw or semi-finished materials.

Figure 7.18 Breakdown of the levelised cost of production for selected clean energy technologies in China, 2024



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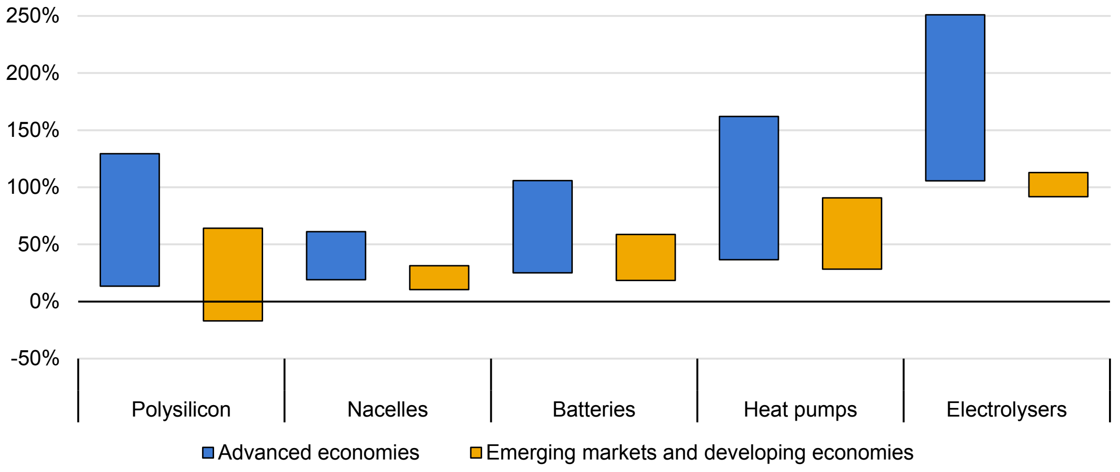
Notes: OPEX = operating expenditure; CAPEX = capital expenditure. Batteries refer to lithium-ion batteries; costs are based on the global weighted average battery chemistry sales. Cathodes and anodes refer to active materials.

The shares of different manufacturing cost components vary by technology and supply chain stage, but materials and components make up the bulk of costs for all technologies

Relative to most advanced economies, China generally retains a significant production cost advantage (Figure 7.19). This is particularly pronounced in technologies where labour, capital equipment or small component costs make up significant parts of the overall costs – for example, wind turbine nacelles or heat pumps – since these inputs are much cheaper in China. For energy-intensive manufacturing steps, such as polysilicon production, the picture is more mixed. In North America, energy prices can be as low as in China, narrowing the cost gap: for example, the LCOP of polysilicon in the United States is estimated to be only just around 15% higher than in China.

Figure 7.19 Additional cost of manufacturing selected clean energy technologies compared with China, 2024



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Notes: Based on the levelised cost of production. Batteries refer to lithium-ion battery cells.

China generally retains a significant cost advantage over advanced economies, while cost gaps with other EMDEs are smaller, due to comparable or lower labour and energy costs.

In EMDEs, cost gaps with China are often smaller, reflecting comparable or even lower labour and energy costs. However, low production costs alone are not sufficient to establish global manufacturing hubs: local demand, infrastructure and skilled labour availability are also essential. For energy-intensive processes, some EMDEs with particularly low energy costs – such as countries in the Middle East – could achieve production costs even lower than China's. This advantage is already triggering investment, with two new polysilicon plants currently under construction in the region.

Box 7.2 Analysing regional cost gaps in clean energy technology manufacturing

Our analysis focuses on identifying key strategies that can contribute to closing the manufacturing competitiveness gap with the cheapest producer for key clean energy technologies. This analysis is grounded in detailed, bottom-up assessments of the structure and regional differences in the levelised costs of production for key technologies and components. For supply chain steps that are not currently being produced in a given country, theoretical costs of production were estimated. This allows for an estimation of the cost differences across an entire supply chain if it were to take place in a single region (except for mineral mining and processing). The specific contributors to manufacturing costs along different steps of supply chains are based on assessments of plant-level datasets as well as a thorough review of the publicly available literature.

The resulting regional differences in manufacturing costs for relevant contributing factors were used to identify, assess and quantify the specific strategies that could be pursued to reduce such differences. The analysis has been enriched and validated through consultations with a wide range of experts in different supply chains, including experts in different relevant functions within manufacturing companies, technical analysts and data providers with deep supply chain knowledge.

An assessment of production costs across clean energy technology supply chains shows that no single factor explains China's cost advantage. Comparing production in China with Europe illustrates that structural cost differences, such as energy and labour, account for a large share of the gap in steps that are particularly energy- or labour-intensive, including upstream solar PV manufacturing and wind blade production (Figure 7.20). Economies of scale are especially important for heat pumps and solar PV, while for batteries over 40% of the cost gap reflects higher manufacturing efficiency in China. Pathways to narrow these gaps exist, but they differ markedly by technology (see Chapter 8).

Levelised production costs alone are not sufficient to determine whether manufacturing a given technology in a given region can generate profitable operations and attract private capital. Financial performance indicators such as the relationship between the average Return on Invested Capital[7] (ROIC) and Weighted Average Cost of Capital[8] (WACC) provide a more nuanced picture.

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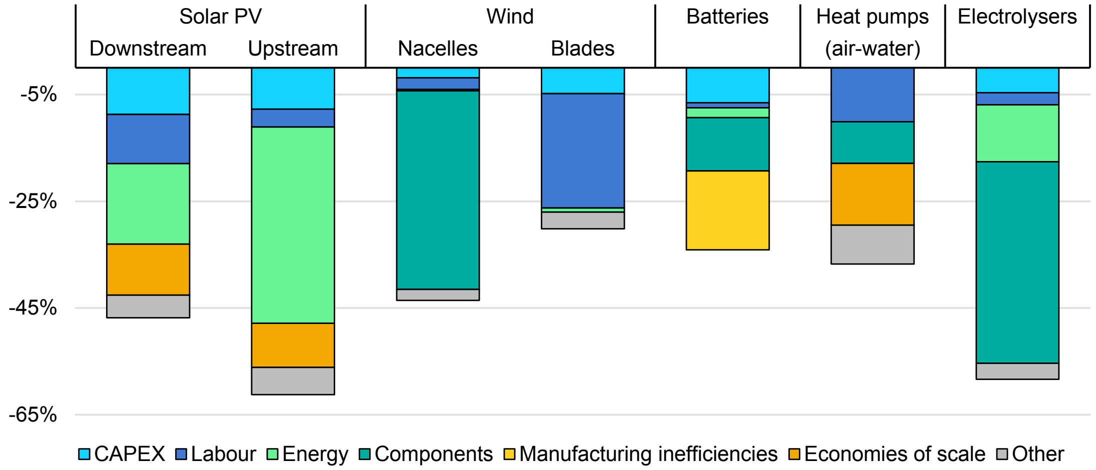
[7] ROIC is calculated by dividing net operating profit after taxes by the invested capital and measures how efficiently a company allocates its capital to generate profits.

[8] WACC refers to the average rate of return required by all providers of capital, both debt and equity, based on their proportional contribution to the capital structure.

A company generates value for private investors when its ROIC exceeds its WACC. In 2019, China's solar PV industry presented a mixed picture, with some firms operating above their WACC. By 2024, however, intense competition had pushed manufacturers along the supply chain into loss-making territory (see Chapter 4). Since 2024, more than 40 Chinese solar firms have been delisted, gone bankrupt or been acquired (Reuters, 2025c) and financial reports suggest this trend is likely to continue for now (BNEF, 2025a). In response, firms have taken steps to reduce the polysilicon supply glut by cutting capacity by about one-third (Reuters, 2025a) and the government has introduced cost guidelines to establish a price floor for state-owned procurement (Reuters, 2025b), which could help lift capital efficiency. Outside China, solar PV manufacturers have often been loss-making as companies struggled to compete with China, though conditions improved modestly in 2024 thanks to tariffs and other industrial support measures.

Figure 7.20 Difference in production cost between the European Union and China for selected clean energy technologies by contributing factor, 2024



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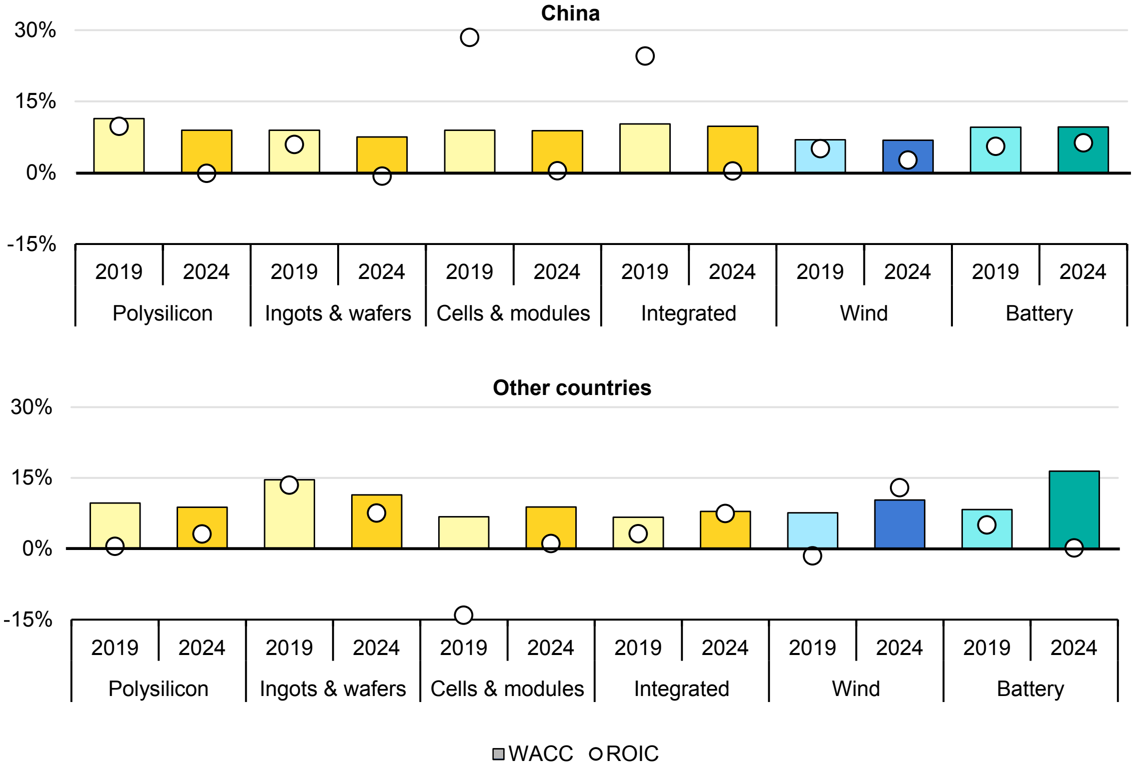
Notes: CAPEX = capital expenditure. Based on the levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Batteries refer to battery cells using lithium nickel cobalt manganese oxide (NMC) 811 as cathode active material and graphite as anode active material. Labour cost for battery production in the European Union is calculated as the production weighted average of labour costs in 2024. Heat pumps refer to air-water units. Production efficiency is directly proportional to automation of production processes and inversely proportional to scrap rates and manufacturing lines downtime.

The reasons for China's competitive advantage over Europe differ markedly across clean technologies, so there is no one-size-fits-all solution to bridge the competitiveness gap.

In the wind sector, profitability in China remains under pressure, with ROIC still below WACC amid strong competition and oversupply. Elsewhere, wind manufacturing showed signs of recovery in 2024. For batteries, China's industry appears at first glance to struggle to earn its cost of capital, but performance has become more diverse: some firms recorded sharp declines in revenue, while others posted strong gains and high profitability, contributing to modest overall improvement. Outside China, high WACC and deteriorating ROIC, reflecting a surge in investment and factories still ramping up, means that value continues to be eroded from an investor perspective.

Taken together, financial performance for clean energy technology manufacturing in China weakened between 2019 and 2024 as competitive pressures intensified, while conditions outside China remained difficult (Figure 7.21). The main exceptions are wind manufacturing outside China, which is now generating profits, integrated solar operations, and some top-performing battery makers. With investment incentives outside China constrained by higher levelised costs of production, much of the capital currently being deployed appears to be motivated by long-term strategic considerations, such as securing future market share or technological leadership, or enabled by government policy support rather than near-term returns.

Figure 7.21 Return on invested capital and weighted average cost of capital in China and the rest of the world for solar PV value chains, wind and batteries, 2019-2024



IEA. CC BY 4.0

Notes: WACC = weighted average cost of capital; ROIC = Return on Invested Capital. WACC and ROIC are averaged across companies using company revenues weighted by their respective share of total revenues in a particular value chain segment (e.g. polysilicon) and headquarter location.

Sources: IEA calculations based on BNEF (2025b) and S&P Global (2025).

Financial performance for clean energy technology manufacturers in China has weakened with more intense competition, while conditions outside China remain difficult.

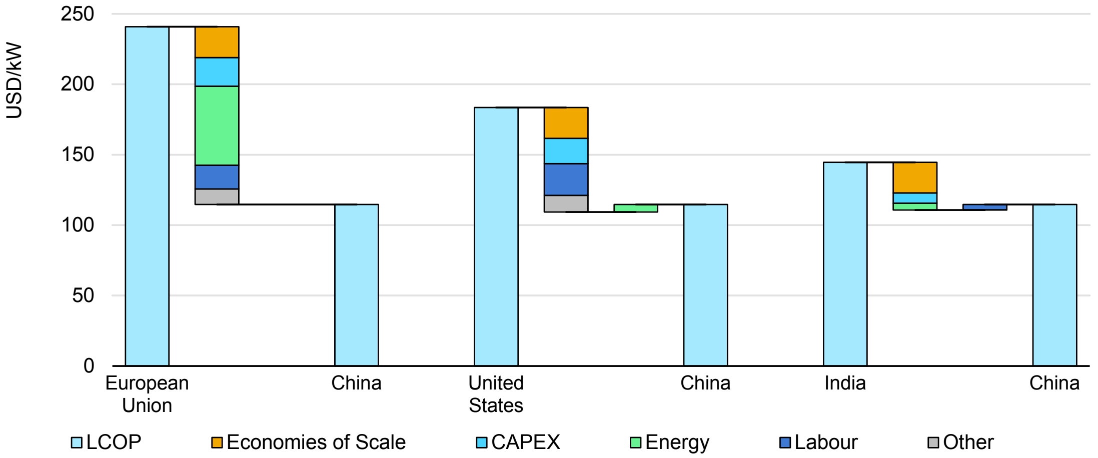
Solar PV

The economics of solar PV module production have improved significantly in recent years. Between 2019 and 2024, module prices fell by over 60%, reflecting sharp reductions in production costs, supported by rising efficiencies and economies of scale, especially in China, and intense competition between manufacturers. Following the easing of polysilicon supply bottlenecks in 2021-22 (Hall, 2021), prices have remained relatively stable, at around USD 0.10 per Watt since late 2023.

While cell technologies have evolved over time, silicon-based versions continue to dominate, accounting for around 98% of global production, with thin films representing the remaining share. The result has been relatively minor shifts in the cost structure of PV modules. For example, the transition from Passivated Emitter and Rear Cell (PERC) – the leading silicon technology from the late-2010s – to Tunnel Oxide Passivated Contact (TOPCon), which dominates today, involved changes in wafer thickness, higher efficiency and increased silver use, but has had only limited changes to the cost structure (Touloupas & Hansen, 2024). As a result, solar PV is one of the most homogeneous clean energy products: modules are largely commoditised, with cell efficiency per surface area the main differentiator.

In this context, cost-competitiveness is a decisive factor in decisions about where to invest in new manufacturing capacity. China is by far the lowest-cost solar PV producer, with module production costs about half those in the European Union and almost one-fifth less than in India (Figure 7.22). Several factors underpin this advantage. Energy costs account for more than 40% of the cost gap with Europe, though their significance varies by production step: polysilicon and wafer manufacturing are highly energy-intensive, whereas cell and module assembly are less so. Labour costs also contribute to the gap, with China benefiting both from lower wages and greater robotisation. As a result, wafer and cell manufacturing capacity remains limited outside China and absent in many advanced economies.

Figure 7.22 Decomposition of production cost gap between China and selected countries and regions for solar PV modules, 2024



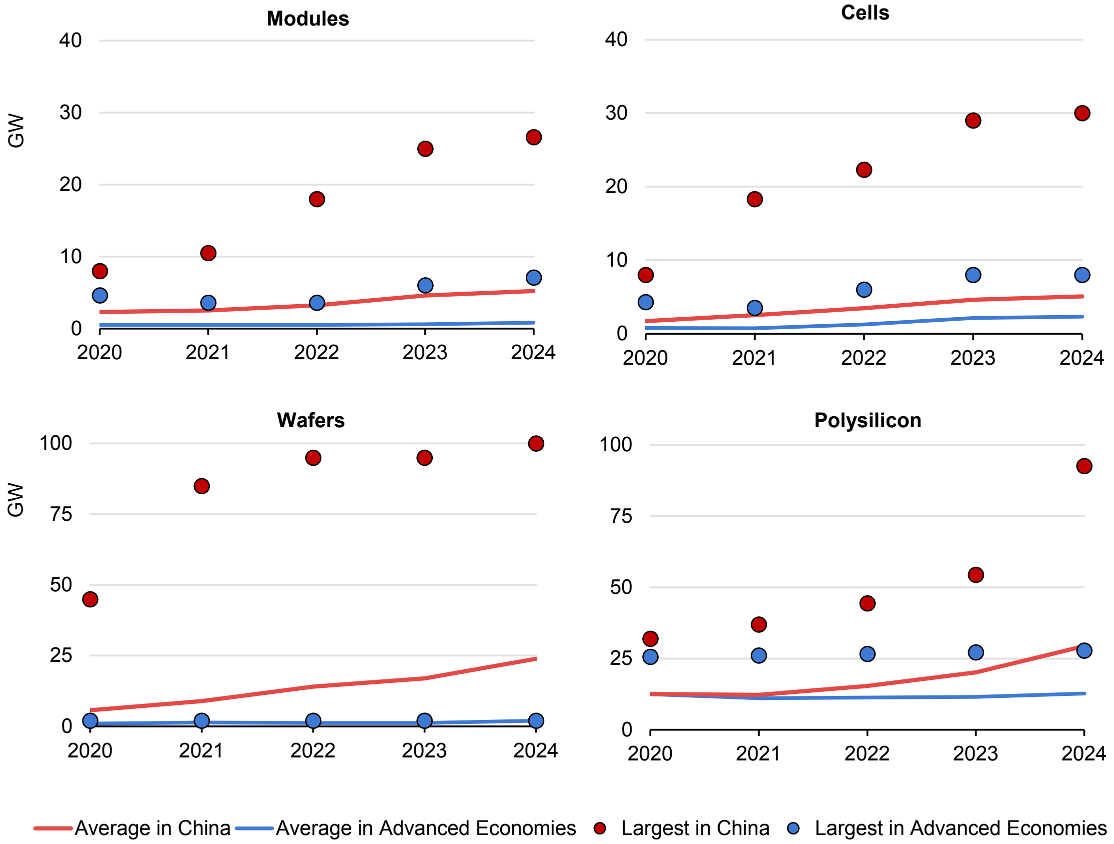
Notes: CAPEX = capital expenditure. LCOP = levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Assumes a vertically integrated supply chain. Assumes domestic production of polysilicon and intermediate components.

Sources: IEA analysis based on InfoLink (2025); BNEF (2025b); IEA (2025c); and Japan External Trade Organization (2025).

China is by far the lowest-cost producer of solar PV modules, with production costs nearly half those in the European Union, thanks to scale and lower labour, energy and CAPEX.

Economies of scale play an important role in determining the cost gap between China and other countries. Chinese manufacturing plants are on average six times larger across the supply chain than their counterparts in advanced economies (InfoLink, 2025) (Figure 7.23). For example, total EU module installations in 2024 amounted to around 60 GW – roughly double the capacity of a single large Chinese factory. This scale not only reduces unit costs but also accelerates technology learning.

Figure 7.23 Solar PV supply chain manufacturing plant sizes in China and in advanced economies, 2024



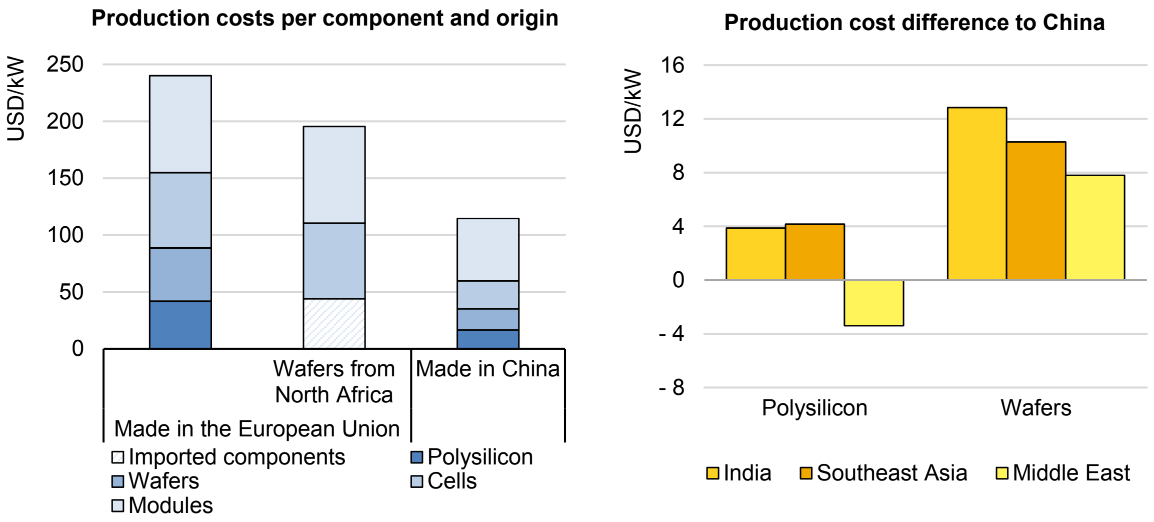
Source: IEA analysis based on InfoLink (2025).

Chinese solar PV manufacturing plants are, on average, six times larger than their counterparts in advanced economies, lowering unit costs and accelerating learning.

These structural advantages make it difficult for other regions to compete directly with China on cost. Yet, as noted above, the impact of these cost gaps on the overall economics of a solar PV project is only modest, especially for residential systems, which dilutes the effect of cost differences on deployment decisions (Figure 7.17). For example, relying solely on non-Chinese modules in Europe would increase the total capital costs for a utility-scale project by only around 15%, and even less for residential. Nonetheless, the sharp decline in the prices of solar PV modules has accounted for nearly half of the overall fall in the LCOE of solar PV over the past decade, underpinning the surge in global installations (IRENA, 2025). Against this backdrop, China's sustained cost leadership remains a central concern for existing manufacturers and prospective market entrants alike.

Different strategies are available to non-Chinese solar PV manufacturers to reduce cost gaps and, for governments, to foster domestic industries. These range from developing capabilities across the full supply chain to concentrating efforts on downstream activities, such as cell and module production, while sourcing wafers from countries with lower energy costs. For example, importing wafers from North Africa into the European Union would reduce the cost gap with China by 40% (Figure 7.24). The downstream focus has two advantages: it is less energy-intensive and captures a larger share of the added value in module manufacturing. However, it does not address security of supply risks unless upstream components are sourced from a diverse set of suppliers.

Figure 7.24 Module manufacturing costs in selected countries and regions, 2024



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Note: The levelised cost of production is based on a comparison of facilities of the same size.

The Europe Union could reduce significantly the solar PV module cost gap with China by importing components, particularly from countries with lower energy costs.

In the near term, partnerships with leading Chinese manufacturers could also provide a route to build capabilities, particularly through joint ventures and technology transfers. This is especially relevant as next-generation technologies, such as tandem perovskite-silicon cells, advance through R&D. Their commercialisation is likely to follow similar bottom-up cost structures, meaning that mastery of current silicon processes remains essential.

Wind turbines

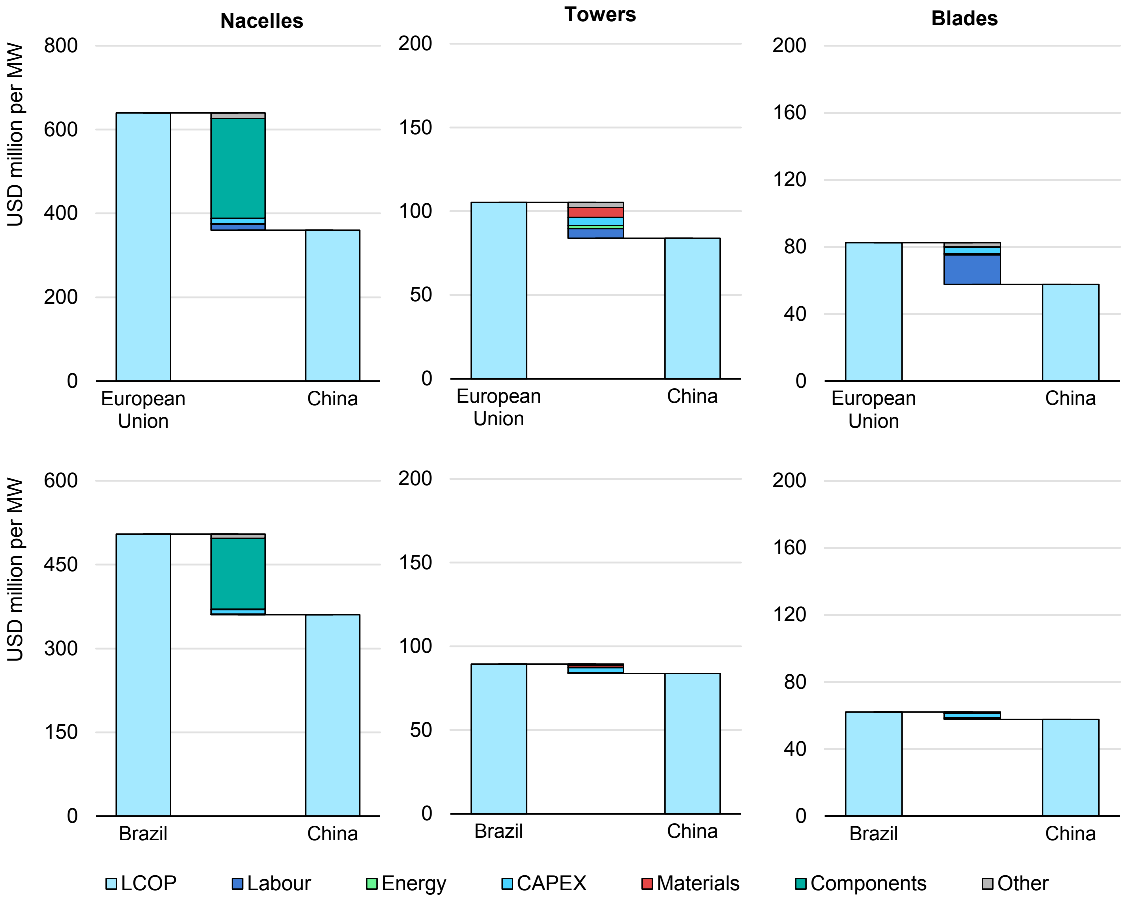
Wind turbine prices vary widely across regions. In Europe and the United States, turbines cost on average around USD 1 million per MW, compared with USD 280 000, or about 75% less, in China (BNEF, 2025c). This largely reflects differences in the levelised cost of manufacturing, with labour and component costs accounting for most of the cost gap between China – the lowest-cost producer – and higher-cost regions; but other factors also contribute to explaining this difference.

In the European Union and the United States, labour accounts for about one-quarter of production costs for the most labour-intensive components such as blades. By contrast, towers – which can represent up to 20% of turbine costs – are more material-intensive and therefore less affected by labour costs; steel and welding costs are the main cost factors.

Nacelles, which house the most complex components, are central to the overall cost advantage of China: producing a nacelle entirely in the European Union would be about 75% more expensive than in China due to higher labour costs, more expensive materials and less integrated supply chains (Figure 7.25). In practice, however, many nacelle sub-components are made in China and imported for assembly elsewhere, reducing the cost difference to just 10% in Europe when all components are imported (Figure 7.26). This pattern is global; in Brazil, for instance, a fully domestically manufactured turbine would cost about 30% more than a Chinese turbine, driven largely by higher nacelle component costs.

Beyond differences in manufacturing costs, two additional factors influence regional price disparities: turbine size and order volume. Turbines in China tend to be larger on average and are often ordered in bulk for gigawatt-scale wind parks (see Chapter 5, Box 5.3). Larger turbines reduce costs per unit of power output, while large orders support economies of scale in manufacturing. However, there are reports that turbine failure rates in China are higher than in other regions, linked to rapid prototyping and installations, pressure to maintain low prices, and limited incentives for manufacturers to prioritise reliability (Li & Ho, 2024) (Totaro, 2023).

Figure 7.25 Decomposition of production cost gap between China and the European Union and Brazil for wind turbine components, 2024



Notes: CAPEX = capital expenditure; LCOP = levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. The prices of key blade materials such as carbon fibre, fibre glass and resin are assumed to be equal across regions. All nacelle components are assumed to be domestically produced; however, nacelles manufactured in the European Union today include components sourced internationally. See notes in Figure 7.26 for more details on the components of the nacelle. Costs are weighted averages of onshore and offshore turbines according to deployment.

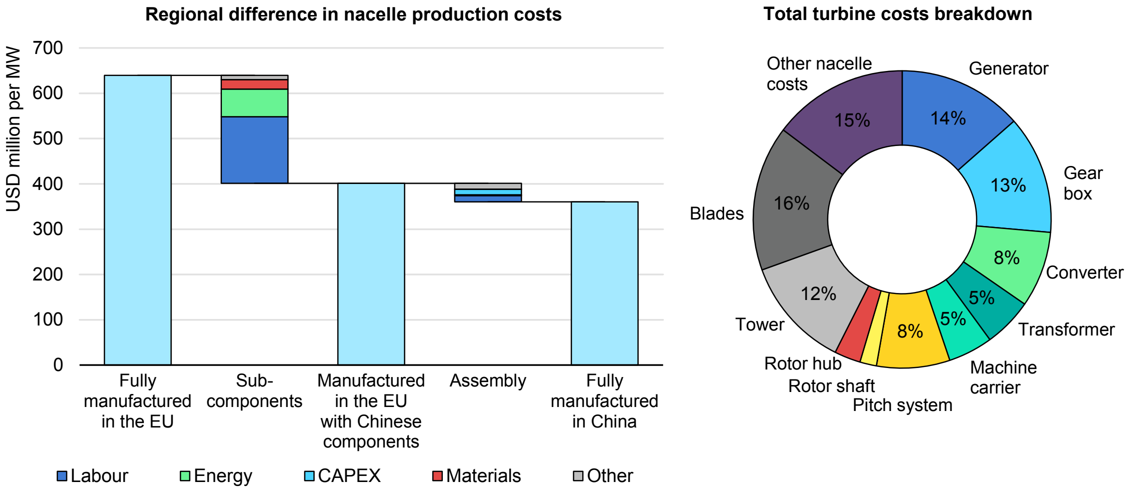
Sources: IEA analysis based on data from the Center for Wind Power Drives (RWTH); Reichartz et al. (2024); BNEF (2025b); Joint Research Centre (2020); and National Renewable Energy Laboratory (2019).

Wind turbine components cost substantially more to produce in the European Union and Brazil than in China, largely due to more expensive components and labour.

A closer look at nacelle costs highlights the weight of technically advanced sub-components such as gearboxes, generators, transformers and associated converters (Figure 7.26). These are among the most expensive items, reflecting both the value of materials – including rare earth elements for permanent magnets mostly used in offshore turbines and large amounts of copper for generators and transformers – and the skilled labour needed for machining and assembly. For these sub-components, labour can represent about 35% of total costs, thus making regions with low labour costs particularly competitive. Importing certain labour-intensive components can help with competitiveness, for example, producing in Europe while importing components from India could cost only 15% more than producing turbines in China, cutting 75% of the production cost gap between Europe and China. By contrast, large cast-iron parts such as the machine carrier, rotor hub and main shaft are more material- and energy-intensive, with costs driven largely by foundry operations and heat treatment.

Design choices also influence production costs. Direct-drive (DD) turbines remove the need for a gearbox but require larger, material-intensive permanent-magnet generators. Doubly fed induction generators (DFIGs), by contrast, rely on gearboxes but do not need rare earth elements. Offshore projects are increasingly dominated by DD systems, raising the material intensity of nacelles. Total production costs for DD systems can be up to 40% higher than for DFIG systems.

Figure 7.26 Decomposition of production cost gap between China and the European Union for nacelles and the shares of sub-components in total turbine costs in the European Union, 2024



IEA. CC BY 4.0.

Notes: EU = European Union. Production costs refer to the levelised cost of production. Production costs of nacelle components include the generator, gearbox (with roller bearings rather than plain bearings), converter, transformer, machine carrier, pitch system, rotor shaft, rotor hub, yaw drive and bearings. Costs for these components are modelled using the work of the Center for Wind Power Drives, which uses material costs from public sources and may reflect single-day prices. Furthermore, inflation rates were applied to align data years. The shown values are weighted averages between onshore and offshore turbines based on global deployment.

Sources: IEA analysis based on data from the Center for Wind Power Drives (RWTH); Reichartz et al. (2024); Joint Research Centre (2020); National Renewable Energy Laboratory (2019); and BNEF (2025b).

Labour- and energy-intensive sub-components such as the generator, gearbox and heavy materials account for a large share of total nacelle production costs

Beyond the turbine itself, broader industrial dynamics impact competitiveness. In China, the geographic clustering of suppliers reduces transaction and transport costs and supports economies of scale, reinforcing the country's position as the lowest-cost producer of wind turbine components.

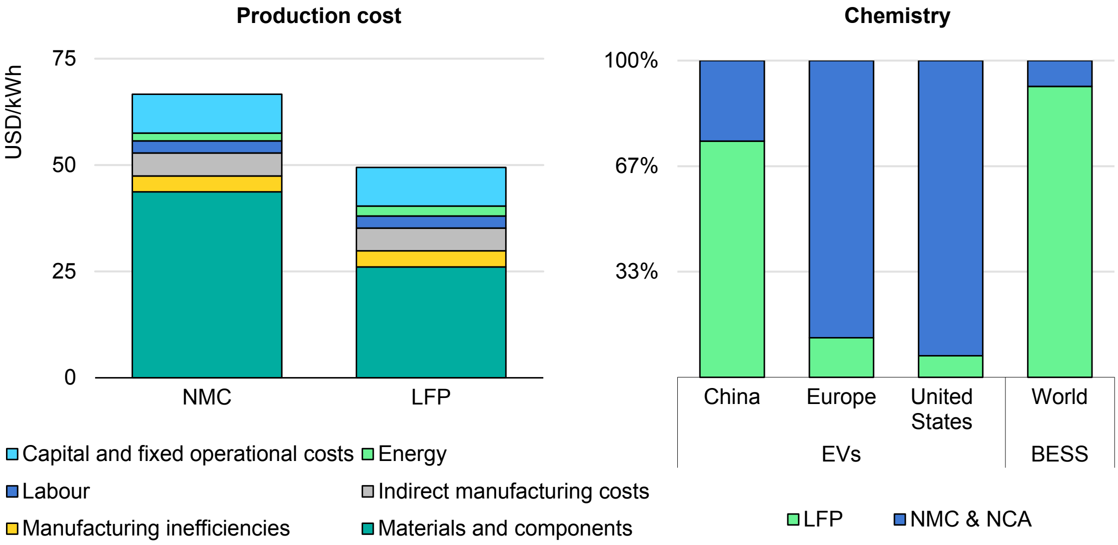
While these differences give China a clear cost advantage in turbine manufacturing, their effect on overall project economics is more limited. Turbines represent only a portion of the capital expenditures for wind projects, and capital costs, in turn, are only part of the levelised cost of electricity. Nonetheless, reducing production costs outside China remains key to future deployment and security of supply.

Batteries

As in other clean energy technology sectors, competitiveness in the battery industry is determined by a combination of factors, including manufacturing capability, technological expertise, supply chain integration and access to skilled labour. It is also strongly influenced by battery chemistry, which shapes performance characteristics, material requirements and production costs. Today's EV and battery storage markets are dominated by two lithium-ion chemistries: lithium iron phosphate (LFP) and lithium nickel manganese cobalt (NMC). NMC batteries deliver higher energy density, enabling longer driving ranges, but at higher cost and with shorter lifespans – though still sufficient for EV use. By contrast, LFP batteries have traditionally been cheaper and longer-lasting, but offered lower range. Recent innovations by Chinese manufacturers have closed much of this gap: modern LFP systems now support ranges of 300 km in small battery electric vehicles and up to 750 km in large SUVs (CATL, 2025).

On average, LFP batteries were almost 30% cheaper than NMC batteries worldwide in 2024, reflecting lower production costs (McKerracher, 2024). In China, LFP production costs are about one-quarter lower than for NMC. LFP batteries already account for nearly half of global EV sales and more than 90% of stationary storage demand. LFP adoption for stationary uses is broadly even globally, whereas in the EV market, it has been led by China, where LFP made up around three-quarters of the EV market in 2024, compared with just over 10% in Europe and even less in the United States. However, interest outside China is rising rapidly. In emerging economies such as India, Brazil and Southeast Asia, LFP already represents more than half of the electric car market. European and North American automakers are also scaling up LFP use to improve affordability, prompting Korean and Chinese battery manufacturers to announce plans for LFP production in these regions (S&P Global, 2024) (CATL, 2025a).

Figure 7.27 Lithium-ion battery cell production costs by chemistry in China and chemistry sales share by region and application, 2024



IEA. CC BY 4.0.

Notes: NMC = lithium nickel cobalt manganese oxide; LFP = lithium iron phosphate; NCA = lithium nickel cobalt aluminium oxide; EV = Electric vehicle; BESS = battery energy storage system. NMC production costs refer to NMC811. Production cost is the levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Indirect manufacturing costs include administration, retail and R&D costs. Manufacturing inefficiencies are directly proportional to scrap rates and manufacturing lines downtime and inversely proportional to automation of production processes.

Sources: IEA analysis based on data from IEA (2024b); CRU (2025); BNEF (2025b); EV Volumes (2025); China Automotive Power Battery Industry Innovation Alliance (2025); and battery companies' annual reports.

LFP batteries cost about a quarter less to make than NMC batteries in China, and already account for nearly half of global EV sales and more than 90% of stationary storage demand.

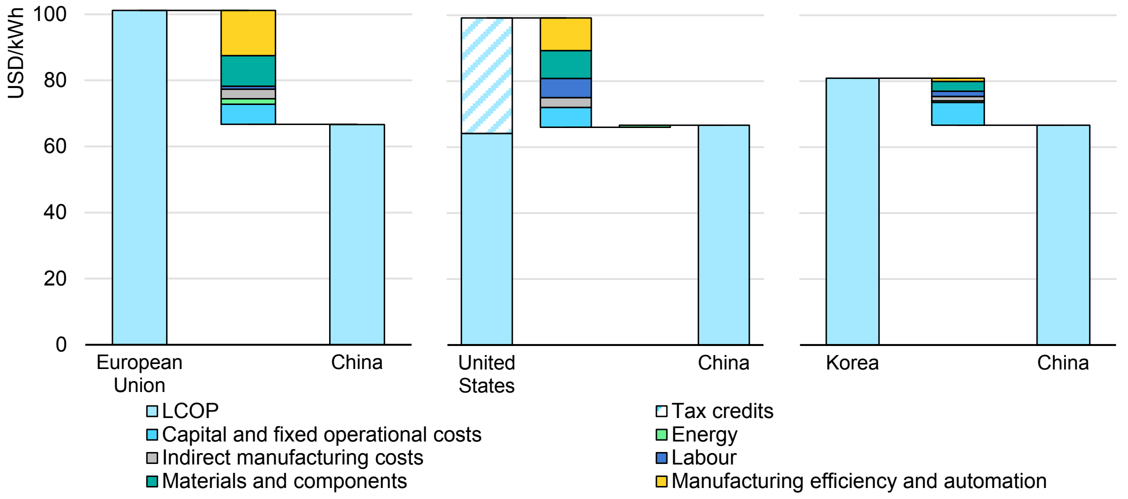
Despite their higher production costs, NMC batteries will nonetheless remain important, especially for applications demanding greater range than LFP can deliver as yet. Research is under way to raise manganese content to reduce the need for more expensive nickel and cobalt as a way of lowering overall material costs, which could narrow the price gap with LFP (GM, 2025). For this reason, expertise in both chemistries remains essential.

China currently holds a near monopoly over LFP, with only a handful of manufacturers able to produce or access the latest generation of this technology, even within China. Given its strategic value, China has introduced export restrictions on LFP technologies and related equipment that, if fully implemented, would narrow options for procurement abroad (China, Ministry of Commerce, 2025). Investment in capacity elsewhere – including by Korean firms and through Chinese companies with factories overseas – will be needed to strengthen supply chain security and resilience.

Beyond chemistry, competitiveness in the battery industry depends on manufacturing know-how, technological expertise, availability of specialised labour and the efficiency of supply chains. To date, nearly all EV batteries have been produced by companies headquartered in Asia – particularly in China, Korea and Japan – leaving both supply chains and skilled workforces heavily concentrated in the region (IEA, 2025e). In 2024, China alone accounted for around 80% of global production, while the European Union and the United States together held about 15%. Although Europe and North America remain far behind China, they are making clear progress in ramping up capacity, largely thanks to heavy investment from major Korean, Chinese and Japanese manufacturers (see Chapters 4 and 5).

Battery manufacturing costs remain considerably lower in China than anywhere else. The LCOP for NMC battery cells is around one-fifth higher in Korea than in China, and about 50% higher in the European Union and the United States (excluding tax credits). Much of those cost gaps stem from differences in manufacturing efficiency and automation levels. Chinese facilities typically operate with more advanced manufacturing equipment, higher throughput per line and fewer unplanned stoppages, supported by access to a large pool of skilled labour. This results in both higher productivity and lower staffing needs, reinforcing their competitive edge.

Figure 7.28 Decomposition of the production cost gap for lithium nickel cobalt manganese oxide battery cells between China and selected countries and regions, 2024



IEA. CC BY 4.0.

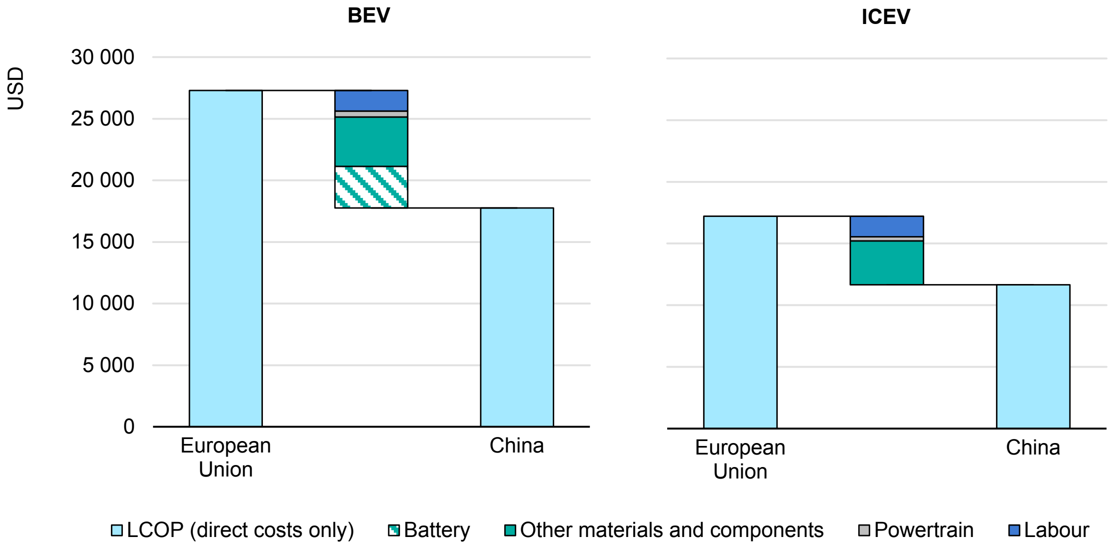
Notes: LCOP = levelised cost of production. Based on the LCOP, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. The “Manufacturing efficiency and automation” cost category is directly proportional to scrap rates and production-line downtime and inversely proportional to automation levels of production processes. Labour in the European Union is calculated as the production weighted average of labour costs in 2024, when the majority of production was concentrated in Poland and Hungary. Indirect manufacturing costs include administration, retail and R&D costs. Energy prices are for the overall industrial sector.

Sources: IEA analysis based on data from IEA (2024b); CRU (2025); BNEF (2025b) and battery companies’ annual reports.

Battery manufacturing costs remain considerably lower in China than anywhere else, in large part due to differences in manufacturing efficiency and automation levels.

China's cost leadership in battery manufacturing shapes the entire EV supply chain, as batteries account for over a quarter of total production costs (including indirect manufacturing costs). While lower labour costs and lower costs for non-powertrain components (such as the interior, body-in-white and chassis) explain a significant share of the cost advantage of Chinese-made battery electric cars over EU-made equivalents, lower battery prices still account for over one-third of the estimated direct cost gap.[9] Other electric powertrain components are also cheaper to produce in China, but contribute only around 5% to this difference (IEA, 2025a). This underscores the importance for other regions of securing access to competitively priced batteries and developing domestic manufacturing capabilities if they are to remain competitive in the EV market.

Figure 7.29 Decomposition of the direct manufacturing cost gap for a small SUV between the European Union and China, by powertrain, 2024



IEA. CC BY 4.0.

Notes: LCOP = levelised cost of production; BEV = battery electric vehicle; ICEV = internal combustion engine vehicle; SUV = sport utility vehicle. Only direct manufacturing costs are shown in the figure: overheads like R&D, selling, general and administrative expenses, and profit margins are excluded from the figure scope. Germany is considered as a proxy for the European Union. In both analysed regions, BEV assumes a 150-kW electric drivetrain with a 75-kWh battery and ICEV an 80-kW engine. Other components include the chassis, body-in-white, exterior, interior and electronic equipment. Labour and energy costs relate to the car assembly manufacturing step only.

Source: IEA analysis based on IEA (2025a).

China's strength in battery manufacturing carries through the vehicle supply chain, with batteries accounting for over one-third of the BEV direct cost gap with the European Union.

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[9] Direct manufacturing costs exclude overheads (or indirect manufacturing costs) such as R&D, selling and administrative expenses, manufacturer profit margins and dealer markups.

Foreign investment remains one of the fastest ways to accelerate domestic battery manufacturing in regions with limited expertise. In particular, Chinese, Korean and Japanese firms bring not only capital but also technical knowledge, training and established supply chains. Such partnerships – whether through joint ventures or direct investment – can help improve local workforce skills, reduce production costs through efficiency gains and secure access to high-quality and lower-cost components.

Heat pumps

Heat pump production costs vary widely by region, shaped by general manufacturing conditions (notably skills, infrastructure and labour) and market-specific factors such as product type (typically air-to-air or air-to-water), unit size, compressor choice, performance standards and regulations. Final assembly requires little energy or raw materials, so components dominate overall costs, accounting for 60-85% of production costs. Compressors are the most complex part, representing about 30% of production costs alone. This gives countries with strong component industries and access to materials a clear competitive edge and explains why, as for other technologies, China is the largest manufacturer, accounting for over 35% of global heat pump output.

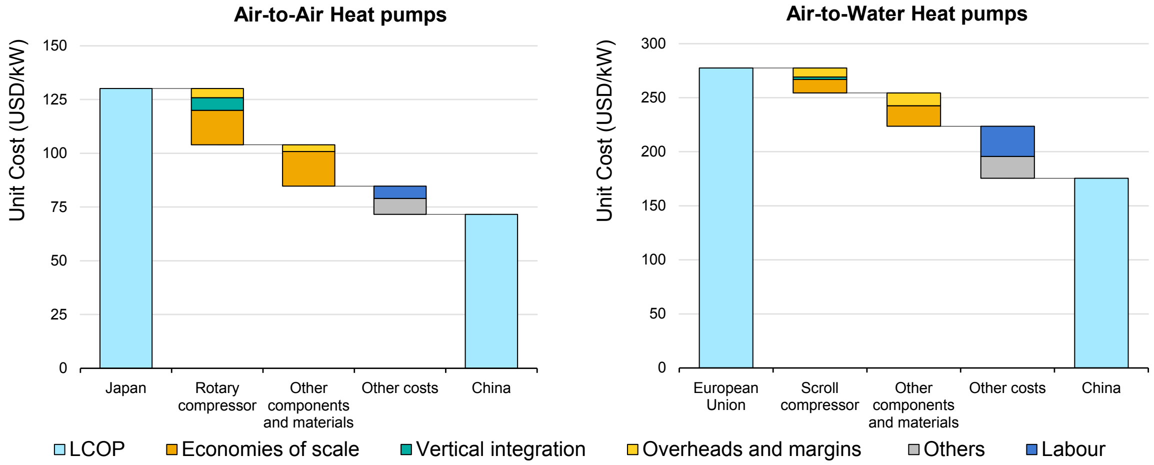
Rotary compressors, commonly used in small heat pump units, are overwhelmingly manufactured in China, which supplies about 90% of global output through vertically integrated supply chains closely linked to heat pump and air-conditioner (AC) producers. By contrast, production of scroll compressors, used mainly in larger, more efficient, heat pump units, is more geographically diverse: about one-third come from China, 30% from other Asian countries, over 30% from the United States and about 5% from Europe. Scroll compressors offer higher efficiency and lower noise performance but cost more; combined with more limited demand for larger units, this results in a smaller overall market compared with rotary compressors. China’s outsize role in rotary compressor manufacturing, together with its large domestic market for ACs and air-to-air heat pumps, reinforces its strong competitive position in this segment.

Air-to-air heat pumps also share core components, supply chains and production processes with ACs. This allows AC-like manufacturing scale to reduce costs for heat pumps; shared R&D, as well as testing and distribution spillovers, further reinforce competitiveness in countries with a strong AC base.

Manufacturers located in China and Japan are the main suppliers of air-to-air heat pumps. The strength of Japanese companies reflects long-standing expertise across a range of companies such as Daikin, Panasonic, Fujitsu General and Mitsubishi Electric, supported by a domestic market where over 90% of households own reversible ACs (which can produce either hot or cold air). China, however, leads by scale, with production an order of magnitude higher than in Japan. Several major Chinese compressor manufacturers are owned by or closely integrated with leading air-conditioner/HVAC (heating, ventilation and air conditioning) firms – a structure that can ensure tight co-ordination across the supply chain. Other compressor suppliers that remain independent are supplying components to multiple original equipment manufacturers (OEMs) that can benefit from a highly localised supply chain. Beyond compressors, China's high-volume production makes control systems, chips, motors, casings, and other shared components far cheaper to source. High production volumes and integrated supply chains reduce per-unit costs and create spillover benefits, such as streamlined logistics and faster innovation cycles.

Taken together, these structural factors translate into a large competitive advantage for China. Air-to-air models cost 40% less to produce in China than in Japan (Figure 7.30). Over 40% of this cost gap comes from economies of scale and vertical integration in compressor manufacturing, 30% from cheaper components and raw materials, and over 20% from lower labour and compliance costs. In practice, not all these differences make it to the final product; Japanese firms have expanded production in China, while maintaining Japan-focused models at home. This dual footprint allows them to combine domestic expertise with China's economies of scale.

Figure 7.30 Decomposition of the production cost gap for heat pumps between China and selected countries and regions, 2024



IEA. CC BY 4.0.

Notes: LCOP = levelised cost of production, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Assumes a typical air-to-air heat pump with capacity of 4 kW, a typical air-to-water heat pump with capacity of 12 kW and a utilisation factor of 85% for both. "Others" includes costs associated with compliance with local standards such as certification, aesthetics and noise.

China is the lowest-cost producer of both air-to-air and air-to-water heat pumps, thanks mainly to economies of scale and access to low-cost components.

The cost gap for air-to-water units between China and the European Union is narrower than for air-to-air, but European units still cost around 60% more. Europe and China are the largest markets for air-to-water heat pumps, with China supplying over 15% of European demand, making the China-Europe corridor the biggest global trade flow for heat pumps. Most of the remaining European demand is met domestically. Europe leads in high-efficiency designs and innovation, particularly for large-scale units, but is less competitive in the rest of the market.

Components represent about half of the total gap in production costs, with Europe's reliance on scroll compressors – which are larger, more complex and less geographically concentrated than rotary compressors – limiting China's competitive advantage. Most of the remaining cost gap stems from cheaper labour costs and lower retail margins.

Closing this gap will be difficult. However, the strong engineering base of European compressor and component manufacturers, combined with automation, higher productivity, industrial clustering, joint ventures and technology collaboration offer potential pathways to reduce costs. Importantly, components drive the LCOP but have a very limited impact on retail prices – particularly for air-to-water units – with installation and distribution costs, as well as profit margins, playing a bigger role in final costs. In addition, demand is strongly influenced by prevailing electricity-to-gas price ratios, which determine the potential savings that can be made by switching from a gas boiler to a heat pump.

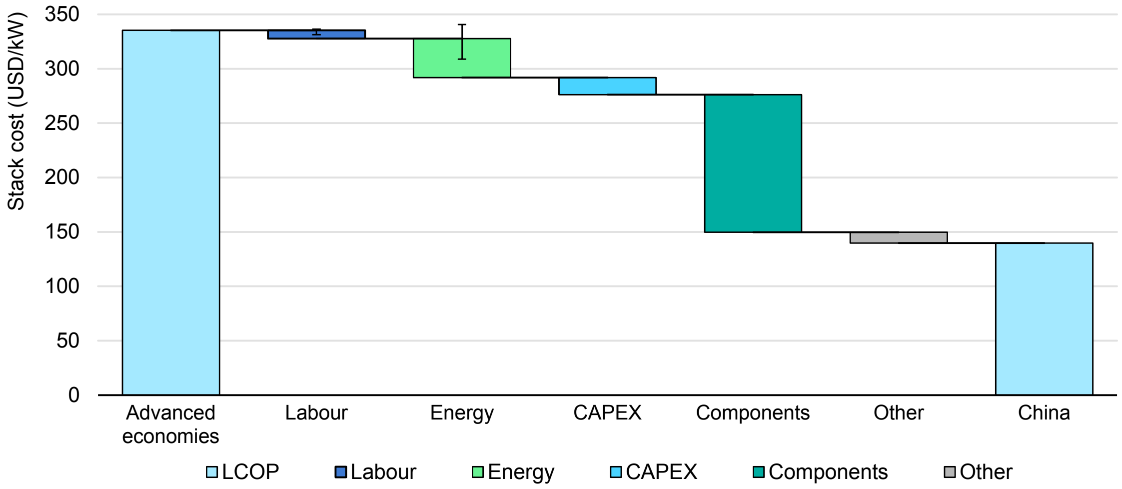
Electrolysers

Broadly speaking, electrolysers operate in a similar way to batteries, using stacks of connected cells in which water is split into hydrogen and oxygen. Each stack contains an anode and a cathode separated by an electrolyte that carries ions. A porous layer separates the electrodes, water and gases, while bipolar plates link the cells, spread gases evenly, manage heat and provide structural support. Catalysts accelerate the electrode reactions. Several designs exist depending on materials and configurations, with alkaline electrolysers the most established and widely deployed today (IEA, 2025d).

In alkaline electrolysis, the diaphragm that separates the electrodes is the single largest cost item, representing about 40% of stack manufacturing costs. Along with nickel-based electrodes and the membrane electrode assembly, these core elements together typically make up nearly two-thirds of the total cost. The remaining share is linked to support layers and assembly. Other costs include energy use (around 17% in Europe), plant costs (14%) and labour (about 3%, depending on automation and scale). Other non-stack costs such as power electronics, gas conditioning, water cooling and circulation, can be almost 40% higher than the stack costs. The rest of the CAPEX are non-equipment costs (Figure 7.17).

China, Europe and the United States are the leading manufacturers of electrolysers today, accounting for nearly 60%, 16% and 10% of global manufacturing capacity, respectively, in 2024. China's manufacturing costs are almost 60% lower on average than in advanced economies, largely due to access to cheaper materials in core components such as catalysts, economies of scale and optimised supply chains for balance-of-stack items such as seals, frames, separators and gaskets (Figure 7.31).

Figure 7.31 Decomposition of the production cost gap for electrolysers between China and advanced economies, 2024



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Notes: LCOP = levelised cost of production; CAPEX = capital expenditure. Based on the LCOP of an alkaline electrolyser, which corresponds to the price that would have to be charged per unit of production to achieve a net present value of zero for a given investment. Cost differences in components reflect different stack design choices. Assumes a 1 GW/year manufacturing plant and a utilisation factor of 85%. The error bars denote the variation in costs across the advanced economies.

Sources: IEA analysis based on industry announcements Krishnan, et al. (2023); Gerloff (2021); and ExoPeak analysis.

Electrolyser manufacturing costs are 60% lower in China than in advanced economies, despite lower unit efficiencies, mainly thanks to cheaper components.

In practice, there is a trade-off between cost, efficiency and durability, making straight production cost comparisons somewhat misleading. Alkaline electrolysers can be designed with more expensive materials[10] to deliver higher efficiency and

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[10] Alkaline electrolysers must withstand highly caustic solutions, requiring more expensive zirconia diaphragms and nickel- or zinc-based materials.

last longer. Using cheaper alternatives reduces performance: a cost differential of around USD 200/kW corresponds to about three percentage points of efficiency[11] – close to the current gap between Chinese electrolysers and those manufactured elsewhere. Despite higher upfront costs, electrolysers produced in advanced economies can therefore be competitive – and in some cases have an advantage – with those from China, not least because electricity prices are a key factor for the levelised cost of hydrogen production. However, as China continues to close the efficiency gap, its broader cost advantage is expected to reassert itself, particularly for non-stack components.

Competitiveness is also shaped by market maturity. In 2024, global electrolyser manufacturing capacity stood at 38 GW per year, while actual output was only about 4 GW. This severe underutilisation inflates manufacturing costs: in advanced economies, operating at 20% utilisation adds roughly USD 160/kW, compared with about USD 70/kW in China due to lower plant CAPEX. Plant size further reinforces the differential. The average Chinese facility is almost 890 MW per year, compared with 320 MW in Europe, where several plants are below 50 MW. These smaller facilities can face CAPEX penalties of up to 50%, but because CAPEX accounts for only a modest share of overall costs, the penalty translates to only about USD 15/kW – albeit still a meaningful disadvantage if utilisation remains limited.

Electrolysers remain at an earlier stage of deployment compared with the other clean energy technologies discussed above, leaving greater room for both cost reductions and performance improvements. While China has a clear cost edge today, levelised costs are broadly similar across regions once efficiency is factored in. The European Union and the United States maintain robust research programmes focused on reducing stack costs, improving efficiency and extending lifetimes, suggesting that global competitiveness in electrolyser manufacturing remains open to shifts as the industry matures (Clean Hydrogen, 2024) (US Department of Energy, 2024).

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[11] Assuming an electricity price of USD 60/MWh, 5000 full load hours per year and a system lifetime of 25 years.

References

Agora Industry. (2023). *15 Insights on the Global Steel Transformation*. Retrieved from https://www.agora-industry.org/fileadmin/Projekte/2021/2021-06_IND_INT_GlobalSteel/A-EW_298_GlobalSteel_Insights_WEB.pdf

Agora Industry. (2025). *The role of green iron trade in accelerating competitive steel transformation.* Retrieved from https://www.agora-industry.org/publications/the-role-of-green-iron-trade-in-accelerating-steel-transformation

Argus. (2024a). *Dow to close German cracker, other assets by 4Q 2027*. Retrieved from https://www.argusmedia.com/en/news-and-insights/latest-market-news/2707474-dow-to-close-german-cracker-other-assets-by-4q-2027

Argus. (2024b). Sabic to begin Geleen cracker closure this week. Retrieved from https://www.argusmedia.com/en/news-and-insights/latest-market-news/2556639-sabic-to-begin-geleen-cracker-closure-this-week

Argus. (2025). *Argus TTF*. Retrieved from https://www.argusmedia.com/en/methodology/key-commodity-prices/argus-ttf

Bataille, C., Pai, S., Stiebert, S., Mishra, M., Patil, G., & Francis, L. (2025). *Meeting climate targets will lead to major steel production technology shifts and preserve jobs.* Retrieved from https://dx.doi.org/10.2139/ssrn.5278075

Bloomberg. (2023). Europe's Petrochemical Industry Is Heading for Death Row. Retrieved from https://www.bloomberg.com/opinion/articles/2023-11-20/europe-s-petrochemical-industry-is-heading-for-death-row

BNEF. (2025a). *3Q 2025 Global PV Market Outlook Prospects of a 1TW Solar Market Fading.* Retrieved from https://www.bnef.com/insights/37617/view

BNEF. (2025b). *Data service*. Retrieved from https://about.bnef.com/

BNEF. (2025c). *Wind Turbine Price Index 1H 2025: Still on the Rise.* BNEF.

Brown, D. (2025). Fortescue inks green iron partnership with China Baowu. *Australian Resources & Investment*. Retrieved from https://www.australianresourcesandinvestment.com.au/2025/01/10/fortescue-inks-green-iron-partnership-with-china-baowu/

CATL. (2025). *CATL Launches Shenxing Pro, Europe’s Optimal Solution for E-Mobility at IAA Mobility 2025*. Retrieved from https://www.catl.com/en/news/6527.html

CEPII. (2025). *BACI*. Retrieved from https://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37

China Automotive Power Battery Industry Innovation Alliance. (2025). *Monthly Data - Power Battery Monthly Information in December 2024*. Retrieved from https://mp.weixin.qq.com/s/W7181pLemWq1eThd4o2vew

China, Ministry of Commerce. (2025). *Announcement No.18 of 2025 of The Ministry of Commerce and The General Administration of Customs of The People’s Republic of China Announcing the decision to implement export control on some medium and heavy rare earth related items*. Retrieved from https://english.mofcom.gov.cn/Policies/AnnouncementsOrders/art/2025/art_0dd87cbee7b045bf93fabe6ab2faceee.html

Clean Hydrogen. (2024). *Programme Review Rport 2024*. Retrieved from https://www.clean-hydrogen.europa.eu/document/download/6b6584d0-f259-436a-8fe8-3a6bf9d0761c_en?filename=20242823_PDF_EGAA24001ENN_002.pdf

Climate Group. (2025). *SteelZero*. Retrieved from https://www.theclimategroup.org/steelzero-members

CRU. (2025). *Multi Commodity Asset Data*. Retrieved from https://www.crugroup.com/en/

European Aluminium. (2025). Industry & Market Data. Retrieved from https://european-aluminium.eu/about-aluminium/aluminium-industry/

European Commission. (2025a). *FIGARO tables*. Retrieved from https://joint-research-centre.ec.europa.eu/projects-and-activities/trade-and-industrial-policy-analysis/input-output-accounts/figaro-tables_en

European Commission. (2025b). *The Draghi report on EU competitiveness*. Retrieved from https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en

European Commission. (2025c). *Eurostat: Production in industry - monthly data*. Retrieved from https://ec.europa.eu/eurostat/databrowser/product/page/STS_INPR_M

EV Volumes. (2025). *Global Electric Vehicle Sales Data, Market Trends & Forecasts You Can Trust*. Retrieved from https://ev-volumes.com/

Gerloff, N. (2021). Comparative Life-Cycle-Assessment analysis of three major water electrolysis technologies while applying various energy scenarios for a greener hydrogen production. *Journal of Energy Storage*. Retrieved from https://www.sciencedirect.com/science/article/pii/S2352152X21004874

GM. (2025). *News Release Details*. Retrieved from https://investor.gm.com/news-releases/news-release-details/gm-and-lg-energy-solution-pioneer-lmr-battery-cell-technology/

Green Hydrogen Innovation Centre. (2024). *Africa's first green hydrogen-based ironworks signs offtake deal as it receives electrolysers*. Retrieved from https://isa-ghic.org/africas-first-green-hydrogen-based-ironworks-signs-offtake-deal-as-it-receives-electrolysers

Growth Lab. (2025). *Country & Product Complexity Rankings*. Retrieved from https://atlas.hks.harvard.edu/rankings

Hall, M. (2021). Polysilicon shortage will continue through 2021. *PV Magazine*. Retrieved from https://www.pv-magazine.com/2021/07/22/polysilicon-shortage-will-continue-through-2021/

Hydrogen Europe. (2025). *Meranti Green Steel eyes 2026 FID for 2.5 mtpa green iron project in Oman*. Retrieved from https://hydrogeneurope.eu/meranti-green-steel-eyes-2026-fid-for-2-5-mtpa-green-iron-project-in-oman/

ICIS. (2024). Exxon Mobil to close Gravenchon, France cracker and related derivative units in 2024. *ICIS*. Retrieved from https://www.icis.com/explore/resources/news/2024/04/11/10989084/exxonmobil-to-close-gravenchon-france-cracker-and-related-derivative-units-in-2024/

IDDI. (2025). *The Industrial Deep Decarbonization Initiative*. Retrieved from https://decarbonization.unido.org/projects/iddi/

IEA. (2024a). *A Global Review of Patent Data for Smart Grid Technologies.* Retrieved from https://www.iea.org/reports/a-global-review-of-patent-data-for-smart-grid-technologies

IEA. (2024b). *Energy Technology Perspectives 2024.* Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2024

IEA. (2025a). *What Next for the Global Car Industry*. Retrieved from https://www.iea.org/reports/what-next-for-the-global-car-industry

IEA. (2025b). *Cost of Capital Observatory*. Retrieved from https://www.iea.org/reports/cost-of-capital-observatory

IEA. (2025c). *Energy Prices*. Retrieved from https://www.iea.org/data-and-statistics/data-product/energy-prices

IEA. (2025d). *Global Hydrogen Review 2025.* Retrieved from https://www.iea.org/reports/global-hydrogen-review-2025

IEA. (2025e). *The battery industry has entered a new phase*. Retrieved from https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase

InfoLink. (2025). *InfoLink Consulting*. Retrieved from https://www.infolink-group.com/

International Aluminium Institute. (2025). *Primary Aluminium Smelting Power Consumption.* Retrieved from https://international-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/C

International Labour Organization. (2025). *Application of International Labour Standards 2025.*

IRENA. (2025). *Renewable power generation costs in 2024.*

Japan External Trade Organization. (2025). *Japan External Trade Organization*. Retrieved from Japan External Trade Organization: https://www.jetro.go.jp/world/search/cost.html

Joint Research Centre. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.* European Union. Retrieved from https://publications.jrc.ec.europa.eu/repository/bitstream/JRC119941/rms_for_wind_and_solar_published_v2.pdf

Krishnan, S., Koning, V., De Groot, M. T., De Groot, A., Mendoza, P. G., Junginger, M., & Kramer, G. J. (2023). Present and future cost of alkaline and PEM electrolyser stacks. *International Journal of Hydrogen Energy*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360319923022590

LESS. (2025). *LESS AISBL Awards First Certifications to Six Companies – A Step Toward Decarbonised Steel*. Retrieved from https://lowemissionsteelstandard.org/details/LESS-AISBL-Awards-First-Certifications-to-Six-Companies

Li, J., & Ho, M. (2024). End-year China wind power installation rush reduces electric system reliability. *Energy Economics*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0140988324002159?

McKerracher, C. (2024). China's Batteries Are Now Cheap Enough to Power Huge Shifts. *Bloomberg*. Retrieved from https://www.bloomberg.com/news/newsletters/2024-07-09/china-s-batteries-are-now-cheap-enough-to-power-huge-shifts

National Renewable Energy Laboratory. (2019). *A detailed Wind Turbine Blade Cost Model.* Retrieved from https://docs.nrel.gov/docs/fy19osti/73585.pdf

New Energy and Industrial Technology Development Organization. (2024). *Overview of the Green Innovation Fund Projects*. Retrieved from https://green-innovation.nedo.go.jp/en/about/

OECD. (2019). *Measuring distortions in international markets: The aluminium value chain.* Retrieved from https://www.oecd.org/content/dam/oecd/en/publications/reports/2019/01/measuring-distortions-in-international-markets-the-aluminium-value-chain_058cb425/c82911ab-en.pdf

OECD. (2022a). *An Industrial Policy Framework for OECD Countries*. Retrieved from https://www.oecd.org/content/dam/oecd/en/publications/reports/2022/05/an-industrial-policy-framework-for-oecd-countries_233e3061/0002217c-en.pdf

OECD. (2022b). *Quantifying industrial strategies.* Retrieved from https://www.oecd.org/en/publications/quantifying-industrial-strategies-quis_ae351abf-en.html

OECD (2024a). *The Role of Incentives in Investment Promotion*. Retrieved from https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/12/the-role-of-incentives-in-investment-promotion_f27f6ff4/e3338264-en.pdf

OECD. (2024b). *Quantifying the role of state enterprises in industrial subsidies.*

OECD. (2024c) Retrieved from OECD Inventory of Support Measures for Fossil Fuels 2024: https://www.oecd.org/en/publications/oecd-inventory-of-support-measures-for-fossil-fuels-2024_a2f063fe-en.html

Oxford Economics Limited. (2025). *Global Industry Service*. Retrieved from https://www.oxfordeconomics.com/service/subscription-services/industries/global-industry-service/

Reichartz et al. (2024). *Introducing a partial bottom-up model for onshore wind turbine CAPEX estimation.*

Responsible Steel. (2024). *U. S. Steel earns world's first ever certification for ResponsibleSteel Certified Steel at Big River Steel*. Retrieved from https://www.responsiblesteel.org/news/u-s-steel-earns-worlds-first-ever-certification-for-responsiblesteel-certified-steel-at-big-river-steel

Reuters. (2025a). China polysilicon firms plan $7 billion fund to shut a third of industry capacity. *Reuters*. Retrieved from https://www.reuters.com/sustainability/climate-energy/china-polysilicon-firms-plan-7-billion-fund-shut-third-industry-capacity-2025-07-31/

Reuters. (2025b). China solar group, regulator propose tendering reforms to boost prices. Retrieved from https://www.reuters.com/business/energy/china-solar-group-regulator-propose-tendering-reforms-boost-prices-2024-09-02/

Reuters. (2025c). *China's solar giants quietly shed a third of their workforces last year.* Retrieved from https://www.reuters.com/business/world-at-work/chinas-solar-giants-quietly-shed-third-their-workforces-last-year-2025-08-01/

Rio Tinto. (2024). *Rio Tinto signs Australia's biggest renewable power deal as it works to repower its Gladstone operations.* Retrieved from https://www.riotinto.com/en/news/releases/2024/rio-tinto-signs-australias-biggest-renewable-power-deal-as-it-works-to-repower-its-gladstone-operations

RMI. (2024). *Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future*. Retrieved from https://rmi.org/wp-content/uploads/dlm_uploads/2024/09/green_iron_corridors_steel_supply_chain_report.pdf

S&P Global. (2024). *BriefCASE: South Korean companies eye low-cost LFP battery market*. Retrieved from https://www.spglobal.com/mobility/en/research-analysis/briefcase-south-korean-companies-eye-low-cost-lfp-battery-mkt.html

S&P Global. (2025). *S&P Capital IQ*. Retrieved from https://www.spglobal.com/market-intelligence/en/solutions/products/sp-capital-iq-pro

SSAB. (2025). *SSAB achieves IEA threshold for near-zero CO_2 emissions steel*. Retrieved from https://www.ssab.com/en/news/2025/09/ssab-achieves-iea-threshold-for-nearzero-co2e-emissions-steel

Stadler, K. R.-J. (2025). *Exiobase 3*. Retrieved from https://zenodo.org/records/14614930

Totaro, P. (2023). China's wind turbines are bigger than ever – but they're no more financeable in the West. *ReCharge*, https://www.rechargenews.com/wind/chinas-wind-turbines-are-bigger-than-ever-but-theyre-no-more-financeable-in-the-west/2-1-1403767

Touloupas, G., & Hansen, B. (2024). From PERC to TOPCon: Navigating the evolution of solar technology. *PV Tech*. Retrieved from https://www.pv-tech.org/cea-on-perc-and-topcon-solar-technology/

Tullo, A. (2024). Eni to shutter plants in Italy. *C&EN*. Retrieved from https://cen.acs.org/business/petrochemicals/Eni-shutter-plants-Italy/102/web/2024/10

United Nations Trade and Development. (2025). Retrieved from Data Hub: https://unctadstat.unctad.org/EN/RcaRadar.html

US Department of Energy. (2024). *HFTO Hydrogen Production Overview*. Retrieved from https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/p000_peterson_2024_obf4cdd3d-5f59-4fe7-88f9-bca9b4de74c6.pdf?sfvrsn=aab8e82_4

US Energy Information Administration. (2025). *Petroleum & Other Liquids*. Retrieved from https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=m_epllea_eex_nus-z00_2&f=a

World Bank. (2017). *Industry Competitiveness and Jobs*. Retrieved from https://documents1.worldbank.org/curated/en/171501476992732097/pdf/109333-WP-REVISED-PUBLIC.pdf

World Economic Forum. (2018). *The Global Competitiveness Report 2018*. Retrieved from https://www.weforum.org/publications/the-global-competitveness-report-2018/

World Economic Forum. (2025). *First Movers Coalition - Steel*. Retrieved from https://initiatives.weforum.org/first-movers-coalition/steel

World Steel Association. (2025). *World Steel in Figures 2025*. Retrieved from https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2025/

Chapter 8. Strategic considerations for clean energy technology supply chains

Highlights

- Securing clean energy technology supply chains depends on minimising the potential economic and social risks resulting from a disruption. These can be significant: we estimate that each month of an interruption in battery supply chain exports from the largest supplier would lead to output loss worth USD 17 billion from electric car plants elsewhere, with almost two-thirds of these losses in the European Union.
- Enhancing supply chain security can go hand in hand with improving industrial competitiveness. These objectives are deeply intertwined and have profound implications for other policy goals beyond energy. Supply chain security improves with diversification, which can be supported by increasing domestic production in more countries. But this comes at a cost, especially if the domestic industry struggles to become competitive. There can be trade-offs: a narrow focus on improving cost advantage by sourcing components as cheaply as possible risks leaving the industry more vulnerable to upstream supply disruptions.
- Improving the competitiveness of domestic manufacturing can help maximise the economic returns and create other benefits, such as for innovation. The economic opportunity is increasing: the combined global market value for key technologies grows in all IEA scenarios, reaching almost USD 3 trillion by 2035 in the Stated Policies Scenario (STEPS), up from nearly USD 1.2 trillion today.
- Working towards these policy objectives is complex, as such technologies encompass a broad set of components and materials, and require diverse competencies and processes. For most countries, it is not possible to compete in all steps of a technology supply chain, let alone in all supply chains. Governments will therefore need to be mindful of respective strengths and weaknesses when designing industrial strategies and prioritising action.
- Strategic international partnerships – based on trade or industrial agreements, and including foreign direct investment – are central pillars of a co-ordinated strategy to advance on both policy objectives. Policy measures that foster economies of scale, support innovation and address energy prices also provide opportunities for governments to boost competitiveness.

Competitiveness and security objectives are intertwined

Ensuring the competitiveness and enhancing the security of clean energy technology supply chains are distinct but not wholly independent policy objectives. Supply chain security is first and foremost about minimising the potential economic damage that could result from a supply chain interruption. Ensuring competitiveness is a matter of maximising the domestic economic returns that could arise from developing and operating clean energy technology manufacturing facilities and reaping the associated innovation benefits.

For clean energy technologies, working toward both of these policy objectives simultaneously is a complex undertaking. Clean energy technologies encompass a broad set of component technologies which require a wide range of industrial competences, from energy- and capital-intensive processes, to precision automated chemical processes or advanced mechanical processing steps. For most countries, it would be very difficult and hardly desirable to develop and maintain international competitiveness for all clean energy technology supply chains, or for all steps in a given supply chain.

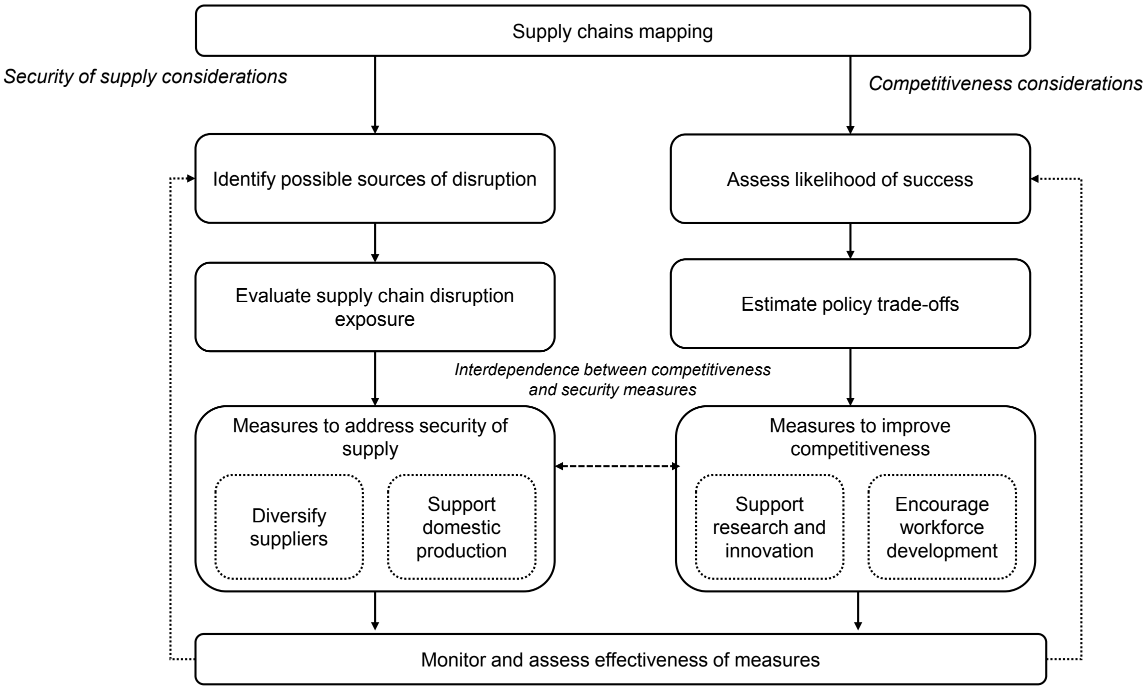
As in most high-tech sectors, specialisation is often a winning strategy, and so taking into account comparative advantages is important when designing industrial strategies. Similarly, ensuring appropriate levels of security of supply for clean energy supply chains can require significant government action to diversify highly concentrated supply chains. Policies aimed at either increasing security of supply or improving the competitiveness of industries are likely to come at a cost, at least in the short term.

Ensuring competitiveness and enhancing security of clean energy technology supply chains can, in some instances, go hand in hand. For example, the security of supply chains can be improved by increasing the diversity of supply, so that any reduction in access to one particular source of supply could be compensated by alternative sources. For clean energy technology supply chains, increasing the share of domestic production can be a viable pathway to diversifying supply, whereby a focus on the development of a competitive domestic industry can reduce the cost implications of increased domestic production. A diverse supply chain can prove to be an advantage and improve the competitiveness of domestic industries in case of supply chain disruptions.

Efforts to ensure competitiveness and enhance security of supply are, however, sometimes in tension with one another. Specialising in the final step of the supply chain is often a strategy to enter international markets competitively, since it offers more product diversification options than upstream products, which tend to be more commodified. However, a narrow focus on uniquely reducing production costs by sourcing upstream components as cheaply as possible, and downplaying technology performance and quality, can leave an industry highly exposed to disruptions from a small number of low-cost suppliers. For example, producing solar modules by purchasing solar cells and wafers exclusively from the lowest-cost producer country (The People's Republic of China, hereafter, "China") may result in competitively priced modules, but does not reduce supply chain risks.

Given the close connection between these two policy objectives, some considerations are shared between the two, while others are best considered in isolation. To help governments navigate the complexities involved in selecting or prioritising which clean energy technology supply chain steps to focus on for their security or competitiveness goals, we provide in this section a series of considerations. While these considerations are geared towards clean energy technologies, many of these aspects are also relevant for other established industries (specific considerations for energy-intensive industries are provided in Box 8.1).

Figure 8.1 Strategic considerations for enhancing security of supply and competitiveness



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Efforts to enhance security of supply and the competitiveness of clean energy technology manufacturing need to be co-ordinated to maximise impact.

The dynamic nature of clean energy technology supply chains and technologies means that market conditions can change rapidly, and potential opportunities and risks may change over time. It is therefore important to include, from the outset of any policy targeting these objectives, a periodic review to assess the effectiveness of the policies in place and their suitability to current market conditions. Any measures put in place can be assessed with regards to competitiveness and security of supply simultaneously, to understand how synergies and trade-offs are playing out. The following set of considerations could be made while assessing progress:

- Are the components used in the supply chain being sourced from a wider set of supplier countries and/or companies?
- Have domestic manufacturers increased their local, or global market share?
- Has innovation activity (measurable in number of patents, private R&D spending, or number of employed researchers) in the given industry increased?
- Have local prices for a given technology increased or decreased compared to the global average?
- Have price changes impacted the local demand for a given technology?
- Are local producers better equipped to deal with potential supply disruptions?

Box 8.1 Strategic considerations for energy-intensive industries

The competitiveness and operations of all energy-intensive industries will be affected by the energy transition, but the pace and scale of these changes are inevitably uncertain. In this context, governments looking to ensure security of supply and competitiveness for these industries need both vision and flexibility, adapting industrial strategies and energy policy as the market evolves. Security of supply is less of a concern for most energy-intensive industries since raw materials (e.g. iron ore, bauxite, limestone) and energy can be sourced from a large set of global suppliers. Competitiveness, on the other hand, is tightly related to energy prices, and the energy transition is likely to further strengthen this link (see Chapter 7).

A wide array of policy measures are at governments' disposal to improve local competitiveness, but many come at a cost. Trade-offs exist between the cost of support measures and the risks associated with deindustrialisation, such as employment losses, erosion of technical expertise, and weakened security of supply for downstream industries. Governments may consider focusing first of all on "low-regrets" actions – measures that strengthen both competitiveness and resilience under a wide range of future scenarios – and identifying strategic sectors that are vital for economic, defence and supply chain security. Tools may include energy costs mitigation, trade measures, or support to mitigate production cost premiums for low-emissions production routes. Considerations vary according to different regional factors, including each country's energy prices and existing industrial base, and interlinkages between energy-intensive industries and other strategic local industries downstream along supply chains. Different archetype cases could be identified across regions based on different combinations of those factors.

Archetype #1: High energy price environment and leading industries

Prioritise energy efficiency: While energy-intensive industries inherently have the economic incentive to improve energy efficiency (particularly when operating in high energy price locations), any potential further improvements should be exploited to minimise energy costs. Energy efficiency can be further incentivised through regulation, information dissemination and financial schemes (IEA, 2025c). However, major energy efficiency investments in conventional plants may not be economically justified if they are approaching the end of their operational lifetimes.

Leverage comparative advantages: Long-standing know-how, product quality, and strong customer links will remain important strengths to maintain the competitive advantage of these industries in countries that fit into this archetype. Governments can foster sector-specific innovation and deploy expertise at national labs or universities to help retain or increase their competitive edge. This, however, may not be sufficient to offset long periods with significantly higher energy costs.

Build strategic partnerships: Public leadership can help companies create new cross-border supply chain connections by removing barriers, aligning incentives and co-ordinating the build-out of infrastructure. Governments could consider establishing win-win partnerships to offshore the most energy-intensive steps of supply chains to regions with cheaper energy, and focus on retaining downstream jobs and more specialised semi-finishing and finishing industries (see Chapter 7).

Archetype #2: Low energy price environment and emerging or existing industries

Seize the opportunity: Governments can seek to develop partnerships to develop strategic energy-intensive industries to boost production for exports and growing domestic markets, to enhance infrastructure and to encourage economic development. Countries facing high energy prices with leading established industries could be good candidates for partnerships. Stable policy frameworks are vital to attract investment in new or emerging industries: policy and regulatory uncertainty are a major cause of high financing costs and lower investment to date in many emerging markets and developing economies (IEA, 2025b).

Strengthen local capacity: Partnerships could help establish domestic material production to supply the domestic market as well as opening new export markets, reducing import dependence for the producing country and strengthening supply chain diversification and competitiveness of downstream industries in targeted export countries. To avoid any form of extractive investment, agreements should be mutually beneficial, so that the host country benefits from local job and broader economic developments. Over time, these investments can build know-how and position countries to move further up the value chain.

Focus on flexible assets: Investing in production capacity that is near-zero emission capable can be a good strategy to diversify and expand access to targeted export markets that have or will have different environmental requirements. This would also allow industrial assets to benefit from ongoing or upcoming infrastructure developments in the future that allow for the use of alternative energy sources.

Archetype #3: Low energy price environment and leading industries

Maintain global roles: Continue to exploit comparative advantages, while fostering a diverse domestic base to reduce geopolitical risks. Focus on high quality, specialised and innovative products to build an industry that is resilient to potential changes in relative energy prices and global competition.

Secure supply chains: Where geographic concentration is high, diversify export and import partners, encourage strong domestic supply chains and explore alternative sources of raw materials.

Positioning for the energy transition: Consider investments that could serve global demand for low-emissions products and identify locations that are best suited for low-emissions production. Flexible and near-zero capable designs could offer a compromise between retaining competitiveness in existing markets, while providing a head-start for low-emissions material markets that could grow rapidly in the future.

Mapping the supply chain

A useful starting point is to map the entire supply chain with a view to the positioning of a given country at every step of the supply chain, identifying how each step is connected to economic activities in other supply chains within the country, and understanding the key cost components for each technology. This mapping stage is crucial before developing policies targeting both security of supply and competitiveness.

Clean energy technology supply chains often comprise an array of complex components, materials and minerals. While some inputs will be common to many supply chains (e.g. copper), others will be highly specialised (e.g. a specific rare earth element). Mapping a supply chain requires careful technical assessment of each component, which in turn requires data. Data on fundamental quantities like demand, production, manufacturing capacity and trade flows is often unavailable, incomplete or outdated. The data compiled for this and other IEA publications on energy technology supply chains constitute important contributions to improving the data landscape in this area. Nonetheless, further international collaboration on data collection methodologies and standards could help facilitate this crucial mapping step.

Cybersecurity considerations might have implications for the assessment of risk related to certain steps of the supply chain. For this reason, distinguishing between “smart” components – i.e. those that have the potential to compromise the digital security of the networks where they operate, such as inverters or advanced meters – and pure hardware components (e.g. solar PV modules) is particularly important.

Moreover, clean energy technology supply chains are often composed of technologies or components that continuously evolve as the technologies advance and so supply chain mappings are not static; keeping abreast of the ongoing technological trends can help anticipate changes. Tools such as the IEA’s C*lean Energy Technology Guide* (IEA, 2026a) and the IEA’s *The State of Energy Innovation annual report* (IEA, 2026b) can help in this regard, but may need to be complemented by more granular assessments adapted to the technology and regional context.

Understanding the production cost structure of each technology can help governments to shed light on the main drivers behind supply chain security and competitiveness, including whether a technology may be limited by access to critical minerals, exposed to high energy prices or constrained by capital-intensive manufacturing steps.

Key considerations on security of supply

Improving the security of supply for a given clean energy technology supply chain requires a clear analytical framework to ensure the efficacy and efficiency of suggested measures. The potential impact of a disruption is directly linked to the level of concentration (i.e. the share of imports sourced by a single country, entity or facility) and the fungibility in the most vulnerable step along the supply chain, as well as to the economic relevance of industrial activities that would be affected by such disruption.

Assessing possible sources of disruptions

The first step is to list potential hazards – be they geopolitical, physical or others – that might affect supply chains and lead to disruptions, and assess their likelihood. Some trade measures, in particular, can be extrajudicial, meaning that they might affect production even outside the borders of the country in question. Physical hazards, meanwhile, can include natural hazards or other accidents, which might affect the ability to produce or transport a given good. A more comprehensive discussion of supply chain risks is provided in Chapter 6 of *Energy Technology Perspectives 2023* (IEA, 2023).

Assessing the likelihood of disruption depends on many factors that are not necessarily tied to concentration. However, the higher the supply concentration, the greater the likelihood that a disruption may have sizeable consequences. An assessment of global concentration levels is a useful start, but governments may need to develop more granular and country-specific assessments to better inform their decisions. This includes mapping precise supply chains for their own country and identifying critical trade infrastructure, including key routes, facilities and institutional arrangements that support them. Some of the key information to consider for each individual component in a supply chain includes:

- **Geographical concentration**: Share of supply dependency by country or region.
- **Company concentration**: Share of supply dependency by company or conglomerate. Knowledge about the ownership of the companies involved can also help assess risks related to extrajudicial trade measures.
- **Facility concentration**: Share of supply dependency of each manufacturing facility.
- **Trade concentration**: Share of supply sourced by trade route, including maritime routes and land-based routes. Maritime chokepoints and ports can be critical for the security of maritime trade, while individual highways or railways can be critical for land-based trade.

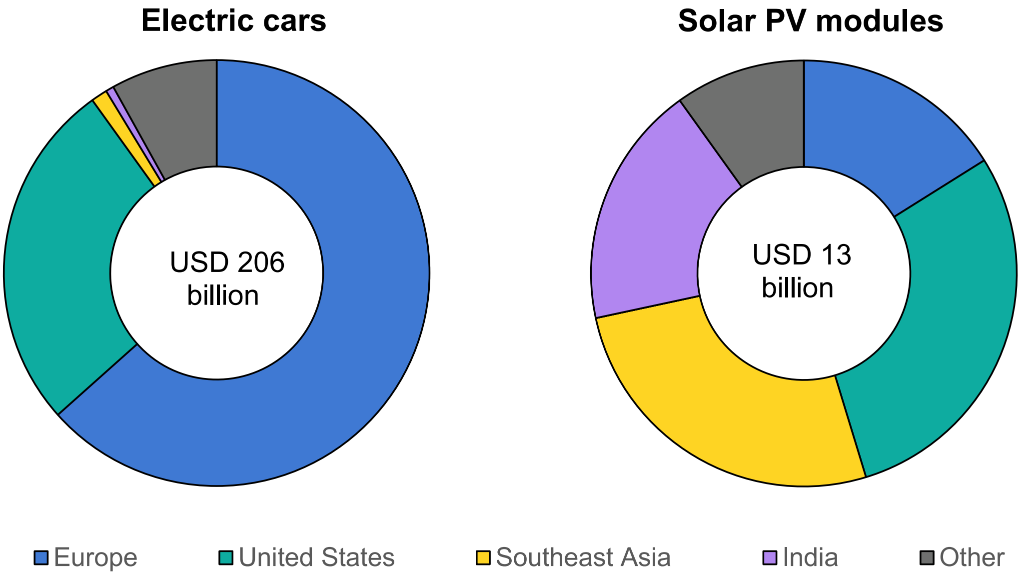
Assessing potential impacts of disruptions

A potential interruption of supplies for clean energy technologies does not have the same disruptive impact on the economy as an interruption of energy supplies. Energy is necessary to run and operate equipment used in all productive activities as well as in dwellings. As such, a halt or restriction of energy supplies has impacts that are measured economy-wide, and has, in several instances, resulted in considerable economic damage that necessitated several years of recovery.

Clean energy technologies, meanwhile, are capital equipment, which either produces energy carriers (e.g. solar PV, electrolysers) or delivers energy services (e.g. electric cars, heat pumps). An immediate supply chain disruption can severely affect the industries directly involved, making it essential to understand how much economic activity depends on a given technology or component. At the economy-wide level, however, the impact may remain manageable, helped by alternative suppliers and temporary substitution with fossil fuel powered technologies.

When imports of an intermediate product are reduced or halted, factories that depend on that input must scale back or suspend production, and output prices may rise. The first-order monetary loss in such a scenario is the value of the lost output. These estimates reflect the immediate, direct loss from factories that cannot operate without the affected inputs. They do not capture how the wider economy might adjust over time. For example, we estimate that each month of a halt in battery cell exports from China would lead to an output loss of USD 17 billion from electric car factories elsewhere, with facilities in the European Union – the largest importer – accounting for almost two-thirds of the losses. Each month of disruption of Chinese exports of wafers would mean that solar PV cell production plants outside China lose output worth around USD 1 billion, with more than 40% of the affected output located in Southeast Asia and India. A sustained halt to production may have wider economic and social impacts, including layoffs.

Figure 8.2 Value of produced goods that would be affected by a year-long interruption in upstream supply chain components, by region, 2024



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A halt in exports of battery cells or solar PV components from China would lead to annual output losses worth billions in manufacturing facilities elsewhere.

The risks of disruptions to the supply of clean energy technologies have become evident as a result of recent measures. The full implementation of such measures – though uncertain – could restrict access to capital equipment, with direct implications for the ability of firms to maintain or expand manufacturing capacity. For example, since 2023, China has expanded export controls to cover high-purity graphite, rare earth elements, advanced lithium iron phosphate (LFP) technologies and, in some cases, the specialised equipment used to produce them (IEA, 2026b). Similar restrictions have been applied elsewhere, including the

United States' controls on advanced semiconductor manufacturing tools (US Congressional Research, 2025). Further detail is provided in Chapter 4.

Above and beyond the potential impact of disruptions to the supply of technology hardware, there is a need for particular care related to devices connected to the internet in the context of clean energy technology supply chains. The connectivity of such devices can have security consequences if exposed to malicious cyber actions (see Box 6.1).

Measures to address security of supply risks

There is no single accepted definition of supply chain security, nor is there a fixed threshold for what constitutes adequate diversification. A safe level of diversification can be understood as a configuration in which alternative supply options, whether domestic or international, and sufficient flexibility in the system, allow major disruptions to be absorbed without causing economic impacts greater than the cost of maintaining that resilience.

Supply chain security can be improved either by reducing the probability of hazards occurring, or by reducing the impact that these may have. Increasing the diversity of supply is a key means for doing so and requires action by the private and public sector alike. Private actors often have their own risk mitigation measures already in place, although they may not always fully price-in the downstream impacts of disruptions, and might struggle to deal with "unknown unknowns" for which probability assessments are impossible to conduct (OECD, 2025).

Governments have different tools at their disposal. They can facilitate diversification by supporting domestic supply (where domestic production only accounts for a small share of total supply) and by collaborating with other governments to scale up production in their countries and build partnerships. They can also trade with a more diverse set of countries through collaboration; they can discourage excessive reliance on any single supplier and let the market adjust; or they can deploy a combination of both measures. Collaboration with partner countries that have competitive advantages in a given technology is an obvious pathway. The industrial competitiveness assessment in Chapter 7 can help identify potential partners to target, but country-specific assessments will need to be conducted. Measures available to governments include:

- **Foreign direct investment:** Governments can lay the groundwork for investment in partner countries with lower structural cost by establishing memorandums of understanding or other bilateral agreements, which typically serve as a first step in defining areas of co-operation. These agreements can then be operationalised through targeted financial support measures – such as loan guarantees for investments from domestic development finance institutions – to expand production capacity in specific supply chain steps.

- **Trade agreements:** Governments can facilitate trade agreements with partner countries (other than the largest trading partner) that have existing or growing production capacity for a given step of the supply chain in order to foster access to those products.
- **Trade measures:** Governments can use trade policy tools to disincentivise or incentivise trade with other suppliers. The impact on trade costs could impact trade routes and increase diversification.
- **Conditions for public procurement or subsidies:** Adding supply chain security-related criteria to access subsidies or public procurement tenders. Such a measure could incentivise the sourcing of a given supply chain from sources other than from the largest producer.

Supporting domestic supply can also increase supply security. Governments have a very wide range of tools at their disposal to support domestic supply, again either supporting domestic production or affecting imports.

- **Tariffs and non-tariff measures** can limit exposure of the market for a given technology to the global market, creating an incentive for domestic production.
- **Local content requirements** can create more limited pockets of market protection that can support domestic production.
- **Production subsidies** targeting either capital or operational expenditure can stimulate domestic producers.

These measures can have rapid impacts, but they always come at a cost and do not solve the underlying structural issues. For that reason, many of these measures must be time-bound and monitored carefully, and governments will need to balance security objectives with affordability considerations. Some of the measures above can result in domestic price increases. Therefore, understanding how the market would respond to higher prices is important to gauge the amount of demand destruction that such a measure would entail. Stimulating domestic production can be less costly for countries that already have a globally competitive industry for the target technology. Nonetheless, boosting domestic production requires careful balance with and attention to competitiveness (see the next section).

Supporting recycling and the circular economy can also help support security of supply. While recycling is particularly important for minerals and metals, circularity, together with other demand-side measures, can help reduce overall levels of demand. For example, supporting schemes to re-use batteries from automotive applications in stationary storage applications can reduce the overall demand for batteries, effectively generating a domestic demand source.

Technology substitution can also play an important role in reducing medium- to long-term supply chain vulnerabilities. The early commercialisation of sodium-ion batteries could ease reliance on a wider range of battery metals. Permanent magnets that use fewer rare earth elements and transformers that avoid grain-oriented electrical steel could also offer substitution pathways. Some of these options can already be reflected in procurement and tendering decisions, while others belong to medium- and long-term industrial strategies.

Stockpiling is also a typical tool for enhancing security of supply, but in the case of clean energy technologies this is most likely to only be effective for minerals and metals (IEA, 2026c). Several countries are already developing or expanding strategic stockpiles for critical minerals such as rare earth elements (Bloomberg, 2026). By contrast, most clean energy technologies and their components are too diverse and complex for stockpiling to be a universally useful tool. However, certain clean energy technologies are increasingly moving towards commodification – for example, solar PV supply chain components are increasingly standardised. Commodified technologies might eventually be more suitable for stockpiling; however, technical considerations regarding shelf life should always be considered.

Prioritising competitiveness actions

It is important to consider that supporting a domestic industry for strategic reasons comes at a cost to government budgets and to consumers when the industry is not cost-competitive. Such support must be used carefully, as investing in sectors with weak long-term prospects can create path dependence and lock-in effects that become costly and difficult to unwind. Yet, in many cases, unlocking the economic opportunities of a new industry requires government support to increase competitiveness. Achieving low costs of production is an important factor for competitiveness, but it is not the only one. Producing high-performance, innovative, or specialised products is another way to gain or retain global competitiveness. For example, some producers outside China are specialising in higher-value and less price-sensitive markets that are less common in Chinese portfolios, such as high-density nickel manganese cobalt (NMC) batteries, flexible proton exchange membrane (PEM) electrolysers, or highly reliable wind turbines.

An opportunity assessment framework – which assesses the likelihood of success of competitiveness measures and quantifies the benefits that could be achieved if the measures were successful – can serve as a guiding principle.

Assessing the likelihood of success

There are many examples of government policies aimed at boosting the competitiveness of specific industries. The extent of success varies, and there is a large body of literature on this topic that allows to draw lessons on the reasons for success or the conditions under which certain measures can become counterproductive (IMF, 2025). The topic remains complex, nevertheless, but it is clear that there are several factors to take into account for countries that aim to develop a competitive industry on a given technology. Without aiming to be exhaustive, we present a list of key considerations here:

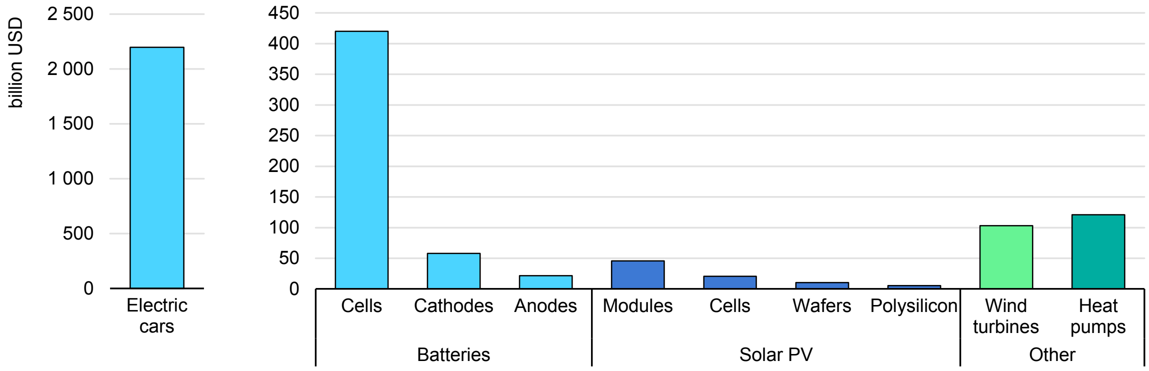
- **Size of the competitiveness gap:** Understand the level of the production cost difference between a local industry and the lowest-cost producers at the technology frontier (See Chapter 7). Distinguish between structural reasons (labour, energy) for the cost gap and technology or know-how related reasons.
- **Synergies with existing industries**: Most countries have specialised in certain sectors and have developed a pool of skilled workers for that sector; it is therefore important to map how new industries might interact with existing industries, both in terms of demand and supply.
  - **Supply:** For countries with strong mechanical industries (transport equipment, aerospace, machine tools) it might be easier to establish a competitive clean energy technology industry that requires large mechanical components (wind is a key example), as skills can more easily be transferred. Countries with specialised electronics industries might have a workforce and industrial environment that is more conducive to achieving a competitive solar PV or battery industry. For countries starting with little or no relatable industries, it can be more difficult to reach international competitiveness.
  - **Demand:** it is important to clarify the extent to which certain clean energy technologies might interact with other economic sectors. Batteries are a key example, with their strong connection to electric car manufacturing, as well as with growing demand sectors, such as grid storage or the defence sector.
- **Level of maturity of the industry**: It is important to understand the level of maturity of a clean energy technology industry at home and in other countries. Infant industries can achieve rapid production cost declines as production volumes increase, making them stronger candidates for targeted support. Mature industries, by contrast, see slower productivity and cost improvements, limiting the gains that policy intervention can deliver. Evidence of sustained cost declines in a certain industry is a good indication that it might eventually reach global competitiveness under the right circumstances.
- **Availability of trade partners:** Assessing the feasibility of meaningful co-operation with trade partners that already produce, or have the potential to produce, certain supply chain components at a competitive cost, is important to determine a balanced strategy for international collaboration in order to help domestic industries reach global competitiveness.

Assessing the potential costs and benefits

Enhancing the competitiveness of an existing industry – or establishing a new one – requires careful consideration of the potential costs and benefits of government measures. While these will typically be linked to the policy measures that are ultimately chosen, there are some upfront considerations to take into account ahead of the design of support schemes. A non-exhaustive list includes the following key questions:

- **What is the potential market size?** The potential market size of a given technology provides an indication of the future revenues for companies in a given industry. Although a large market in itself does not necessarily make an industry strategic from a policy perspective, it is nonetheless a simple metric that reveals the upper bound of the economic opportunity involved. Distinguishing between domestic and global market sizes can inform strategy, as achieving competitiveness may be more feasible in domestic markets than in international ones.
- **Can the industry become profitable?** Whether or not a productive industry can become profitable is an important consideration as to its ability to become self-sustaining and generate growth. Beyond demand projections, profitability depends on structural characteristics such as market size, the underlying cost structure of production (including capital intensity and learning-curve potential), and the degree of competitive intensity shaped by market concentration and barriers to entry. Predicting profitability is very difficult, but economic analysis can help to identify cases in which reaching profitability is very unlikely and guide policy makers toward interventions that use public resources most effectively.
- **Does the industry have important employment potential?** Supporting the creation of jobs is an important policy consideration, but not all industries are equally labour-intensive. Assessing the impacts of a prospective investment on the creation of a future workforce, as well as on the types and skill level of jobs can help size the benefits of gaining competitiveness in each industry.
- **What is the innovation potential?** Innovation is a key engine of economic growth, which makes it desirable for policy support to an industry to generate know-how and high-tech products. Certain industries have higher innovation intensity than others. Therefore, gauging the innovation spillovers from a certain industry is important to quantifying the benefits of government action.

Figure 8.3 Global market size by selected clean energy technology in the Stated Policies Scenario, 2035



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The market size potential varies widely across different clean energy technology supply chain steps.

Measures to improve competitiveness

Closing the cost-competitiveness gap in clean energy technology manufacturing is possible, but requires a focus on areas where efficiency gains, scale effects and innovation can make a particular difference rather than only trying to address structural disadvantages that concern access to cheap energy or labour. Efforts to improve competitiveness can be costly at the start as investments and support measures might be required, while economic and social benefits might take some time to materialise. Lithium-ion battery production is a key example: the production cost in Europe could be cut by over 25% through measures to improve manufacturing efficiency and secure access to cheaper components, which are key opportunities for policy action (see Figure 7.20).

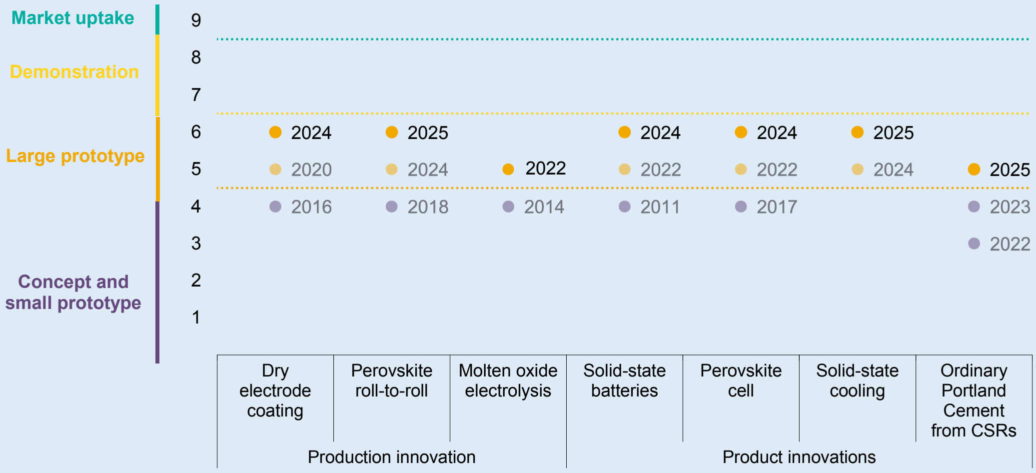
Economies of scale are indispensable for any technology that can be mass-manufactured, and no manufacturer will invest in new capacity without confidence in future demand. Such confidence is closely linked to government policy, and the tools are available and proven: energy efficiency and emissions standards for road vehicles, for example, give clarity to investors on the market opportunity for electric vehicles and batteries. Targets for clean energy deployment and long-term public procurement programmes are other potential tools. Large, predictable markets also encourage standardisation, learning by doing and lower unit costs – a key driver behind wind turbine price reductions in recent years. Tax credits, concessional loans and investment guarantees can help attract capital for larger plants, although the goal must be to reach competitive scale. For those reasons, "ramp up" subsidies might be considered that help protect firms in reaching commercial production but have a clear end date to ensure that subsidy reliance does not translate into poor performance.

Innovation is a necessary condition for success, though insufficient on its own. Governments can make a difference through direct involvement in research, development and demonstration projects, or through incentives for private sector projects. Achieving technology breakthroughs is a desirable outcome, but only if they deliver significant improvements over today's low-cost and sufficiently performing products. Other global producers will inevitably continue to innovate and optimise at the same time, which means that closing the innovation gap is a moving target. Public funds are usefully focused on technologies that promise significant performance gains, or that can help lower the production cost gap with others, or both (Box 8.2). This requires an approach that supports early-stage pilots and demonstrations, embeds mechanisms to learn from these projects, and includes clear conditions for phasing out support as technologies mature and become commercially viable.

Box 8.2 The role of innovation in boosting competitiveness

Technological innovation has been central to reducing costs and improving the performance of clean energy technologies, and much of today's deployment is possible only thanks to past advances. Innovation can reshape the competitive landscape for a given technology in three main ways: by lowering manufacturing costs; enabling designs with superior performance compared to existing options; and creating products that combine improved performance with manufacturing processes that rely on cheaper inputs. Several emerging technologies in manufacturing and product design have recently reached the demonstration phase and could soon be commercialised on a large scale.

Figure 8.4 Technology readiness level timeline for selected emerging clean energy technologies and production processes



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Notes: CSRs = calcium silicate rocks (e.g. basalt). Solid-state cooling uses caloric effects in solid materials (e.g. baro-, magneto-, elasto- and electro-caloric) instead of vapour compression refrigeration.
Source: IEA, 2026b.

Manufacturing costs can be reduced through process innovations that improve efficiency. Those targeting energy efficiency can be especially relevant for narrowing the cost gap between China and advanced economies. For batteries, a promising next step is dry electrode coating – an emerging technology that eliminates solvents and the energy-intensive drying stage in battery cell manufacturing. This innovation could reduce energy use in the coating step by about 20% (Degen et al., 2023) and lower total cell manufacturing costs by around 5-10% versus conventional process, including CAPEX, labour and energy savings (Greitemeier et al., 2026).

New designs and technologies with superior performance can open markets and create a first-mover advantage for the countries that develop them, on the condition that they are supported by intellectual property rights protection, the availability of local expertise and the development of robust industrial ecosystem and supply chains (IEA, 2025a). Solid-state batteries (SSBs) are a leading example. They promise higher energy density and improved safety compared with today's lithium-ion batteries, which could provide a competitive edge to early developers. Yet, SSBs are expected to carry a higher price tag, at least initially, making them more suitable for premium market segments in the initial stages of deployment (see question 5 in Chapter 1).

Some technological innovations can simultaneously improve performance and enhance cost competitiveness. These include technologies that replace critical minerals with more abundant materials, or that require significantly less material and/or energy inputs while at the same time delivering superior performance. Such advances not only offer a first-mover advantage to countries that develop them, but also allow those countries to decouple from existing supply chains that were built on the basis of earlier competitive advantages. A particularly important example is perovskite solar cells. The material requirements for these cells are far lower than for conventional silicon cells, and many of the emerging manufacturing routes operate at lower temperatures (Afre and Pugliese, 2024). This means the energy intensity of production is considerably lower per unit of power output, lowering the impact of energy prices on cost competitiveness. These cells can be used in tandem with silicon cells, reducing the silicon requirements, or – in the longer term – could be used standalone, thus completely substituting silicon.

Encouraging international partnerships, whether through industry partnerships with established equipment makers or through government collaboration with trade partners, is another important area of potential action. New market entrants in complex industries, such as batteries or solar PV, often struggle with low manufacturing yields. Partnerships with established equipment makers can raise quality faster, enable transfer know-how and strengthen local supply chains. High-yield factories, with less waste and fewer defects, mean lower costs. To reinforce and scale these gains, governments can deepen broader international co-operation through coalitions of willing partners, more supportive trade agreements, and efforts to lower tariff and non-tariff barriers.

Lowering energy prices is a key priority in segments where energy costs strongly influence competitiveness, particularly for solar PV manufacturing. Structural measures, such as wholesale market reform and expanding the role of low-cost renewable generation, can provide competitive prices for energy-intensive and strategic clean technology manufacturing. This can significantly narrow the cost gap with other countries.

References

Afre and Pugliese. (2024). Perovskite Solar Cells: A Review of the Latest Advances in Materials, Fabrication Techniques, and Stability Enhancement Strategies. *Micromachines*, 192. Retrieved from https://www.mdpi.com/2072-666X/15/2/192

Bloomberg. (2026). *Trump to Launch $12 Billion Critical Mineral Sockpile to Blunt Relience on China*. Retrieved from https://www.bloomberg.com/news/articles/2026-02-02/trump-launches-12-billion-minerals-stockpile-to-counter-china

Degen et al. (2023). Energy consumption of current and future production of lithium-ion and post lithium-ion battery cells. *Nature Energy*. Retrieved from https://www.nature.com/articles/s41560-023-01355-z

Greitemeier et al. (2026). Costs and carbon footprint analysis of dry manufacturing battery LiFePO4-based cathodes. *Cell Reports Physical Science*. Retrieved from https://www.sciencedirect.com/science/article/pii/S2666386425006575

IEA. (2023). *Energy Technology Perspectives.* Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2023

IEA. (2025a). *How can innovation help secure future battery markets and mineral supplies?* Retrieved from https://www.iea.org/commentaries/how-can-innovation-help-secure-future-battery-markets-and-mineral-supplies

IEA. (2025b). *Cost of Capital Observatory*. Retrieved from https://www.iea.org/reports/cost-of-capital-observatory

IEA. (2025c). *Gaining an Edge.* Retrieved from https://www.iea.org/reports/gaining-an-edge

IEA. (2026a). *ETP Clean Energy Technology Guide.* https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.

IEA. (2026b). *The State of Energy Innovation.* Retrieved from https://www.iea.org/reports/the-state-of-energy-innovation-2026

IEA. (2026c). *Designing an effective strategic stockpiling system for critical minerals*. Retrieved from https://www.iea.org/commentaries/designing-an-effective-strategic-stockpiling-system-for-critical-minerals.

IMF. (2025). *World Economic Outlook.*

OECD. (2025). *OECD Supply Chain Resilience Review.* Paris.

US Congressional Research. (2025). Retrieved from https://www.congress.gov/crs-product/R48642

Annex - Definitions

Glossary

This glossary provides general information on terminology used in this report, including definitions of technologies, fuels and processes, as well as descriptions of scenarios used.

Ad valorem tariff: A tariff rate levied as a fixed percentage of the value of an imported product at customs. This value includes the product's price, in this report modelled as the LCOP 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.

Battery: Batteries considered in the *ETP-2026* 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 lithium-ion battery cells, except when discussing market sizes and import/export values, where it refers to final applications or traded goods (a combination of lithium-ion battery cells, packs and systems).

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 expenditures (or expenses).

Clean energy technology: An energy technology that results 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, Electrolysers, Heat pumps, Solar PV, and Wind.

Container shipping: 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* (IEA, 2021).

Current Policies Scenario (CPS): This scenario sets out a pathway for the future of the energy system in which no change in energy-related policies is assumed beyond what is already in place. The CPS therefore builds on a narrow reading of today's policy settings, only considering those that are adopted in legislation and regulation, and assuming no change, even where governments have indicated their intention to do so. Where existing policies target a range of outcomes, it is assumed that the lower end of the range is achieved. In the CPS, policies that are time-bound or that target specific years are not strengthened after they expire. Alongside this view of the policy landscape, the CPS also offers a generally cautious perspective on the speed at which new energy technologies are deployed and integrated into the energy system. It tends to project slower growth in the adoption of new technologies in the energy system than seen in recent years, or than projected in the STEPS.

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* (IEA, 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.).

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, SUVs and passenger 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-2026* 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.

HS codes: Harmonized System (HS) Codes are a standardised numerical system used 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 to 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 quota: 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. An absolute import quota strictly limits the physical quantify of a product that can enter into a country, while a tariff-rate import quota allows 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, specific tariffs, tariff-rate quotas (see the relevant entries in this glossary) 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: Includes 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 chokepoint: 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 batteries), as well as the value of batteries (pack or system) 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 to 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’’.

Net Zero Emissions by 2050 Scenario (NZE Scenario): This is a normative scenario that maps out a global pathway for the energy sector to achieve net zero carbon dioxide (CO_2) emissions by 2050, consistent with the long-term goal of limiting the rise in global average temperatures to 1.5°C (with a 50% probability). In contrast with previous editions, the NZE Scenario used in *ETP-2026* is no longer a low-overshoot scenario: it assumes that warming exceeds 1.5°C degrees for several decades before returning below 1.5°C by 2100. This adjustment reflects persistently high emissions in recent years and the slow deployment of some key technologies. Achieving this pathway requires not only a very rapid transformation of the energy sector but also large-scale deployment of CO_2 removal technologies, which remain unproven at large scale.

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 *ETP-2026*, 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 reflect the direction of travel of the global energy sector based on current energy-related policies, including those that have already been adopted, announced, or are in the advanced planning stage – even if they are not yet enshrined in law or regulations. Examples of the latter include power sector development plans aimed at achieving a certain mix of generation assets by a specific date, regulatory reforms in the transport sector and energy efficiency targets for appliances. Policy targets are not assumed to be automatically met: in each case, their prospects are assessed taking account of market, infrastructure readiness and financial constraints. The STEPS assumes that time-bound policies continue beyond the currently-stated durations and retain a similar pace of change. However, it does not assume that aspirational goals, such as those included in the Paris Agreement, are achieved.

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. 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-2026* and its respective modelling, this period is a calendar year. The default assumption the maximum practical utilisation rate is 85%.

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

AAM	anode active material
AC	air conditioner
ADD	antidumping duties
AE	advanced economies
AI	artificial intelligence
ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy with carbon capture and storage
BEV	battery electric vehicles
BF	blast furnace
BF-BOF	blast furnace-basic oxygen furnace
CAM	cathode active material
CAPEX	capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCDC	Concessional Custom Duty Certificates
CCfD	carbon contract for difference
CCS	carbon capture and storage
CCUS	carbon capture utilisation and storage
CDR	carbon dioxide removal
COP	coefficient of performance
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO_2	carbon dioxide

CPS	Current Policies Scenario
CSAM	Central and South America
CSPF	cooling seasonal performance factor
CVD	countervailing duties
DAC	direct air capture
DD	direct-drive
DFIG	doubly fed induction generators
DRI	direct reduced iron
DRC	Democratic Republic of the Congo
DSO	distribution system operator
EAF	electric arc furnace
EBIT	earnings before interest and tax
ECI	Economic Complexity Index
EMDE	emerging markets and developing economies
ETP	Energy Technology Perspectives
ETS	Emissions Trading Scheme
EV	electric vehicle
FCEV	fuel cell electric vehicle
FDI	foreign direct investment
FID	final investment decision
GDP	gross domestic product
GEC	Global Energy and Climate
GHG	greenhouse gas
G7	Group of Seven
HEFA	hydroprocessed esters and fatty acids
HFC	hydrofluorocarbon
HJT	heterojunction technology
HS	Harmonized System
HVAC	heating, ventilation and air conditioning
H_2	hydrogen
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IDDI	Industrial Deep Decarbonisation Initiative
IMF	International Monetary Fund
IMO	International Maritime Organization
IRA	Inflation Reduction Act
ISIC	International Standard Industrial Classification
ISO	International Organization for Standardization
IT	information technology
LCOE	levelised cost of electricity
LCOP	levelised cost of production
LESS	Low Emission Steel Standard
LFP	lithium iron phosphate
Li-ion	lithium-ion
LNG	liquefied natural gas

LPG	liquefied petroleum gas
MaT	Manufacturing and Trade
MEPS	Minimum Energy Performance Standards
MeOH	methanol
MREE	magnet rare earth elements
NACE	Nomenclature of Economic Activities
NCA	lithium nickel cobalt aluminium oxide
NH_3	ammonia
NMC	lithium nickel manganese cobalt oxide
NZIA	Net-Zero Industry Act
NZE	Net Zero Emissions by 2050 Scenario
OEM	original equipment manufacturer
OPEC	Organization of the Petroleum Exporting Countries
OPEX	operating expenditure
PEM	proton exchange membrane
PERC	Passivated Emitter and Rear Cell
PFE	Prohibited Foreign Entity
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
RCA	revealed comparative advantage
RD&D	research, development and demonstration
REE	rare earth elements
ROIC	return on invested capital
RoW	Rest of World
SAF	sustainable aviation fuel
SMR	small modular reactor
SSB	solid-state battery
STEPS	Stated Policies Scenario
SUV	sport utility vehicle
TCO	total cost of ownership
TRL	technology readiness level
TSO	transmission system operator
TOPCon	Tunnel Oxide Passivated Contact
USMCA	United States-Mexico-Canada Agreement
VALCOE	value-adjusted levelised cost of electricity
VC	venture capital
WACC	weighted average cost of capital
WTIV	wind turbine installation vessels
ZCRB	zero-carbon-ready buildings
ZETI	Zero-emission Technology Inventory

Units of measure

°C	degrees Celsius
EUR	euro

EJ	exajoule
GBP	pound sterling
GJ	gigajoule
GW	gigawatt
GWh	gigawatt hour
GWth	gigawatt thermal
kb/d	thousand barrels per day
kg	kilogramme
km	kilometre
kVA	kilovolt-ampere
kW	kilowatt
mAh	milliampere hour;
Mgt	million gross tonnes
Mt	million tonnes
Mtpa	million tonnes per annum
MVA	megavolt amperes
MW	megawatt
MWh	megawatt hour
TEU	twenty-foot equivalent units
t	tonne
TW	terawatt
TWh	terawatt hour
USD	United States dollars
V	volts
Wh/kg	Watt-hour per kilogramme

See the *Manufacturing and Trade Model Documentation* (IEA, 2026) and the IEA glossary for a further explanation of many of the terms used in this report.

Currency conversions

Exchange rates (2024 annual average)	1 US dollar (USD) equals:
British pound sterling	0.78
Canadian dollar	1.37
Chinese yuan renminbi	7.20
Euro	0.92
Indian rupee	84.60
Japanese yen	151.37
Korean won	1 363.37
New Zealand dollar	1.65
Thai baht	35.29

Regional groupings

Advanced economies: Australia, Austria, Belgium, Bulgaria, Canada, Chile, Colombia, Costa Rica, Croatia, Cyprus,[1,2] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel,[3] 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.[4]

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.[5]

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, Suriname, Trinidad and Tobago, Uruguay and other Central and South American countries and territories.[6]

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[1] 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".

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[6] 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.

China: Includes (The People's Republic of) China and Hong Kong, China.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

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,[7] Kosovo, Montenegro, North Macedonia, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus,[5,6] 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.

Other Africa: Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Chad, Côte d'Ivoire, Djibouti, Cameroon, Central African Republic, Democratic Republic of the Congo, Comoros, Eritrea, Ethiopia, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Kingdom of Eswatini, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo (Congo), Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Uganda, Zambia and Zimbabwe.

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). Timor-Leste joined ASEAN on 26 October 2025 and is excluded from this grouping for this publication, but is included in aggregate within the overarching Asia Pacific excluding China group.

References

IEA. (2021). *The Role of Critical Minerals in Clean Energy Transitions.* Retrieved from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IEA. (2026). *Manufacturing and Trade Model Documentation.* Retrieved from https://www.iea.org/reports/manufacturing-and-trade-model

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