Securing Clean Energy Technology Supply Chains

International Energy Agency

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Summary of recommendations

	Lead by	Actions
Diversify	Industry	Identify and develop new and more diversified supply sources for critical minerals, prioritising partners and projects with strong environmental, social and governance (ESG) credentials
	Government	Pursue coordinated measures to bolster supply chain resilience, including critical mineral stockpiles and improving geological surveys for critical mineral sources
	Government	Use industry policy levers to expand and diversify clean energy technology manufacturing capacity
	All stakeholders	Support the development of a robust recycling industry to reduce demand for raw materials, with industry to invest in recycling and reuse friendly design and production
Accelerate	Government	Fast-track and streamline permits and approvals for clean energy and critical minerals while maintaining environmental and other standards
	Government	Use government procurement to create demand for new clean energy technologies and fuels
	Government	Accelerate the creation of markets using targets, standards, fiscal incentives and regulatory reform
Innovate	Industry	Lead the innovation and commercialisation of technologies and manufacturing processes that rely less on critical minerals or on a more diversified material mix
	Government	Increase and prioritise investment and support for research, development and demonstration (RD&D) and de-risk private investment in clean energy technologies, fuels and supply chains needed for net zero
	Industry	Adopt advanced digital technology approaches to improve energy and material efficiency and reduce costs
Collaborate	All stakeholders	Map supply chains for clean energy technology at a national, regional and sectoral level to identify potential vulnerabilities, opportunities and strategic partnerships
	All stakeholders	Enhance market transparency through the development and uptake of international standards that promote higher ESG performance for key materials, technologies and fuels
	Government	Support emerging market and developing economies in building secure, sustainable and resilient supply chains
Invest	Government	Improve access to sustainable finance and adopt financial tools that cater to different stages of clean energy technology supply chains
	All stakeholders	Invest in the development of an appropriately skilled workforce by upskilling and reskilling the existing workforce for emerging clean energy roles and ensuring labour force mobility in the region
	All stakeholders	Identify opportunities for the strategic reuse or redeployment of existing infrastructure compatible with net zero pathways

Industry | All stakeholders | Government and other multilateral organisations

About this report

- **Secure, resilient and sustainable clean energy supply chains are central to the global energy transition**. The fallout from the Covid-19 pandemic and Russia's invasion of Ukraine has put global energy supply chains under enormous pressure, leading to soaring prices of oil, gas and coal, as well as shortages of semiconductors and the critical minerals needed to manufacture clean energy technologies. While the current energy crisis poses a threat to near-term economic prospects, it also provides an opportunity to accelerate the shift away from fossil fuels through a massive surge in investment in renewables, energy efficiency and other clean energy technologies. As the IEA has repeatedly stressed, the world does not have to choose between solving the energy crisis and the climate crisis.
- **Yet we must ensure that the path out of the current energy security crisis and the race to net zero emissions do not simply replace one set of concerns with another.** Clean energy supply chains largely depend on minerals, not fossil fuels. As a result, the related energy security considerations will be about access to the critical minerals, materials and components needed to manufacture clean energy technologies rather than the supply of fuels alone. Establishing secure, resilient and sustainable supply chains for these technologies will be essential. Important lessons can be drawn from established markets and technologies such as solar photovoltaics (PV) – where China has secured a dominant position at each step of the global supply chain – to shape emerging markets for batteries, low-emissions hydrogen and other technologies vital to the clean energy transition.
- **This report has been prepared for the Sydney Energy Forum, which the IEA is proud to co-host with the Australian Government and in partnership with the Business Council of Australia**. It summarises developments in selected clean energy technology supply chains and future needs, focusing on solar PV, batteries for electric vehicles (EVs) and low-emissions hydrogen, and provides a framework for governments and industry to identify, assess and respond to emerging opportunities and vulnerabilities, with specific insights for the Indo-Pacific region. It draws on the IEA's analysis of critical minerals, recent detailed analysis of technology supply chains, notably the IEA's Global Supply Chains of EV Batteries and Special Report on Solar PV Global Supply Chains[1], as well as the IEA's extensive clean energy technology tracking and analysis, including ongoing work on the IEA's flagship Energy Technology Perspectives (ETP) publication. The next edition of ETP, due to be released in early 2023, will focus on what is needed to develop and expand clean energy technology supply chains to achieve net zero emissions across a broad range of technologies.

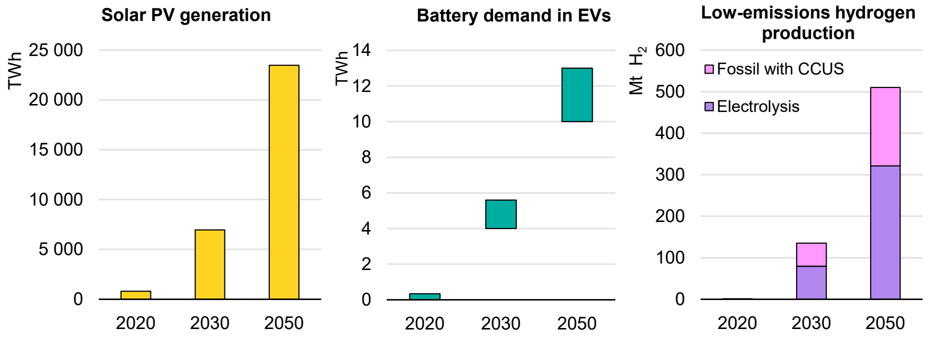
[1]Both reports will be launched in early July 2022. Key insights of the Global Supply Chains of EV Batteries have been published as part of the Global Electric Vehicle Outlook 2022.

Scaling up clean energy supply chains

Sustainable supply chains are key to sustainable energy

The deployment of clean energy technologies needs to be scaled up rapidly around the world to avert the worst effects of climate change. The IEA's Net Zero Emissions by 2050 Scenario, described in detail in the Net Zero by 2050: A Roadmap for the Global Energy Sector report prepared in 2021 for the Conference of the Parties in Glasgow, sets out an energy pathway consistent with limiting global temperature increase to around 1.5 degrees Celsius. The huge increase in the deployment of solar PV, EVs and low-carbon hydrogen in that scenario calls for rapid growth in the manufacturing of these technologies, as well as the production of essential material and mineral inputs (Figure 1).

Figure 1 Global deployment of selected clean energy technologies in the Net Zero Emissions by 2050 Scenario



Rapid expansion of solar energy is central to getting to net zero

The generation of electricity using solar PV technology is a central pillar of the clean energy transition. Annual average capacity additions in the Net Zero Emissions by 2050 Scenario quadruple over 2020-2030, with solar accounting for roughly one-third of total generation by mid-century – up from just 3% today. The annual installation of PV panels reaches 630 GW in 2030 (up from 151 GW in 2021), with associated demand for critical minerals increasing to 4 000 kilo tonnes (kt) by 2030 (up from 1 000 kt in 2021). Solar PV panel production already accounted for 10% of global demand for silver and over 40% of global tellurium use in 2021. The aggregate demand for critical materials for solar PV is estimated to expand by 150% to 400% between 2021 and 2030 in the Net Zero Emissions by 2050 Scenario.

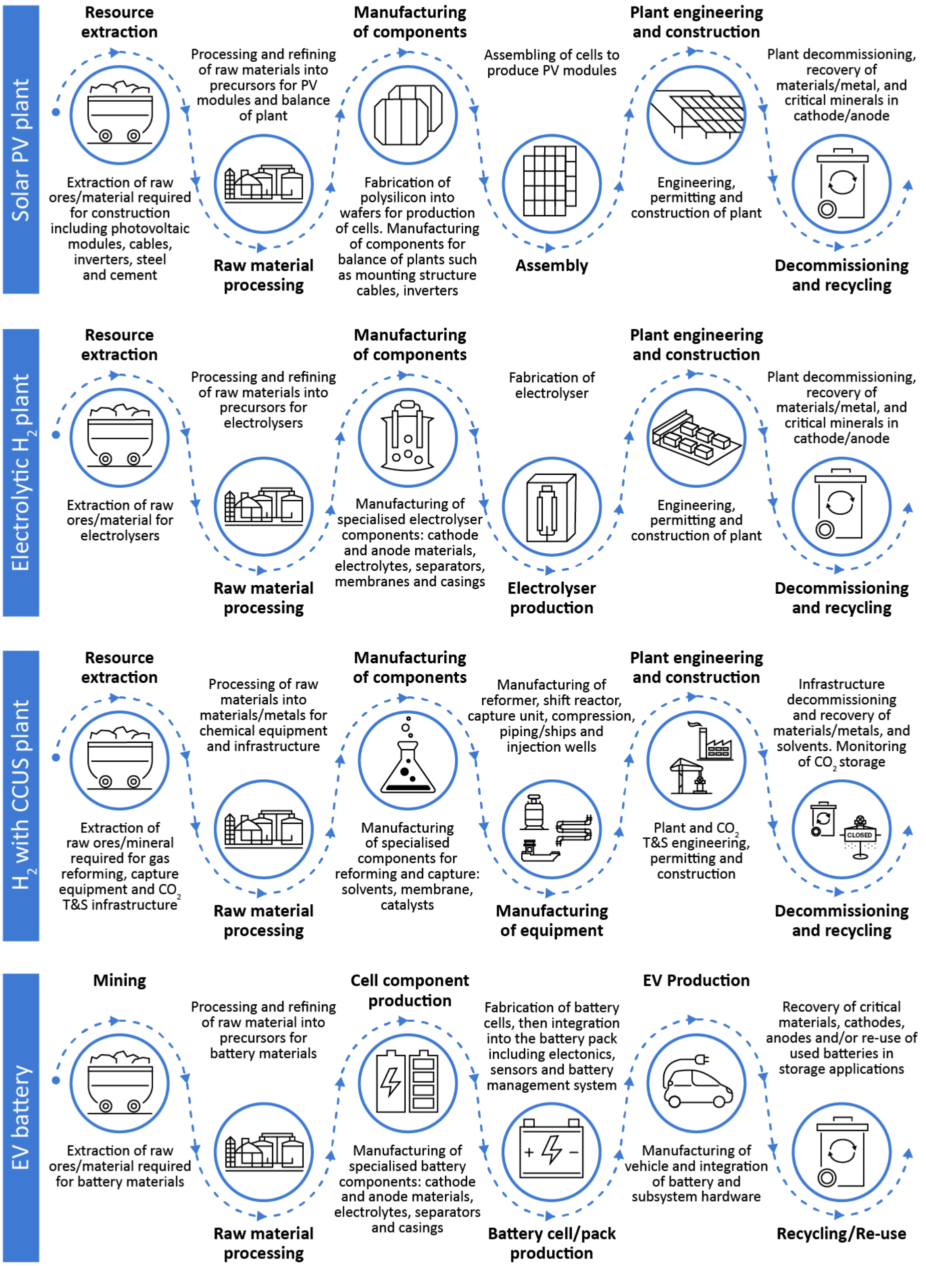
Rising global solar PV needs will boost opportunities for expanding manufacturing capacity in the Indo-Pacific region. Almost all of today's global manufacturing capacity for solar PV is in the Indo-Pacific region, most notably in China. The region also hosts the majority of material processing capacity to sustain such manufacturing capacity. Although there are plans to scale up module manufacturing capabilities in North America and Europe, the region is well placed to remain a major supplier of components and a key manufacturer of panels.

Electrifying vehicles hinges on adequate supplies of critical minerals for batteries

Accelerating the uptake of EVs will require a massive expansion in the supply of batteries, which will drive up demand for several critical minerals. Like solar PV, global sales of electric cars have soared over the last few years, doubling in 2021 alone to a record 6.6 million. Just 120 000 were sold in 2012. Sales of electric buses (up 40%) and medium- and heavy-duty trucks (up 100%) have likewise seen large increases in the last year. In the Net Zero Emissions by 2050 Scenario, the global fleet of EVs reaches 350 million (excluding two/three-wheelers) and their share of the total vehicle fleet around 20% in 2030. By then, EV sales reach over 65 million per year – almost 60% of total vehicle sales. This contributes to an average increase of 30% per year over 2021-2030 in global demand for lithium (compared with 6% over the last five years), 11% annual demand growth for nickel (5%) and 9% annual demand growth for cobalt (8%).

Increased material and production requirements for EV batteries are set to benefit the Indo-Pacific region. Australia is the largest producer of lithium, producing over half of global mined production in 2021, and is home to two of the top five global producers – Pilbara Minerals and Allkem. For nickel, laterite deposits are mainly found in Indonesia, the Philippines and New Caledonia. There are plans to launch or expand battery manufacturing in several countries. Indonesia recently created a government-owned battery corporation that aims to build 140 GWh of battery capacity by 2030, of which 50 GWh will be for export. Today's global battery manufacturing production capacity is about 871 GWh.

Figure 2 Supply chains of key energy technologies



Note: The solar PV plant only applies to crystalline-silicon PV modules. Not all hydrogen pathways are represented here (e.g., coal, biomass gasification).

Low-emissions hydrogen is set to play an important and growing role

The emergence of low-emissions hydrogen will also call for expanded and more sustainable supply chains. Compared with solar PV and EVs, low-emissions hydrogen[1] – produced by electrolysis or steam reforming of natural gas with carbon capture, utilisation and storage (CCUS) – is still in its infancy, with production of around 30 kt via electrolysis and 0.7 Mt via CCUS in 2021[2] (less than 0.8% of total hydrogen output). In the Net Zero Emissions by 2050 Scenario, low-emissions production takes off quickly, reaching around 150 Mt in 2030 and 520 Mt by 2050. This requires a massive increase in electrolysis capacity, from 0.3 GW today to close to 850 GW by 2030 and almost 3 600 GW by 2050. The material requirements for electrolysers at this scale would greatly increase overall global demand for platinum group metals, which has a concentrated supply, and nickel, for which demand for batteries is also set to rise sharply. Fossil-based production with CCUS – which is less reliant on critical minerals but relies on the availability of CO_2 transport and storage infrastructure – also increases sharply, from 0.7 Mt today to around 70 Mt by 2030 and 200 Mt by 2050. Hydrogen is particularly promising as a means of storing low-emissions electricity to balance electricity systems and to drastically reduce emissions from sectors where emissions are hard to abate, notably long-distance transport and heavy industry.

[1]Hydrogen can be produced using all types of energy sources and through a variety of technologies. References to low-emissions hydrogen in this report includes hydrogen produced from renewable and nuclear electricity, biomass, and fossil fuels with CCUS. Further details on the IEA approach to hydrogen classification can be found in the 2021 Global Hydrogen Review.

[2]These include facilities that produce pure hydrogen and capture CO_2 for geological storage or sale; CO_2 captured from ammonia plants for use in urea manufacturing is excluded.

Table 1 Key milestones for clean energy technologies in the Net Zero Emissions by 2050 Scenario

	2020	2030	2050
Solar PV	Solar accounts for roughly 3% of global electricity generation Annual capacity additions of around 130 GW	Nearly 25% annual growth required over 2020-2030 More than 600 GW per year of capacity additions	Solar accounts for over 30% of global electricity generation
Hydrogen	Production of low-emissions hydrogen is less than 0.8% of total production Global electrolyser capacity is around 0.3 GW. CO_2 captured in low emissions hydrogen production is around 10 Mt Hydrogen demand is less than 90 Mt	Production of low-emissions hydrogen reaches 70% Global electrolyser capacity must increase to close to 850 GW CO_2 captured in low-emissions hydrogen production must increase around 70-fold from 2020 levels Annual investment in hydrogen reaches USD 165 billion	Global electrolyser capacity must increase to around 3 600 GW of capacity CO_2 captured in low-emissions hydrogen production must increase 180-fold from 2020 levels Hydrogen demand multiples almost six-fold, with half of this demand in industry and transport. Annual investments reach USD 470 billion
Electric Vehicles	Around 16.5 million EVs on the road Battery demand for EVs is around 340 GWh	EVs account for 20% of the global stock Battery metal demand for EVs increases by around one-third per year for lithium and around 10% for nickel and for cobalt over 2020-2030	EVs account for 86% of the global stock of passenger cars At over 60% of the total, batteries account for the lion's share of the estimated market for clean energy technology equipment

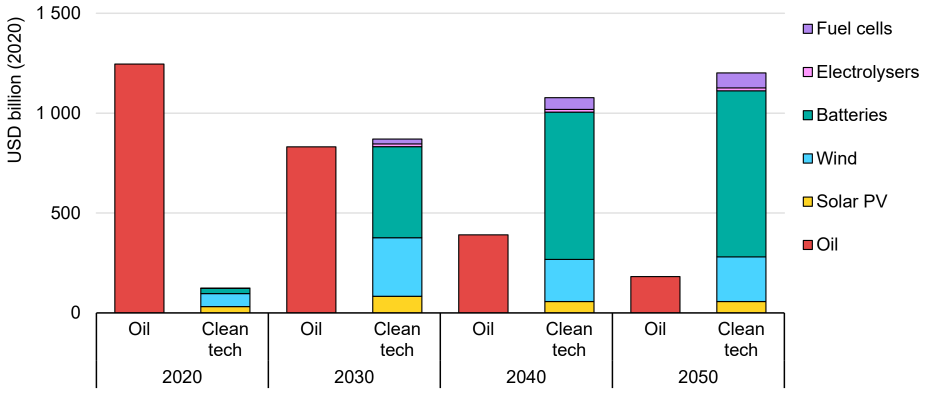
The new energy security paradigm

Striving for net zero will redefine global energy security

The clean energy transition is fundamentally changing the nature of energy security. The IEA defines energy security broadly as the uninterrupted availability of energy sources at an affordable price. There are several aspects to this. Long-term security hinges on the timeliness of investments to supply energy in line with demand, while short-term security is linked to the ability of the energy system to react promptly to sudden changes in the supply-demand balance. Until recently, discussions about energy security were largely focused on the supply of fossil fuels, notably oil. Indeed, the IEA was born out of the 1973-1974 oil crisis. And almost 50 years on, fossil fuels are again at the heart of the current global energy crisis: oil, gas and coal still account for 80% of the global energy mix. This is a stark reminder of the need to always ensure supply security of traditional fuels during the clean energy transition, but it should not divert our attention from the security of clean energy transitions.

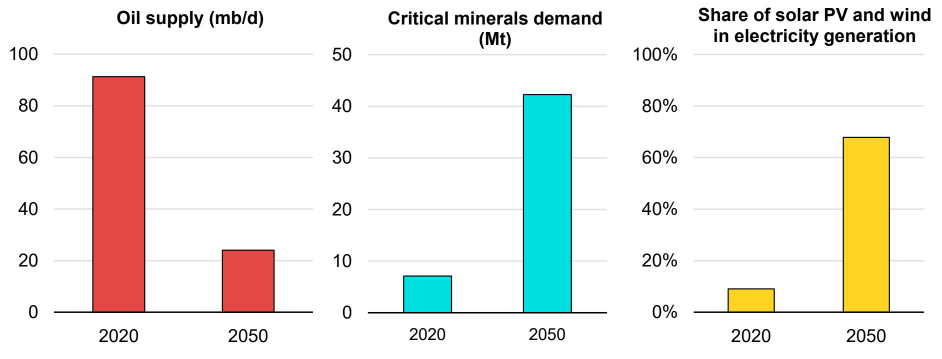
The race to net zero will focus attention on the security of supply for clean energy technologies. In our Net Zero Emissions by 2050 Scenario, renewables meet two-thirds of global energy needs by mid-century. Solar and wind alone contribute more than one-third, compared with just 2% today, and more than two-thirds of electricity generation (9% today). By contrast, in 2050 fossil fuels account for only around 20% of the energy mix, with coal use declining by almost 90%. The combined market for the leading clean energy technologies exceeds that of oil by 2030 (Figure 3). Most of the non-fossil technologies rely on domestic energy resources, like sunshine and wind, but the equipment, critical minerals, materials and components needed to exploit those resources and make the related end-use equipment often rely on global supply chains (Figure 4).

Figure 3 Estimated market sizes, by value, of oil and selected clean energy technologies in the Net Zero Emissions by 2050 Scenario



Disruptions to clean energy technology supply chains bring new energy system challenges. An oil supply crisis, when it happens, has broad repercussions across the economy with existing consumers and industries affected by reduced availability and higher prices. Low-emissions hydrogen and its derivatives (including ammonia) and bioenergy/biofuels, may face similar energy security challenges to traditional fuels. By contrast, a shortage or spike in the price of a raw materials or component required for producing batteries and solar panels will primarily affect the roll-out and availability of new capacity additions. Consumers driving existing EVs or using solar-powered electricity are unlikely to be affected. The main threats from these supply chain disruptions are therefore delayed and more expensive energy transitions.

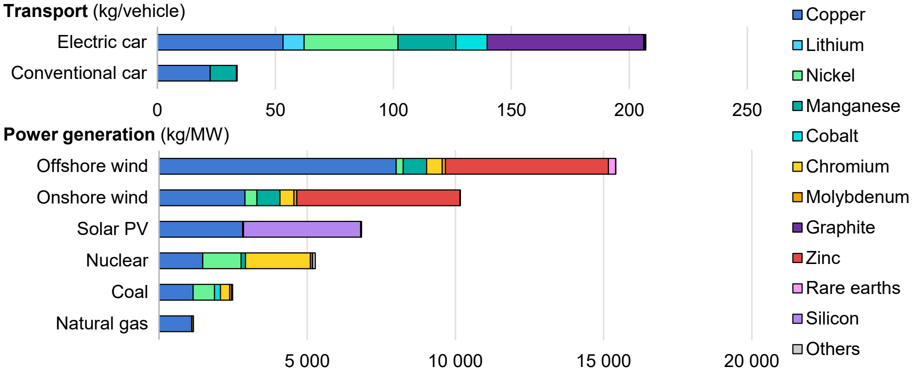
Figure 4 Key indicators of energy security in the Net Zero Emissions by 2050 Scenario



Note: mb/d = million barrels per day; Mt = million tonnes

The supply of critical minerals such as copper, lithium, nickel, cobalt and rare earth elements will be of particular importance. These critical minerals are essential for many clean energy technologies (Figure 5). The world's resources of these minerals are undoubtedly big enough to meet this increase, but production and processing operations for many of them are highly concentrated in a small number of countries at present, making supplies vulnerable to political instability, geopolitical risks and possible export restrictions.

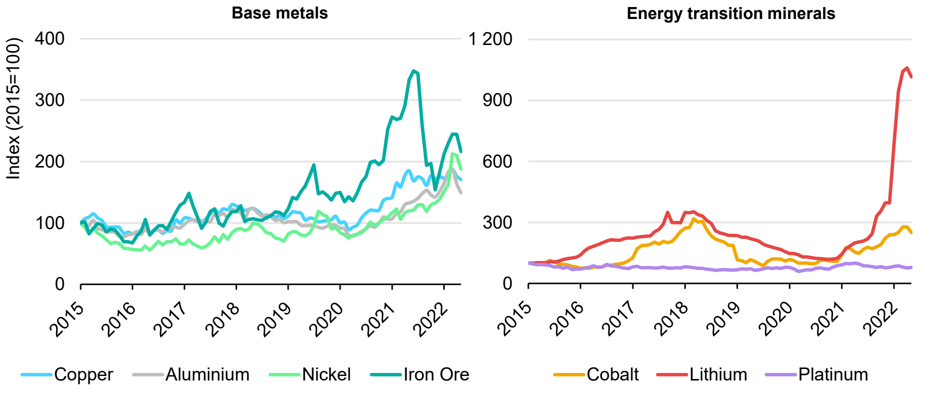
Figure 5 Mineral intensity of selected clean and fossil energy technologies



Source: IEA (2022), The Role of Critical Minerals in Clean Energy Transitions.

The effects of the economic disruption caused by the Covid-19 pandemic and Russia's invasion of Ukraine are being felt across the energy system, threatening the decades-long trend of cost declines for clean energy technologies. The international prices of the leading critical minerals and metals have soared since 2020, with those of lithium and cobalt more than doubling and those of copper, nickel and aluminium rising by around 25% to 40% in 2021 (Figure 6). Prices have continued to rise in 2022, with the price of lithium jumping by two-and-a-half times since the start of the year, before falling back somewhat. In most cases, the price increases since 2020 have exceeded by a wide margin the largest annual increases seen in the 2010s. In the case of Class 1 battery-grade nickel, prices have been driven higher by worries about supplies from Russia, which is the world's largest producer accounting for about one-fifth of the global supply.

Figure 6 International prices of selected metals and critical minerals for clean energy technologies



Source: IEA analysis based on S&P Global (2022).

These price increases threaten to reverse the long-term downward trend in the cost of clean energy technologies that had been driven by innovation and economies of scale, with a major impact on financing needs for clean energy transitions around the world. The share of raw materials in the total cost of all clean energy technologies is rising sharply. The cost of building wind turbines jumped by 9% and that of manufacturing solar modules by 16% in 2021 – the first annual increase in real terms for decades. The cost of shipping is also rapidly increasing due to rising fuel prices and supply constraints. The Shanghai Freight Index, which tracks the price of sending a container from Shanghai to select ports around the world, has increased roughly six-fold since early 2020.

The cost of making EV batteries is also poised to rise, though the full impact of the recent surge in metal and other commodity prices has yet to be felt. Battery prices declined in 2021 – by 6% on average – though this was less marked than the 13% fall in 2020. Several factors partially insulated battery prices from the commodity price rises in 2021, including changes in battery chemistries – with many automakers switching to lower-cost cathode chemistries with less commodity price exposure –and time lags in long-term material supply contracts. If metal prices were to remain at levels experienced in the first three months of 2022 throughout the rest of the year, then we estimate that battery pack prices might increase by as much as 15% from the 2021 weighted average price, all else being equal. Increases in lithium prices are already translating into higher prices for EVs, with Tesla, BYD and Xpeng announcing price hikes of 2% to 9% in March 2022.

Pressure on clean technology supply chains is also affecting the pace of energy transitions. In May 2022, Tesla and Volkswagen warned that supply chain disruptions and higher raw material prices threatened the rollout of EVs, with demand threatening to exceed production capacity Companies are starting to scale back their EV production targets, while higher prices could also delay the achievement of cost parity with conventional internal combustion engine vehicles. Volkswagen sold out of EVs in the United States and Europe in the first three months of 2022 due to shortages of semiconductors and wiring harnesses made in Ukraine. Tesla had agreed a deal with Piedmont Lithium for the supply of 53 000 tonnes of lithium per year for five years starting during the period July 2022 and July 2023, but shipments have been pushed back due to delays in obtaining mining permits. Nio, a Chinese EV manufacturer, had to suspend production in April 2022 due to local supply chain problems caused by Covid-19 restrictions and recently announced an increase in the price of its electric sports utility vehicle due to higher raw material costs.

Future supply chains must be secure, resilient and sustainable

A comprehensive and coordinated approach is required to develop and expand global clean energy technology supply chains that are secure, resilient and sustainable. This means supply chains that can meet the needs of a net zero pathway and that can absorb, accommodate and recover from both short-term shocks and long-term changes, including material shortages, climate change, natural disasters and other potential supply disruptions (Table 2). The goal should be to enhance the security and resilience of supply chains while maintaining a commitment to principles of open and transparent markets and avoiding barriers to trade. Self-sufficiency is not always an option – particularly for critical minerals that are geographically concentrated – nor an economically optimal approach: a combination of open markets, strategic partnerships and diversity of supply sources can deliver security, resilience and sustainability.

Critically, the emissions intensity and environmental impact of clean energy technology supply chains themselves must also be reduced rapidly. The emissions intensity of solar PV manufacturing has decreased by 40% in the last decade thanks to process improvements and a switch to low-emissions power generation. But further steep declines in the emissions intensity of solar PV and other clean energy technology supply chains will be critical in a net zero by 2050 pathway. The global adoption of sustainable mining practices that minimise the environmental, water and social impacts of resource extraction will also be central to the sustainability of many clean energy technology supply chains.

Table 2 Characteristics of secure, resilient and sustainable clean energy technology supply chains

Secure	Adequate, reliable and uninterrupted supply of inputs Stable and affordable prices
Resilient	Able to respond and quickly adjust to disruptions Diversity in market, suppliers and technologies Interconnection across supply chains
Sustainable	GHG emissions as low as possible and consistent with net zero pathways Recognition and adoption of ESG measures along all aspects of the supply chain Efficient and responsible use of natural resources, including through promotion of recycling and end-of-life stewardship

Clean energy technology supply chains involve new opportunities, but also new risks and vulnerabilities that differ from fossil fuel supply. The composition, scale and complexity of the different stages along clean energy supply chains – resource extraction, materials production, equipment manufacturing and construction, transport, operation and end-of-life handling – can vary markedly depending on the technology or fuel. The clean energy technology supply chains needed to deliver a net zero future have several similarities with fossil-based energy supply chains, including strong interdependency between the supply chain steps, dependence on access to upstream fuels or minerals, and a need for infrastructure to transport commodities, equipment or the final energy product. Yet clean energy technology supply chains rely much more on critical minerals and generally involve more technically complex and higher value-added processing and transport. Some technologies, notably hydrogen, remain at an early stage of development so future supply chain risks and vulnerabilities are uncertain.

Assessing risks and vulnerabilities

A framework to map supply chain risks and vulnerabilities

Disruptions to clean energy technology supply chains could have a marked impact on the world's ability to achieve net zero emissions. Understanding the risk profile of each element of the supply chain is a key step in developing an overall appreciation of the risks to and vulnerabilities of the supply chain. It is also critical for establishing where efforts to enhance security and resilience should be focused. These risk profiles can look quite different depending on the country, region and technology. For example, some countries or regions have abundant supplies of raw materials or access to skilled workers. In the case of nickel – used in both batteries and hydrogen electrolysers – the effects of a supply disruption can vary according to the degree of substitutability of nickel in each technology. The risk profile of certain technologies is also likely to change over time as new technologies and materials emerge, and as technologies mature and markets develop.

A risk assessment framework can be used to capture the risks and vulnerabilities of supply chains. Table 3 covers the likelihood of a significant and widespread disruption occurring in one specific part of the supply chain and its potential impact. These aspects need to be considered in government policy responses and corporate strategies. An element of the supply chain is considered to be vulnerable if there is a high chance of significant and wide spread disruption, and the supply chain has minimal capacity to respond and limit the effects of a disruption. The framework is designed to be applied to current supply chain structures, with a view to assessing how well the supply chain can adapt and respond in the short to medium term – recognising that it is easier to adapt to disruptions over longer time frames.

Table 3 Supply chain risk assessment framework

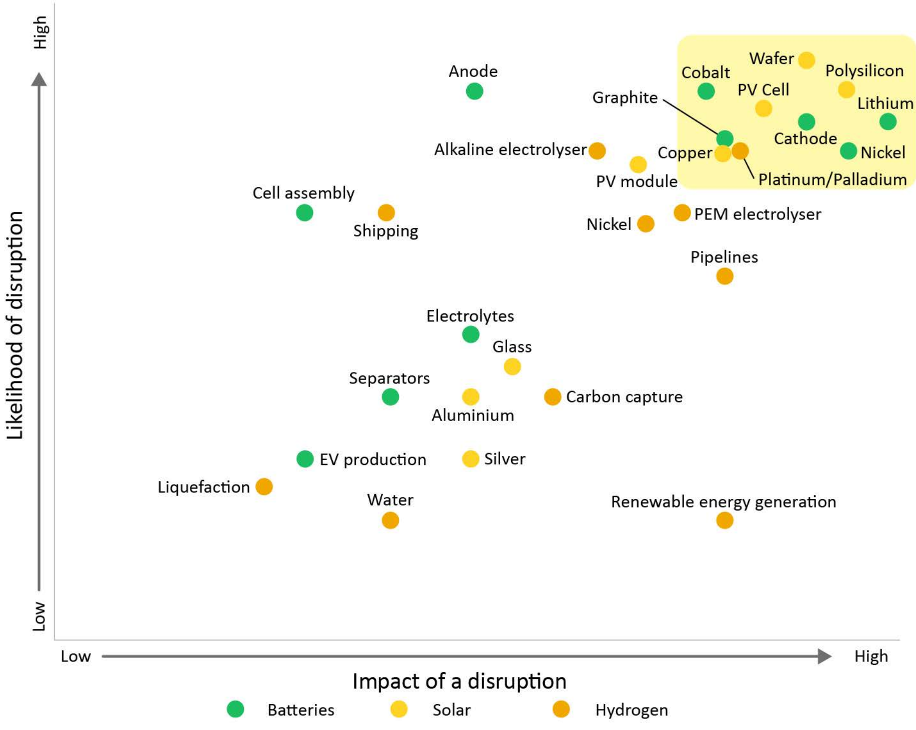
Criteria	Description	Factors to consider
Likelihood: How likely is there to be a significant and widespread disruption to that element of the supply chain?		
Supply chain concentration	Highly concentrated production – either geographically or by firm – will increase the likelihood of a significant disruption due to increased risk of the entire market being exposed to the same shock.	How concentrated is the production at a firm level? How concentrated is the production geographically (both country and region)?
Pace and scale of growth	A larger scale-up requirement compared to the average pace observed in that market, or the rapid development of a new supply chain to reach net zero, will increase the likelihood of a situation where demand and supply become imbalanced.	What is the scale-up requirement in percentage terms, for 2030 and 2050 in the Net Zero Emissions by 2050 Scenario compared to the pace observed in the past 10 years? How in-demand is the element across other supply chains?
Exposure to trade, natural, technical or geopolitical risks	High exposure to potential disruptions, such as trade restrictions, natural disasters, conflict or political instability will increase the likelihood of a disruption – especially when coupled with a highly concentrated market.	Are the major producers located in areas prone to natural disasters that are likely to cause prolonged disruption? Do the major producers uphold ESG standards? Are there geopolitical risks and how well established is the market in the international trading system?

Criteria	Description	Factors to consider
Impact: If a disruption happens, how effectively and quickly could the supply chain reorganize to allow production to continue or resume?		
Ability to pivot to other materials or technologies	In the event of a disruption, the impact will be reduced if there are readily available substitutable technologies and materials, and the supply chain can pivot to them with relative ease. Using a range of materials and technologies would reduce the supply chain impact.	Can the materials be directly substituted with alternatives? (i.e., synthetic for natural graphite) Are there alternative technologies available? (i.e., battery chemistries) Is it possible to use recycled materials? How advanced are the alternatives?
Scale-up or conversion lead times	The speed at which a supply chain can reorganise will have significant impact on the extent of the disruption and the supply chain's resilience. The scale-up and conversion times for infrastructure will be a critical element of the reorganisation.	Is there infrastructure that could be converted or leveraged? Is there latent capacity or inventory that could be utilised? How quickly can new sources of supply (mines, factories, etc.) be scaled up? How responsive is the market to price signals?

Supply risks and vulnerabilities are particularly acute for battery and solar components

The risk of a supply disruption and its potential impact are especially pronounced for several major components of batteries for electric vehicles and solar PV (Figure 7). For example, the supply of lithium – a critical component of batteries – is relatively concentrated, the investments needed to boost supply are large and some sources of supply are vulnerable to trade or natural disruptions. In addition, lithium is irreplaceable in lithium-ion batteries and there are currently no alternative battery chemistries which do not require lithium available at scale. Lead times for opening new mines are also very long. The high concentration of solar PV cell, wafer, and module manufacturing in China and a handful of other countries also makes that component vulnerable to a supply disruption.

Figure 7 Likelihood and magnitude of the impact of potential supply disruptions for leading clean energy inputs



Supply chain risks for solar PV, EVs and low-emissions hydrogen are generally highest in the resource extraction, material production and manufacturing phases of the supply chains (Table 4). For resource extraction, high risk minerals and metals include copper, cobalt, platinum and graphite, as well as lithium. The reliance on critical minerals is a significant vulnerability in the supply chains of all three technologies, especially lithium and cobalt for batteries, copper for solar PV and platinum and nickel for hydrogen electrolysers. Most minerals are subject to moderate (lithium) to severe (graphite and cobalt) levels of concentration, both at the company and geographic/jurisdictional level. In addition, many minerals are also exposed to social, geopolitical and trade disruptions. The lead time for the development of new mines is generally very long, ranging from four to 20 years and averaging over 16 years. Given the need to rapidly scale up supply to meet the milestones of the Net

Zero Emissions by 2050 Scenario, expanding capacity at existing mines and building new ones must start immediately to ensure that the pipeline of projects will be sufficient to cover demand and to avoid bottlenecks. For some technologies, there may be scope to switch to other minerals, giving some supply flexibility, but some – such as sodium-ion batteries – are still under development and may not offer the same advantages as existing technologies.

The processing of critical minerals and the production of polysilicon are most at risk at the material production stage. The processing of critical minerals is typically more concentrated than extraction, as it is heavily dominated by China. Polysilicon manufacturing – a key input to making cell wafers for solar PV panels – is also heavily concentrated in China (see below). Expertise is often highly concentrated as well, which can hold back technology transfer. Yet the lead times to open new processing facilities are generally much shorter than for mines.

Table 4 Assessment of vulnerabilities for selected clean energy technologies by supply chain

	Resource extraction	Material production	Manufacturing/ Construction	Operation
Solar	● Medium	● High	● High	● Medium
Batteries	● High	● High	● High	● Low
Hydrogen	● Medium	● Medium	● Medium	● Low

Note: ●High ●Medium ●Low

At the manufacturing and construction stages, high risk components include cathode and anode production for batteries, as well as PV cells, wafers and modules for solar energy. The sources of risk vary. Concentration is again a key factor, with manufacturing concentrated in China in most cases, as are the large investments required for new capacity. Alternatives for these components are typically at nascent stages of development. For example, for batteries, current cathode and anode materials are not substitutable in the short term, although alternative materials are in the early stages of development. For solar PV, polysilicon wafer technologies dominate solar PV production, although alternative technologies, such as thin-film, exist but have not reached the same scale as the dominant technology. Lead times are typically much shorter and with fewer constraints on starting production in other locations for manufacturing than for resource extraction. Other phases of the supply chain are generally less exposed to disruption risks. The technology and infrastructure for transporting and storing hydrogen is less mature, but significant potential exists for repurposing infrastructure in ways that are both cost- and time-effective. Similarly, the battery recycling industry will need to grow significantly, both to achieve sustainability and to provide an alternative source of critical minerals.

Making clean energy supply chains secure, resilient and sustainable is a priority

Building secure, resilient and sustainable supply chains for clean energy technologies calls for decisive action around the world. We have identified five key areas, or pillars, where governments and industry collectively need to prioritise action to lower the risk of and vulnerability to major supply disruptions: diversifying supply chains, accelerating clean energy transitions, innovating clean energy technologies, collaborating on clean energy supply chains and investing in clean energy. These pillars are discussed below.

1. Diversifying supply chains

Supply chain diversity is vital to the security of supply for clean energy transitions

Supply chain concentration – the extent to which market shares are concentrated among a small number of production facilities, firms, countries or regions – is a primary risk for clean energy technologies. Concentration at any point along the supply chain makes the entire supply chain vulnerable to incidents, be they related to individual country policy choices, natural disasters, technical failures or company decisions (Table 5). Russia's invasion of Ukraine, which could disrupt supplies of class 1 nickel needed for EV batteries, and the recent disruptions to manufacturing of various components for solar PV and batteries in China due to Covid-19 lockdowns, are but two recent illustrations of this risk.

Persistent supply chain interruptions, which could drive up the prices of intermediate and final clean energy products, could delay clean energy transitions, increase the cost of meeting net zero goals and lead to a less equitable transition. Supply chain diversity – at the level of firms, geographies and technologies – is needed to ensure that supply chains are resilient to any shocks and that supplies are secure. Given the scale of the deployment of clean energy technologies required to get to net zero, this presents a sizeable opportunity for firms and regions with access to resources, skills and capital to enter the market.

Table 5 Risks of supply chain disruptions associated with concentration

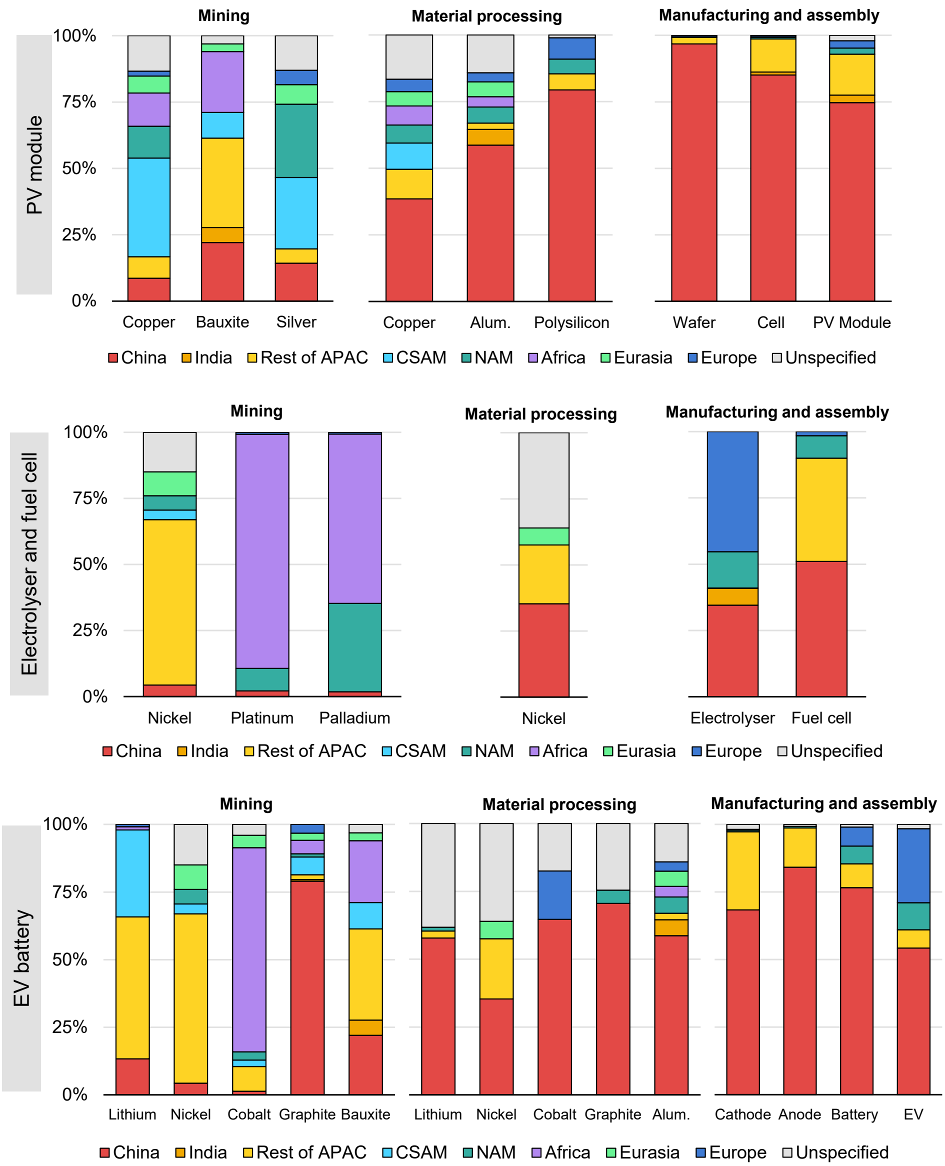
Type of concentration	Description	Associated risks potentially causing supply chain disruption
Jurisdictional concentration	To what extent is production concentrated in a single jurisdiction?	Domestic policy changes Geopolitical event
Geographic concentration	To what extent is production concentrated in a single geographic area?	Natural hazards such as earthquakes and fires, and extreme weather events such as drought and flooding Technical failures of electricity, gas grids or other infrastructure
Facility concentration	To what extent is production concentrated in a single facility?	Risks cited above, plus: Onsite equipment failure
Market concentration	To what extent is production concentrated in a single company?	Risk of collusion, price fixing and dumping
Technology concentration	To what extent is global production centred on a single technology?	All the risks mentioned above would be amplified, especially for material supply risks Intellectual property rights could slow technology transfer

Source: Adapted from IEA (2022) Special Report on Solar PV Global Supply Chains.

Clean energy supply chains are highly concentrated today

There is significant concentration across many clean energy technology supply chains. The supply chain for many clean energy technologies and their raw materials is more geographically concentrated than it is for oil or natural gas. Clean energy technologies often have higher material requirements than traditional energy technologies, they require more manufacturing and processing, and they generally have more complex supply chains. Their manufacturing is often very technically complex and highly specialised, which also lends itself to concentration. In addition, as the technologies have developed, incumbent producers have benefited from economies of scale, which has increased concentration.

Figure 8 Geographic concentration of selected clean energy technologies by supply chain stage and country/region, 2021



Notes: NAM: North America; Rest of APAC: Asia-Pacific excluding China and India; CSAM: Central and South America. Alum: Aluminium. Although Indonesia produces around 40% of total nickel, little of this is currently used in the EV battery supply chain. The largest Class 1 battery-grade nickel producers are Russia, Canada and Australia.

Sources: IEA (2022) Global Supply Chains of EV Batteries; IEA (2022) Special Report on Solar PV Global Supply Chains; and IEA analysis based on internet data and US Geological Survey (2022).

In the case of EV batteries, China dominates production at every stage of the supply chain downstream of mining. This is the result of more than a decade of policies to support the development of an integrated domestic supply chain as a strategic industrial sector. Around three-quarters of the world's production capacity for battery cells, around 70% of cathode capacity and 85% of anode capacity, as well as more than half of the global raw material processing of lithium, cobalt and graphite, are located in China. The country's domination of the entire graphite anode supply chain – including around 80% of mining – is particularly acute. Korea and Japan also have significant battery supply chains downstream of raw material processing, particularly in cathode and anode material production. Korea accounts for 15% of global production capacity for cathodes and 3% for anodes, while Japan accounts for 14% and 11%, respectively. Europe is responsible for more than a quarter of EV production, but holds very little of the rest of the supply chain, apart from cobalt processing (located mostly in Finland).

The downstream EV battery supply chain is set to become less geographically concentrated in the coming years. If current policies and announcements of projects are realised, one- quarter of battery production capacity will be located in Europe and the United States by the end of the current decade. There are also plans to expand cathode materials production in those regions. By contrast, anode material production is likely to continue to be dominated by China, which controls the entire supply chain from mining through to anode material production.

Solar PV supply chains downstream of extraction – including polysilicon, wafer, cell and module manufacturing capacity – are also highly concentrated in China. In 2021, around 40% of global polysilicon manufacturing capacity along the supply chain was located in a single Chinese province – Xinjiang – and as much as 14% of global wafer production took place at a single factory. This concentration is expected to increase over the next five years for most supply chain segments, based on plants under construction and planned. Wafer manufacturing is currently the most concentrated supply chain segment, with China accounting for 97% of global capacity. Its share of cell production is 85% and that of global polysilicon is over three-quarters. The production of solar PV supply chain segments is also concentrated at the company level, with the top five companies holding more than 70% of total production for both polysilicon and wafer production, and around 50% of total production for both cells and modules. In China and elsewhere, governments have supported the development of solar PV manufacturing through general industrial policy, funding of RD&D, and demand-side incentives.

The production of both low-emissions hydrogen and related materials and equipment are likely to be more diversified than existing battery and solar PV

supply chains as the sector develops over the coming decades. China is expected to remain a major hydrogen producer and consumer, but other countries, including Australia and the United States, are well placed to become important players in the sector as it takes off and as production shifts to low-emissions pathways. For now, the global supply chain for all types of electrolysers remains nascent as demand has yet to materialise on any significant scale. Consequently, the supply of membranes for electrolysers is currently very concentrated, with AGFA, a Belgian-German company, the dominant supplier of alkaline electrolysis membranes and the market for PEM membranes being dominated by a few major suppliers.

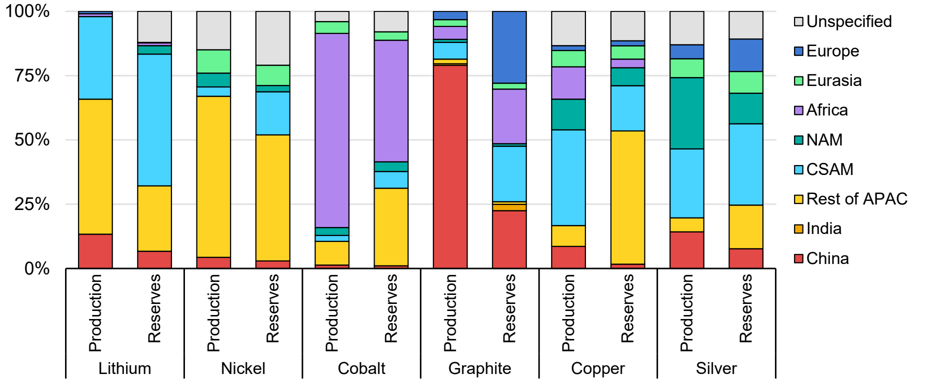
Access to critical minerals threatens to put a brake on energy transitions

The concentration of supply, particularly at the mineral extraction stage, could lead to significant delays in deploying clean energy technologies. A typical electric car requires six times the mineral inputs of a conventional car, while an onshore wind plant requires nine times more mineral resources than a gas-fired plant for the same capacity. Since 2010, the average amount of minerals needed for an additional unit of power generation capacity has increased by half as the share of renewables in incremental capacity has risen. This trend is set to continue. In the Net Zero Emissions by 2050 Scenario, mineral inputs to the production of energy-related infrastructure and end-use equipment are up to six times higher in 2040 than today.

The concentration of the production of many of the critical minerals needed for clean energy technologies is a particular concern. Resources of those minerals are more geographically concentrated than oil, natural gas or coal. For lithium, cobalt and rare earth elements (REEs), the top three producing nations in aggregate control well over three-quarters of global output. In some cases, a single country is responsible for around half of worldwide production. South Africa and the Democratic Republic of the Congo account for around 70% of global production of platinum and cobalt, respectively, while China controls roughly 60% of global mined output for REE. This is a major source of concern for companies that produce solar panels, wind turbines, electric motors and batteries using imported minerals, as their supply chains can quickly be affected by regulatory changes, trade restrictions or political instability.

The current geopolitical situation, rising commodity prices and supply bottlenecks have highlighted the need for action on the part of governments and industry to enhance the diversity and resilience of clean energy supply chains. This implies a need to promote the development of resources, where they exist, and encourage investment in new sources of supply. For most minerals, proven reserves are less concentrated than current production, implying that a significant opportunity exists to diversify supply (Figure 9).

Figure 9 Production and proven reserves of selected critical minerals for battery and PV cell materials, 2021



Notes: NAM: North America; Rest of APAC: Asia-Pacific excluding China and India; CSAM: Central and South America. Reserves refer to economically extractable resource as defined and determined by the US Geological Survey.

Source: IEA analysis based on US Geological Survey (2022).

Work is under way to bolster resilience to potential critical mineral supply disruptions

At the 2022 IEA Ministerial, member countries recognised the growing importance of critical minerals and materials to clean energy transitions and asked that options to ensure the resilience of critical mineral supplies, including stockpiling, be investigated. A range of potential mechanisms exists for bolstering the security of critical mineral supply chains, including stockpiles, public procurement via offtake agreements, regular stress testing, joint recycling targets and measures to award ESG performance. A group of countries interested in closer cooperation launched a voluntary IEA Critical Minerals Security Programme. Under the scheme, which may cover stockpiling and, potentially, other elements such as recycling and resilient and transparent supply chain mechanisms, participating countries plan to share experience and data from their own national programmes to bolster supply chain resilience.

Voluntary strategic stockpiling, where applicable, could help countries weather short-term supply disruptions. Some countries have been operating stockpiling schemes for many years as a means of enhancing supply security. These need to be carefully designed, based on a periodic review of potential vulnerabilities. In general, such schemes can be more effective for minerals with smaller markets, opaque pricing and a concentrated supply structure than those with well-developed markets and ample liquidity.

Table 6 Priority actions for government and industry – Diversify

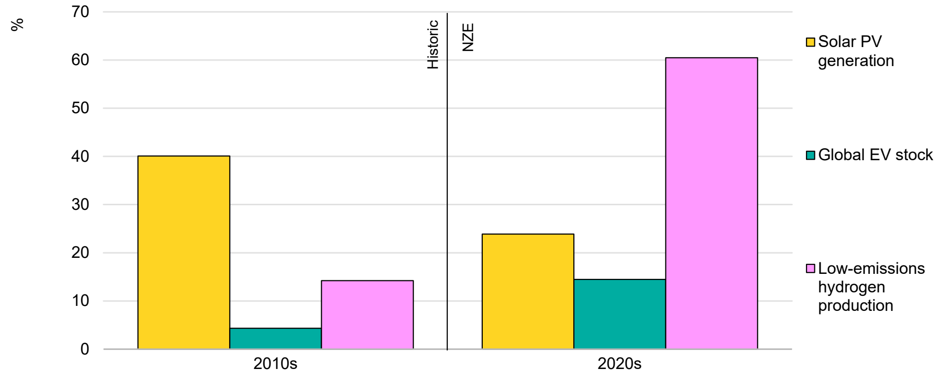
	Lead by	Actions
Diversify		Identify and develop new and more diversified supply sources for critical minerals, prioritising partners and projects with strong environmental, social and governance (ESG) credentials
		Pursue coordinated measures to bolster supply chain resilience, including critical mineral stockpiles and improving geological surveys for critical mineral sources
		Use industry policy levers to expand and diversify clean energy technology manufacturing capacity
		Support the development of a robust recycling industry to reduce demand for raw materials, with industry to invest in recycling and reuse friendly design and production

2. Accelerating the clean energy transition

To get to net zero, the roll out of clean energy technologies must be stepped up

The massive increase in the deployment of clean energy needed for the world to achieve net zero is predicated on an unprecedented acceleration in the scaling up of related supply chains. The next decade will be critical. Any delays in rolling out solar PV, EV and hydrogen technologies will mean that reaching net zero by mid-century will become increasingly more difficult. In our Net Zero Emissions by 2050 Scenario, the electricity sector is the first to achieve net zero emissions, mainly because an array of renewable and other clean energy technologies are already available on the market. Solar PV, which has seen record growth over the last few years (solar generation increased by 26% in 2021, up from the previous record of 23% in 2020) accelerates in the coming years, increasing nine-fold by 2030 and almost a 30-fold by 2050 compared with 2020 levels (Figure 10). This would require a sustained increase in the production of PV modules and related components and raw materials. Sales of EVs also continue to surge in the next few years, driving up both the need to generate electricity and the need for materials and components to make batteries. Hydrogen and hydrogen-based fuels – another key pillar of decarbonisation – take off during the 2020s, calling for new and expanded supply chains for electrolysers and CO_2 capture, transport and storage infrastructure.

Figure 10 Compound annual growth rate in deployment of solar PV, EVs and low-emissions hydrogen in the Net Zero Emissions by 2050 Scenario

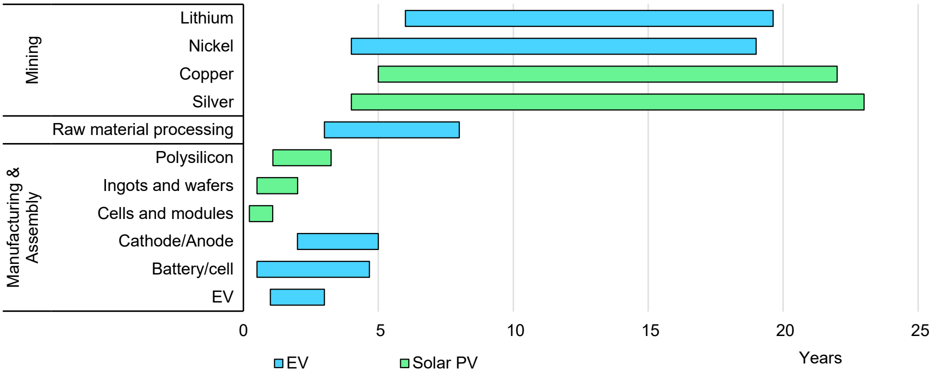


Long project development times risk holding back supply chains as demand grows

The considerable lead times required to develop the raw materials, manufacturing capacity and end-use infrastructure for many clean energy technologies risks constraining the rate at which they can be deployed. The complexity of supply chains means that any shortages or disruptions at one point in the chain can cause significant delays while new facilities are built. This highlights the importance of timely investment across all elements of the supply chain to ensure that sufficient materials are available in the future to meet rising demand for inputs and final products.

Building new mines to extract raw materials generally takes longer than installing production capacity at other stages in the supply chain. Lead times for mining operations (from discovery to first production) exceeded 16 years on average between 2010 and 2019, though they varied greatly by mineral, location and mine type (Figure 11). Exploration and feasibility studies often required 12 years, and construction four to five years. Antimony, cadmium, gallium, germanium, indium and selenium – primarily used in thin-film solar PV technologies – are mostly recovered as mining by-products. It is therefore difficult to rapidly adapt supply to changes in demand, since they are often not economic to mine individually. Both long lead times and dependence on by-products can contribute to price variability, since supply can often lag demand for years.

Figure 11 Typical lead times to initial production for selected stages in EV battery and solar PV supply chains



Sources: IEA (2022) Global Supply Chains of EV Batteries; IEA (2022) Special Report on Solar PV Global Supply Chains.

Manufacturing lead times vary across supply chain segments and locations. New polysilicon factories take longer to build than those for wafers, cells and modules, ranging from 12 to 40 months. In addition, ramping up production of polysilicon to full capacity usually takes time. For ingots and wafers, development timelines are usually quicker and lead times similar across countries and regions. Cell and module factories can generally be commissioned within four to 12 months in most parts of the world. In the case of EVs, lead times are generally fastest for vehicle assembly, since automobile production capacity currently exceeds demand worldwide, allowing automakers to retool existing conventional vehicle factories. For example, work on retooling Volkswagen's Zwickau factory in Germany began in 2018 and the first EVs were produced in November 2019. Similarly, Tesla's EV factory in Shanghai was completed in roughly one year after breaking ground in early 2019. Battery production lead times vary more. In China, CATL was able to complete a new cell manufacturing facility in under one year, but Northvolt's first factory in Sweden took four years.

Regulatory, permitting and approval processes are a major contributor to project development lead times. Securing permits for mining operations can take from one to 10 years, with multiple permits often required due to, the complexity and scale of these projects. This is one of the main reasons why project lead times in the European Union and the United States are generally much longer than in other parts of the world, though land acquisition and construction times are also generally longer too. For example, the 800 km Cortez CO_2 pipeline in the United States took eight years to complete, though construction took only two years. While there is an obvious need to balance environmental standards and consultation and engagement with indigenous peoples with speed, improving the efficiency of the permitting and approvals process for critical mineral and clean energy projects would help to accelerate their deployment. For example, in the European Union strategic energy infrastructure projects that receive a designated status are eligible for accelerated permitting, and in the United States national security laws allow the government to increase domestic manufacturing capacity for critical technologies and materials.

Building clean energy markets requires a focus on both supply and demand

Ambitious government policies are needed to accelerate the roll-out of clean energy technologies and build the supply chains to support them. A mix of technology-push policies that drive innovations to market and market-pull polices that incentivise their use and stimulate economies of scale is the most cost-effective approach. To increase the supply of clean energy technologies, governments need to step up support for RD&D. Policy options include grants, contracts-for-difference, feed-in tariffs, tax incentives, competitive auctions, innovation prizes, and balance sheet support tools such as debt guarantees and equity to cover upfront investment costs – as well as regulatory and other types of support for projects that would otherwise not be viable.

Accelerating the creation of markets for clean energy technologies requires simultaneous demand-side support to stimulate private sector investment and adoption. Action within the next decade on creating demand-side support mechanisms is crucial to establishing defined clean energy markets. Examples of policies to pull clean energy technologies to market include targets or standards, subsidies, tax credits and other financial incentives. Carbon pricing mechanisms, such as a carbon tax and emission trading schemes, can provide policy direction and a level playing field for low-carbon technologies. Public procurement programmes have also proven to be effective in stimulating demand for EVs in particular. In the European Union, Colombia, Chile and India, EV procurement programmes have been established or are being planned. Such programmes could also be used to create demand for low-emissions hydrogen by modifying procurement contracts to require its use for public transport and municipal services, or the use of near zero emissions-produced steel and cement in infrastructure projects. Certification, standardisation and regulatory regimes for clean energy technologies, their connecting infrastructure and end products are also needed to boost demand.

It is vital that support for supply and demand be aligned to avoid supply chain imbalances and inefficiencies. For example, global policy support for low-emissions hydrogen has tended to focus on scaling up supply, and not on creating new demand.

There is sufficient possibility to absorb low-emissions hydrogen production in the near term by replacing fossil-based production in existing applications. But there is a risk that it discourages new investment in production, reducing opportunities for cost reductions from scale economies and delaying the wider adoption of hydrogen as a clean energy vector. Lessons can be learned from solar PV deployment. In Germany, Japan and Korea, a combination of demand and supply incentives helped them become the largest manufacturers in the solar PV supply chain during the late 1990s and early 2000s. The earliest measures in these countries were R&D incentives for solar PV in the late 1970s and 1980s, as well as grants, tax incentives, development funds and loan programmes. In the early 2000s, they introduced attractive feed-in tariffs to stimulate demand.

Table 7 Priority actions for government and industry – Accelerate

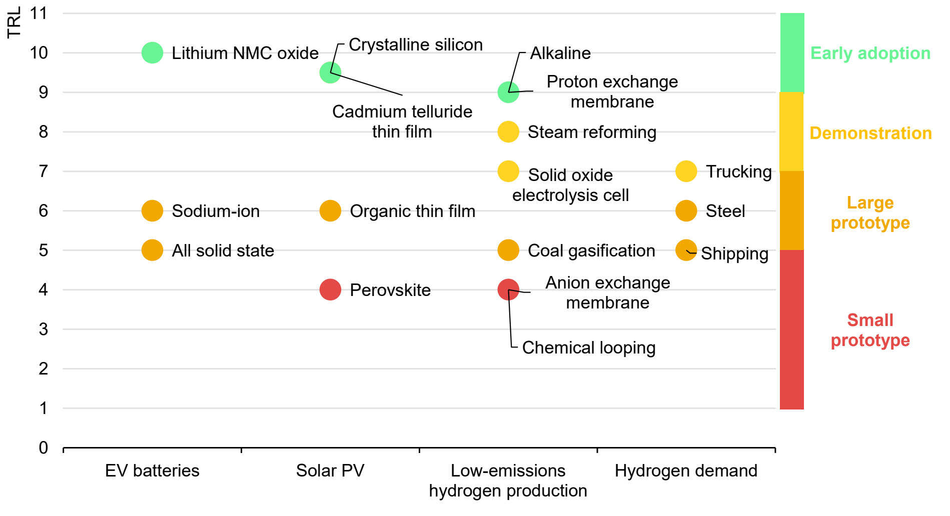
	Lead by	Actions
Accelerate	Government	Fast-track and streamline permits and approvals for clean energy and critical minerals while maintaining environmental and other standards
	Government	Use government procurement to create demand for new clean energy technologies and fuels
	Government	Accelerate the creation of markets using targets, standards, fiscal incentives and regulatory reform

3. Innovating clean energy technology

Many of the technologies needed to reach net zero are not yet commercially available

Achieving net zero by 2050 requires a major acceleration in clean energy innovation, as many of the technologies needed are not yet on the market. Almost half of the emissions reductions in 2050 in the Net Zero Emissions by 2050 Scenario stem from technologies that are only at demonstration and prototype stages today (Figure 12). Commercialising those technologies hinges on faster innovation. The level of technology readiness has significant implications across supply chains. For example, in the case of low-emissions hydrogen, declining electrolyser production costs and the development of dedicated infrastructure will play a crucial role in its widespread adoption. Some emerging electrolysis technologies, such as solid oxide electrolyser cells and anion exchange membranes, rely much less on critical minerals. Markets for batteries and solar PV are more developed and the technologies already cost-competitive in many cases, but there are still emerging technologies in these supply chains that could greatly improve cost and efficiency – especially those that involve recycling and reduced reliance on expensive raw materials. For batteries, emerging sodium-ion technologies rely on abundant and cheap minerals, while solid-state batteries could lead to a step improvement in performance. For solar PV, organic and non-silicon thin-film technologies currently at the prototype stage promise higher efficiencies and lower manufacturing costs.

Figure 12 Technology readiness of solar PV, EV batteries and hydrogen technologies



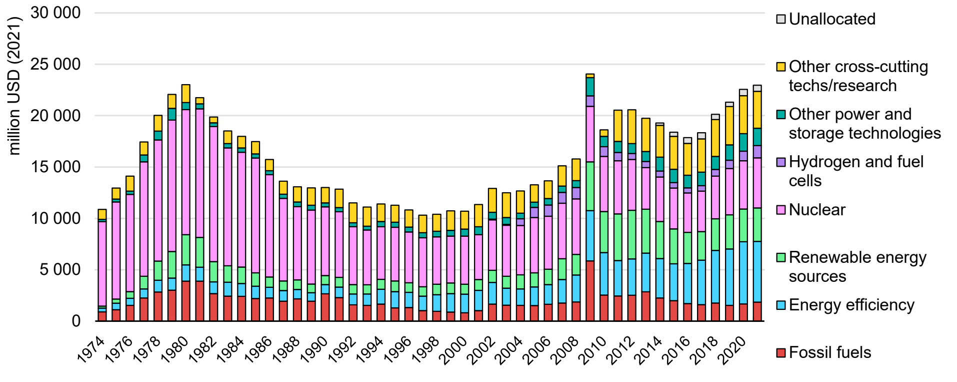
Note: TRL = technology readiness level, a measure of the level of maturity of a given technology within a defined scale (see the IEA's Clean Energy Technology Guide for more details). Steel refers to hydrogen-based direct reduced iron production, trucking refers to hydrogen fuel cell trucks and shipping refers to internal combustion engines fuelled by hydrogen or ammonia.

Innovation is key to technological advances across and along clean energy supply chains. It is particularly important in reducing material dependency, i.e. to make technologies less dependent on individual materials or those exposed to vulnerable supply chains, less material-intensive or easier to recycle. Innovation in digital technologies also presents huge opportunities for building more secure, resilient and sustainable supply chains. The use of advanced digital technologies – such as blockchain, artificial intelligence, data analytics, Internet of Things and automation – can help companies at different stages of the supply chain to improve their responsiveness, transparency and efficiency. They will be key for new market entrants to be competitive. One example is the use of digital twins to model real time disruptions to a company's supply chains, which allows more responsive management of problems through intelligent analytics.

Public funding for innovation must be a key pillar of national net zero plans

Public funding of innovation remains essential to mitigate the risks inherent to developing clean energy technologies and to leverage private investment. In 2021, global public RD&D spending on all types of energy is estimated to have reached about USD 38 billion, of which USD 23 billion, or 61%, was in IEA countries (Figure 12). Although global spending in real terms has been rising in absolute terms in recent decades, it has fallen sharply as a share of gross domestic product, from a peak of 0.1% in 1980 to just 0.04% in 2021. The good news is that the share of this spending in IEA countries going to clean energy has been rising, with 90% going to those technologies in 2021 – one-half to energy efficiency and nuclear energy alone.

Figure 13 Evolution of total energy R&D public budget per year of IEA countries



Source: IEA (2022) Energy Technology RD&D Budgets database.

Given the scale and pace of the required expansion in clean energy and the large contribution of technologies that are not yet commercial, a step increase in public funding of innovation in the near term is vital. We estimate that at least USD 90 billion of public funding will need to be mobilised by 2026 to support completion of a portfolio of demonstration projects in critical areas to be on track for net zero by 2050. There are signs that this could materialise. In the United States, the 2021 Bipartisan Infrastructure Law and the 2020 Energy Act together provide for USD 62 billion of funding for major new clean energy demonstration and deployment programmes, more than tripling total spending and significantly expanding the RD&D budget. A significant share is expected to go to demonstration projects. In total, we estimate that around USD 50 billion of public funds could be available for large-scale low-carbon demonstration projects worldwide over the period to 2030 under current plans.

Government support for RD&D needs to go beyond financing and be tailored in a way that maximises the contribution of the private sector. Energy R&D spending by listed companies reached around USD 117 billion, 5% higher than pre-pandemic levels in 2019. Despite large corporate spending on energy innovation, around 60% of corporate investments in energy R&D are spent in the automotive and oil and gas sectors, and USD 10 billion (around 9%) was spent on renewables in 2021. Policy support that can be particularly beneficial for encouraging innovation includes public procurement, incubation and prizes for entrepreneurs. For large-scale demonstration projects, measures are needed to improve access to low-cost financing, such as credit enhancement (provisions used by a borrower to reduce debt by improving its creditworthiness), risk-sharing schemes and in-kind advisory support.

Table 8 Priority actions for government and industry – Innovate

	Lead by	Actions
Innovate		Lead the innovation and commercialisation of technologies and manufacturing processes that rely less on critical minerals or on a more diversified material mix
		Increase and prioritise investment and support for research, development and demonstration (RD&D) and de-risk private investment in clean energy technologies, fuels and supply chains needed for net zero
		Adopt advanced digital technology approaches to improve energy and material efficiency and reduce costs

4. Collaborating on supply chain development

Net zero requires an unprecedented collaborative effort

Securing the supply chains for clean energy technologies must be a collaborative effort between the public and private sectors, and between governments. All stakeholders need to work together to identify and map out potential opportunities and vulnerabilities in those supply chains, taking account of local circumstances and the specific characteristics of each sector and technology. Addressing the multiple challenges presented by the clean energy transition requires a focus on transparent public dialogue, developing programmes to boost skills in emerging industries and supporting the growth of new job opportunities in more sustainable economic activities. Taking a regional or international approach can facilitate the identification of opportunities for collaboration and the establishment of strategic partnerships.

Governments are already establishing strategic partnerships in the field of clean energy supply chains. For example, the European Union recently signed an agreement with Canada on advancing trade and investment in secure, sustainable and resilient raw materials value chains. This forms part of the EU critical raw materials action plan, which envisages the Union engaging in strategic partnerships with resource-rich third countries, making use of external policy instruments and respecting its international obligations. Similar partnerships have been struck between the United States and Australia, and the United States and Canada. In May 2022, the Indo-Pacific Economic Framework for Prosperity was agreed between 13 nations and included a focus on securing critical supply chains, including to "ensure access to key raw and processed materials, semiconductors, critical minerals, and clean energy technology".

International standards can support markets for clean energy and related materials

As for other economic activities, international standards are an important means of supporting the development of markets for clean technologies and fuels, and associated supply chains, by facilitating trade and technology transfer. They are needed to overcome technical barriers in international commerce caused by differences among technical regulations and standards developed separately by countries, national standards bodies or companies, and should be aligned with sustainability and climate goals. Considerable progress has already been made with established technologies like solar PV and EV batteries. Experience in those fields needs to be applied to emerging technologies, notably low-emissions hydrogen, while regulatory cooperation frameworks, certification schemes and standards will be need to be harmonised to reduce barriers for stakeholders. International agreement on a methodology for calculating the carbon footprint of hydrogen production is critical, as it is the basis from which a global certificates market could develop. Importing countries, regions and companies would then be able to decide what carbon footprint threshold they deem acceptable for imported clean hydrogen (although a commonly agreed international standard is vital to avoid future impediments to cross-border trade in hydrogen). Governments and industry can leverage the work of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which has been leading international efforts in these areas for many years.

Traceability encompassing whole supply chains is an important aspect of international standards. It can help manage supply chains and quality control more effectively, as well as identify and address ESG concerns, such as greenhouse gas emissions, water use, waste management, human rights, fair labour practices, diversity, business ethics and community relations. However, mapping and tracking activity across interconnected global supply chains is complex and requires a combination of tools like blockchain and machine learning. To demonstrate compliance with ESG best practices, the industry and intergovernmental organisations have already developed many new initiatives, tools, standards, and certifications relevant to clean energy supply chains, including the Global Reporting Initiative, the OECD's Due Diligence Guidance for Responsible Supply Chains, the UN Global Compact Principles, the Initiative for Responsible Mining Assurance, and the Responsible Minerals Initiative. Traceability is complex to implement and there is no silver bullet. Effective regulatory enforcement is essential, as well as a strong, unified policy on ESG standards. Degrees of traceability and regulation still vary markedly between supply chains, minerals and materials.

The application of traceability standards in clean energy is progressing, especially in the advanced economies. Traceability protocols have been developed for solar PV and REE supply chains in the United States. And on 23 February 2022, the European Commission published a proposal for a directive on corporate sustainability and due diligence in all value chains. It is also preparing a new legislative instrument to effectively prohibit the sale of products made with forced labour on EU markets. The European Union also issued on 12 July 2021 guidelines on forced labour due diligence to help EU companies address the risk of forced labour in their operations and supply chains, in line with international standards.

Helping emerging markets and developing economies secure supply chains is key to an equitable transition

The world's energy and climate future increasingly depends on decisions made in emerging market and developing economies, so collaboration with and among them is becoming more important. The declining cost of clean energy technologies offers a tremendous opportunity for these countries to chart a new, lower-emissions pathway for growth and prosperity. If this opportunity is not taken, this will become a major fault line in global efforts to address climate change and reach sustainable development goals. For now, investment in clean energy in the emerging economies falls far short of what is needed to make the Net Zero Emissions by 2050 Scenario a reality. Emerging markets and developing economies account for two-thirds of the world's population but only one-fifth of global investment in clean energy. Investment in these countries needs to increase nearly eight-fold, to reach around USD 1.7 trillion annually by 2030 to be consistent with net zero goals. Helping emerging economies to build secure, resilient and sustainable clean energy supply chains could bring major new economic opportunities for all countries.

Table 9 Priority actions for government and industry – Collaborate

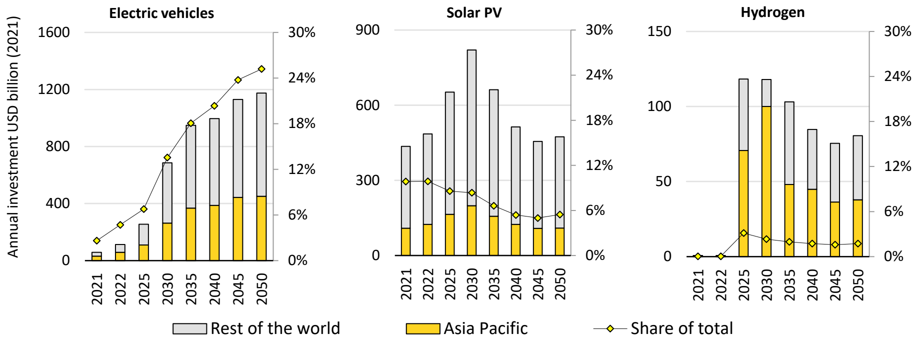
	Lead by	Actions
Collaborate		Map supply chains for clean energy technology at a national, regional and sectoral level to identify potential vulnerabilities, opportunities and strategic partnerships
		Enhance market transparency through the development and uptake of international standards that promote higher ESG performance for key materials, technologies and fuels
		Support emerging market and developing economies in building secure, sustainable and resilient supply chains

5. Investing in clean energy

A massive surge in clean energy investment is urgently needed by 2030

Investment in clean energy needs to increase enormously over the rest of the current decade for the world to get on track for net zero emissions by the middle of the century. The USD 1.4 trillion that is expected to be spent on clean energy technologies and efficiency worldwide in 2022 remains far below what is required in the Net Zero Emissions by 2050 Scenario: almost USD 5 trillion (in real terms) in 2035, falling to USD 4.5 trillion in 2050. Solar PV investment needs peak at around USD 430 billion around 2030, while EV-related investments keep rising to 2050, reaching over USD 1.1 trillion. Capital spending on hydrogen peaks at over USD 120 billion around 2030, falling back to around USD 80 billion by 2050 (Figure 14).

Figure 14 Global investment in selected clean energy technologies in the Net Zero Emissions by 2050 Scenario



Note: APAC = Asia-Pacific (including China and India). Total private and public investment spending in clean energy technologies, which include EVs, low-emissions fuels (modern liquid and gaseous bioenergy, low-emissions hydrogen and hydrogen-based fuels), CCUS, grids and battery storage, energy efficiency, nuclear, renewable power, and renewables for end uses and electrification in the buildings, transport and industry sectors.

In response to rising inflation, central banks around the world have started to raise interest rates, increasing the cost of debt. For energy-related sectors, this has led debt costs to rise by over 30% from pre-pandemic levels and by an average of nearly 50% in the last year alone due to low rates during the pandemic. It is likely that this will delay decisions to invest in energy efficiency measures, reduce the amount of RD&D, especially among small firms, and see a withdrawal of capital from venture capital markets. In this context, public funding support for energy innovation will play a vital role in mitigating exposure to more costly sources of capital.

As the energy system becomes more capital-intensive, keeping financing costs low will be critical to making them affordable and accelerating energy transitions. Upfront financing requirements for clean energy projects are generally bigger than for traditional energy projects per unit of energy produced or used, though they are offset over time by lower operating and fuel expenditures. There is no shortage of global capital, but there is a dearth of opportunities for clean energy investment around the world that offer adequate returns to balance the risks – in large part because the environmental value of clean energy technologies is not adequately reflected in market prices today. At the beginning of 2020, global financial wealth held by potential investors stood at over USD 200 trillion. There is, nonetheless, a growing appetite among investors to fund clean energy projects, with global issuance of sustainable debt soaring to record levels in 2021, though most of this is concentrated in advanced economies.

Reducing investment risks will be essential to mobilise private capital

Most of the increase in funding for clean energy projects will have to come from the private sector. In the Net Zero Emissions by 2050 Scenario, around 70% of clean energy investment over the next decade is carried out by private developers, consumers and financiers. This is likely to be financed mainly by channelling retained earnings from the balance sheets of large energy companies, as well as external sources – notably banks and the enormous pools of capital in financial markets. There is, nonetheless, an important role for governments, not just in funding the other 30% of investment, but also in creating an enabling environment for private investment and facilitating private access to public infrastructure projects. Public actors, including state-owned enterprises (SOEs), will often have a key part to play in funding network infrastructure and clean energy investments in emissions-intensive sectors like heavy industry, as well as accelerating innovation in technologies that are in the demonstration or prototype phase today. Public finance institutions will also need to catalyse private capital.

Clear policy signals from government would reduce uncertainties associated with clean energy and avoid potential costs from investing in assets that risk being underutilised or stranded. Mismatches in the speed of energy transitions can create risks; for example, if a lack of grid investment leads to bottlenecks for wind and solar PV, or if oil and gas suppliers switch from hydrocarbons to clean energy faster than their consumers. As financial regulators work to align capital flows with climate goals, slower progress in the real economy can lead investors to overvalue some sectors while penalising others. To attract investment, policy makers can create market certainty and reduce policy risks through well-designed legislative and regulatory frameworks. Policy risk can be reduced through a combination of dedicated long-term and short-term national targets for specific technologies and roadmaps within an overall net zero plan.

Strategic investment can transform today's infrastructure for a net zero energy system

Investment in infrastructure to connect low-emissions energy sources to end-users will be central to energy transitions. Clean technologies have different infrastructure requirements to existing energy systems, involving connecting the grid to local sources of renewable power generation and building smart grids, public electric vehicle charging infrastructure and hydrogen transport and storage facilities. In the Net Zero Emissions by 2050 Scenario, annual investment in expanding and modernising electricity networks grows from around USD 300 billion on average in recent years to around USD 860 billion by 2030. Investments in CO_2 pipelines and hydrogen-enabling infrastructure increase from around USD 1 billion a year today to

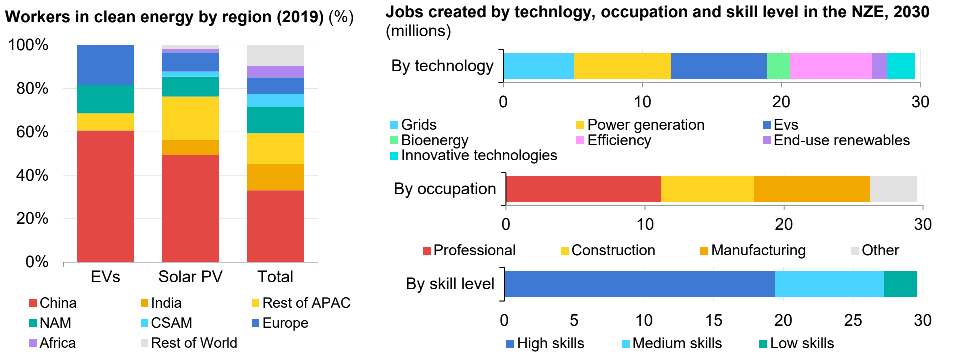
USD 40 billion in 2030. By 2030, the total length of hydrogen pipelines globally quadruples to over 20 000 km, while EV charging infrastructure expands more than 12-fold with 22 million charging points added each year – 1.3 times more than have been installed to date. Deployment of this infrastructure needs to go hand-in-hand with clean technology roll-outs to avoid bottlenecks.

Repurposing existing infrastructure would help keep costs down and speed up the roll out of clean technologies, especially hydrogen and CCUS. Repurposing existing gas pipelines could significantly reduce the cost of establishing national and regional hydrogen transportation and storage networks. The first conversion of a natural gas pipeline for full hydrogen service – a 12 km line with capacity of 4 Mt/year owned by Gasunie in the Netherlands – began commercial service in November 2018. The conversion work took less than seven months. The 2021 European Hydrogen Backbone (EHB) study suggests conversion represents between 21% and 33% of the cost of building a new dedicated hydrogen pipeline. There is also considerable potential to repurpose existing oil and gas pipelines for the transport of captured CO_2 in many parts of the world. This could significantly reduce the costs of developing CO_2 infrastructure: the investment needed to convert an existing pipeline is estimated to be between just 1% and 10% of the cost of building a new one. Two significant projects are currently planned: the Acorn CCS project in the United Kingdom, which involves repurposing an onshore gas pipeline to store captured CO_2 in a depleted gas field in the North Sea, and the Carbon Transport and Storage Company project in Queensland's Surat Basin. Repurposing for hydrogen or CO_2 could help to delay the substantial costs of decommissioning pipelines.

The world needs to invest in the energy skills of the future

A major benefit of the clean energy transition to net zero emissions is a net increase in energy sector jobs, as well as more skilled work. In the Net Zero Emissions by 2050 Scenario, an estimated 14 million new jobs are generated in clean energy supply globally by 2030 – offsetting the loss of 5 million positions in fossil fuel supply and resulting in a net gain of 9 million jobs in this pathway. In addition, clean energy industries – such as those related to more efficient appliances, EV manufacturing, and building retrofits and energy-efficient construction – employs a further 16 million new workers, bringing total creation in clean energy to around 30 million jobs (Figure 15). Nearly two-thirds of the new workers in the clean energy sectors by 2030 are highly skilled, the majority requiring substantial training. For example, solar PV manufacturing requires a diverse set of workers, including production engineers, materials handlers and assemblers. In established markets such as China and countries in Southeast Asia, between1 000 and 1 100 jobs are needed per GW of capacity manufactured – covering polysilicon, ingots, wafers, cells and modules – in large factories. Labour requirements can be nearly 60% higher in smaller plants in countries with cheaper labour.

Figure 15 Employment in clean energy by region (2019) and additional workers by technology, occupation, and skill level in 2030 under the Net Zero Emissions by 2050 Scenario



Sources: IEA (2022) World Energy Employment; IEA (2021) Net Zero by 2050 - A Roadmap for the Global Energy Sector.

It is essential that governments, industry and educational/training institutions put in place training and educational programmes to ensure that sufficient qualified workers are available to fill the new posts. The clean energy sector already faces difficulties hiring qualified personnel to keep pace with demand and labour shortages are holding back investment in some countries and sectors – for example in battery manufacturing in Korea and in building solar PV plants in Australia. Rising competition between countries and companies for scarce qualified personnel is leading to a "brain drain" in some countries where immigration laws permit. Mapping out future job and skill needs in clean energy supply chains can help avoid these problems. While some skills gaps can be filled through short training programmes or by transferring skills from other industries, many require education and/or on-the-job experience, which can often take a long time. Skills needs and labour inputs will change over time once technologies mature, the scale and complexity of operations grows, learning takes effect and automation progresses, so continuous retraining or upskilling may be necessary. At the same time, new jobs will not always be in the same places or sectors where employment is lost, so care must be taken to ensure a just energy transition for all – a key recommendation of the Global Commission on People-Centred Clean Energy Transitions that the IEA convened in 2021.

Table 10 Priority actions for government and industry – Invest

	Lead by	Actions
Invest		Improve access to sustainable finance and adopt financial tools that cater to different stages of clean energy technology supply chains
		Invest in the development of an appropriately skilled workforce by upskilling and reskilling the existing workforce for emerging clean energy roles and ensuring labour force mobility in the region
		Identify opportunities for the strategic reuse or redeployment of existing infrastructure compatible with net zero pathways

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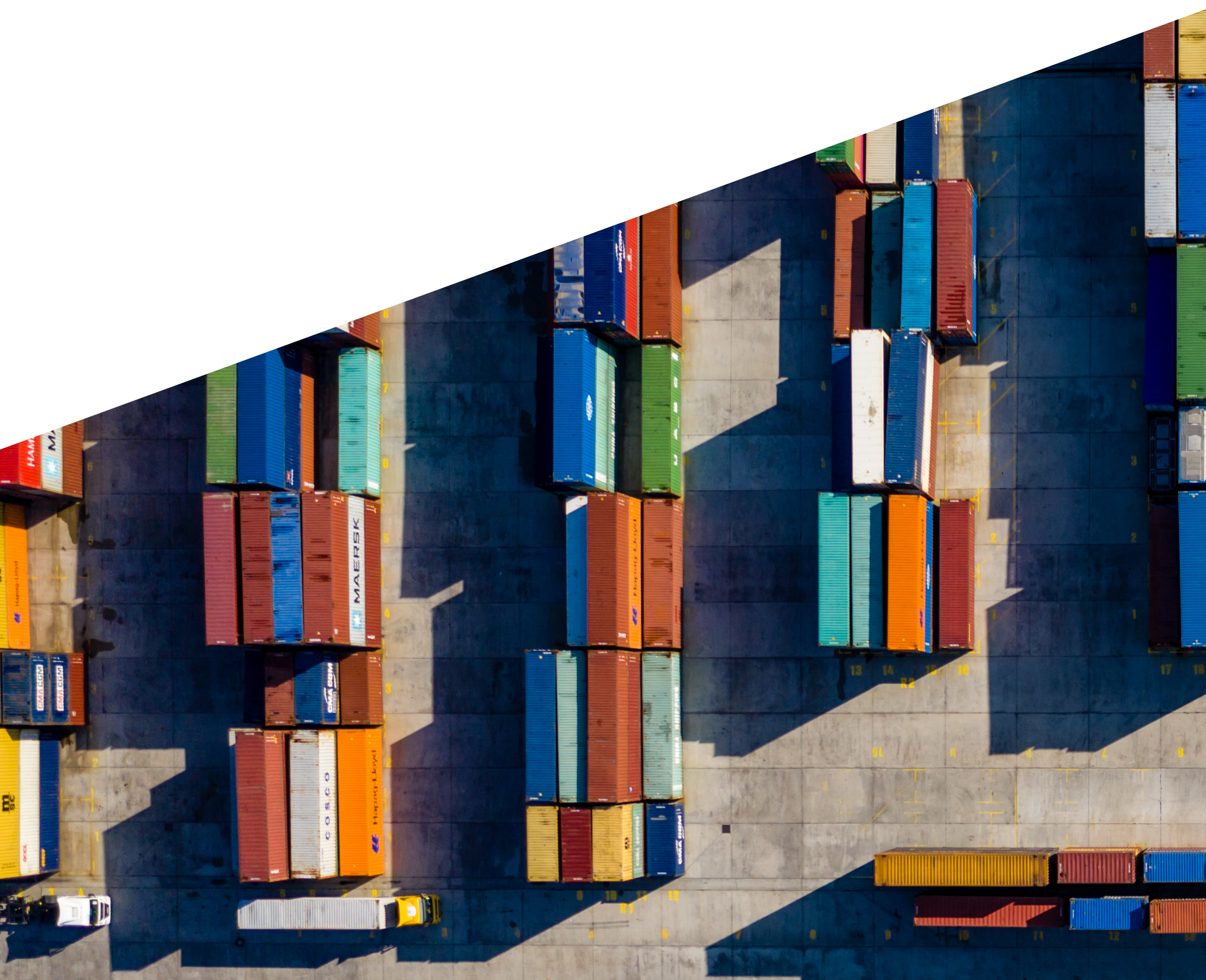
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