Energy Technology Perspectives 2023

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Abstract

The Covid-19 pandemic and Russia's invasion of Ukraine have led to major disruptions to global energy and technology supply chains. Soaring prices for energy and materials, and shortages of critical minerals, semiconductors and other components are posing potential roadblocks for the energy transition. Against this backdrop, the Energy Technology Perspectives 2023 (ETP-2023) provides analysis on the risks and opportunities surrounding the development and scale-up of clean energy and technology supply chains in the years ahead, viewed through the lenses of energy security, resilience and sustainability.

Building on the latest energy, commodity and technology data, as well as recent energy, climate and industrial policy announcements, ETP-2023 explores critical questions around clean energy and technology supply chains: Where are the key bottlenecks to sustainably scale up those supply chains at the pace needed? How might governments shape their industrial policy in response to new energy security concerns for clean energy transitions? Which clean technology areas are at greatest risk of failing to develop secure and resilient supply chains? And what can governments do to mitigate such risks while meeting broader development goals?

The Energy Technology Perspectives series is the IEA's flagship technology publication, which has been key source of insights on all matters relating to energy technology since 2006. ETP-2023 will be an indispensable guidebook for decision-makers in governments and industry seeking to tap into the opportunities offered by the emerging new energy economy, while navigating uncertainties and safeguarding energy security.

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Foreword

The global energy sector is in the midst of profound changes that are set to transform it in the coming decades from one based overwhelmingly on fossil fuels to one increasingly dominated by renewables and other clean energy technologies. A new global energy economy is emerging ever more clearly, with the rapid growth of solar, wind, electric vehicles and a range of other technologies such as electrolysers for hydrogen. This transition is in turn changing the industries that supply the materials and products underpinning the energy system, heralding the dawn of a new industrial age – the age of clean energy technology manufacturing.

At the International Energy Agency (IEA), we are dedicated to improving the security, resilience and sustainability of the global energy system. Those interlinked priorities are at the heart of this edition of Energy Technology Perspectives 2023 (ETP-2023), the latest in the IEA's technology flagship series that began in 2006. As decision-makers seek to understand and adapt to the changes underway, ETP-2023 serves as the world's first comprehensive global guidebook on the clean energy technology industries of today and tomorrow. It provides a detailed analysis of clean energy technology manufacturing and its supply chains around the world – and how they are likely to evolve as the clean energy transition advances in the years ahead.

Major economies around the world – from Asia to Europe to North America – are stepping up efforts to expand their clean energy technology manufacturing with the overlapping aims of advancing net zero transitions, strengthening energy security and competing in the new energy economy. And the current global energy crisis has only accelerated these efforts.

These trends have massive implications for governments, businesses, investors and citizens around the world. Every country needs to identify how it can benefit from the opportunities and navigate the challenges of this new energy economy. This report shows that the rapid growth of clean technology manufacturing is set to create new markets worth hundreds of billions of dollars as well as millions of new jobs in the coming years, assuming countries make good on the energy and climate pledges they have announced.

At the same time, the industrial strategies that countries develop to secure their places in this new energy economy will need to take into account the emerging challenges that these changes bring. Today, we already see potentially risky levels of concentration in clean energy supply chains globally – both in the manufacturing of the technologies and in the critical minerals on which they rely.

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These challenges are what make ETP-2023 such a vital and timely contribution as policy makers are working to devise the industrial strategies to benefit their economies – and project developers and investors are weighing key decisions on future manufacturing operations. Our analysis shows that the global project pipeline is very large – enough to move the world much closer to reaching international energy and climate goals if it all comes to fruition. But the majority of those announced projects are not yet under construction or set to begin construction imminently. Governments have a role here in providing the supportive policies and broader industrial strategies that can provide developers and investors with the visibility and confidence they need to go ahead.

However, this report also shows issues of which governments need to be mindful, such as the importance of ensuring fair and open international trade in clean energy technologies, which will be essential for achieving rapid and affordable energy transitions. ETP-2023 also makes clear that for most countries, it is not realistic to try to compete across all parts of clean energy technology supply chains. Countries will need to play to their strengths, whether that comes in the form of mineral resources, low-cost clean energy supplies, a workforce with relevant skills, or synergies with existing industries. And since no country will be in a position to cover every part of the supply chain at once, international collaboration will be an essential element in industrial strategies. This can include strategic partnerships and foreign direct investment, for example.

These are just some of the key issues on which ETP-2023 provides extremely valuable insights. I'm confident decision-makers around the world will greatly appreciate these and the many others contained in these pages. And for this, I would like to thank the excellent team at the IEA's Energy Technology Policy Division, under the outstanding leadership of my colleague Timur Gül, for all the work that went into producing this report, which will serve as a reference for years to come.

Dr. Fatih Birol

Executive Director

International Energy Agency

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Executive summary

The energy world is in the early phase of a new industrial age – the age of clean energy technology manufacturing. Industries that were in their infancy in the early 2000s, such as solar PV and wind, and the 2010s, such as EVs and batteries, have mushroomed into vast manufacturing operations today. The scale and significance of these and other key clean energy industries are set for further rapid growth. Countries around the world are stepping up efforts to expand clean energy technology manufacturing with the overlapping aims of advancing net zero transitions, strengthening energy security and competing in the new global energy economy. The current global energy crisis is a pivotal moment for clean energy transitions worldwide, driving a wave of investment that is set to flow into a range of industries over the coming years. In this context, developing secure, resilient and sustainable supply chains for clean energy is vital.

Every country needs to identify how it can benefit from the opportunities of the new energy economy, defining its industrial strategy according to its strengths and weaknesses. This 2023 edition of Energy Technology Perspectives (ETP-2023) provides a comprehensive inventory of the current state of global clean energy supply chains, covering the areas of mining; production of materials like lithium, copper, nickel, steel, cement, aluminium and plastics; and the manufacturing and installation of key technologies. The report maps out how these sectors may evolve in the coming decades as countries pursue their energy, climate and industrial goals. And it assesses the opportunities and the needs for building up secure, resilient and sustainable supply chains for clean energy technologies – and examines the implications for policy makers.

The new energy economy brings opportunities and risks

Clean energy transitions offer major opportunities for growth and employment in new and expanding industries. There is a global market opportunity for key mass-manufactured clean energy technologies worth around USD 650 billion a year by 2030 – more than three times today's level – if countries worldwide fully implement their announced energy and climate pledges. Related clean energy manufacturing jobs would more than double from 6 million today to nearly 14 million by 2030, with over half of these jobs tied to electric vehicles, solar PV, wind and heat pumps. As clean energy transitions advance beyond 2030, this would lead to further rapid industrial and employment growth.

But there are potentially risky levels of concentration in clean energy supply chains – both for the manufacturing of technologies and the materials on

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which they rely. China currently dominates the manufacturing and trade of most clean energy technologies. China's investment in clean energy supply chains has been instrumental in bringing down costs worldwide for key technologies, with multiple benefits for clean energy transitions. At the same time, the level of geographical concentration in global supply chains also creates potential challenges that governments need to address. For mass-manufactured technologies like wind, batteries, electrolysers, solar panels and heat pumps, the three largest producer countries account for at least 70% of manufacturing capacity for each technology – with China dominant in all of them. The geographical distribution of critical mineral extraction is closely linked to resource endowments, and much of it is very concentrated. For example, Democratic Republic of Congo alone produces 70% of the world's cobalt, and just three countries account for more than 90% of global lithium production. Concentration at any point along a supply chain makes the entire supply chain vulnerable to incidents, be they related to an individual country's policy choices, natural disasters, technical failures or company decisions.

The world is already seeing the risks of tight supply chains, which have pushed up clean energy technology prices in recent years, making countries' clean energy transitions more difficult and costly. Increasing prices for cobalt, lithium and nickel led to the first ever rise in battery prices, which jumped by nearly 10% globally in 2022. The cost of wind turbines outside China has also been rising after years of decline, with the prices of inputs such as steel and copper about doubling between the first half of 2020 and the same period in 2022. Similar trends can be seen in solar PV supply chains.

Governments are racing to shape the future of clean energy technology manufacturing

Countries are trying to increase the resilience and diversity of clean energy supply chains while also competing for the huge economic opportunities. Major economies are acting to combine their climate, energy security and industrial policies. The Inflation Reduction Act in the United States is a clear articulation of this, but there is also the Fit for 55 package and REPowerEU plan in the European Union, Japan's Green Transformation programme, the Production Linked Incentive scheme in India that encourages manufacturing of solar PV and batteries, and China is working to meet and even exceed the goals of its latest Five-Year-Plan.

There are big dividends for countries that get their clean energy industrial strategies right. Project developers and investors are watching closely for the policies that can give them a competitive edge in different markets, and will respond to supportive policies. Only 25% of the announced manufacturing projects globally for solar PV are under construction or beginning construction

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imminently – the number is around 35% for EV batteries and less than 10% for electrolysers. The share is highest in China, where 25% of total solar PV and 45% of battery manufacturing is already at such an advanced stage of implementation. In the United States and Europe, less than 20% of announced battery and electrolyser factories are under construction. The relatively short lead times of around 1-3 years on average to bring manufacturing facilities online mean that the project pipeline can expand rapidly in countries with an environment that is conducive to investment. Manufacturing projects announced, but not firmly committed, in one country today could end up actually being developed elsewhere in response to shifts in policies and market developments.

Greater efforts are needed to diversify and strengthen clean energy supply chains. China accounts for most of the current announced manufacturing capacity expansion plans to 2030 for solar PV components (around 85% for cells and modules, and 90% for wafers); for onshore wind components (around 85% for blades, and around 90% for nacelles and towers); and for EV battery components (98% for anode and 93% for cathode material). Hydrogen electrolysers are the main exception, with around one-quarter of manufacturing capacity announcements for 2030 being in China and the European Union, respectively, and another 10% in the United States.

Clean energy supply chains benefit from international trade

International trade is vital for rapid and affordable clean energy transitions, but countries need to increase diversity of suppliers. For solar PV, many components are traded today, in particular wafers and modules. The share of international trade in global demand is nearly 60% for solar PV modules, with around half of the solar modules manufactured in China being exported – predominantly to Europe and the Asia Pacific region. The situation is similar for EVs, for which most of the trade in components flows from Asia into Europe, which imports around 25% of its EV batteries from China. Wind turbine components are heavy and bulky, but the international trade of towers, blades and nacelles is quite common. China is a major player in wind turbine component manufacturing, accounting for 60% of global capacity and half of total exports, most of which go to other Asian countries and Europe. In the United States, one of the largest wind power markets, the domestic content of blades and hubs is lower than 25%. For heat pumps, the share of international trade in global manufacturing is below 10%, with most of it from China to Europe.

The announced manufacturing pipeline to 2030 is very large for many clean energy technologies. If all announced projects to expand manufacturing capacities were to materialise and all countries implement their announced climate pledges, China alone would be able to supply the entire global market for solar PV

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modules in 2030, one-third of the global market for electrolysers, and 90% of the world's EV batteries. Announced projects in the European Union would be sufficient to supply all of the bloc's domestic needs for electrolysers and EV batteries, but would continue to be highly dependent on imports for solar PV and wind, an area where it currently has a technological edge. The situation is somewhat similar in the United States, although further capacity additions are highly likely as a result of the Inflation Reduction Act. The current global pipeline of announced projects would exceed demand for some technologies (solar PV, batteries and electrolysers) and fall significantly short for others (wind components, heat pumps and fuel cells). This highlights the importance of clear and credible deployment targets from governments to limit demand uncertainty and guide investment decisions.

Critical minerals bring their own set of challenges

The mining of critical minerals is the only step in clean energy technology supply chains that depends on resource endowment alone. The long lead times for new mines, which can be well over ten years from the start of project development to first production, increase the risk that critical minerals supply becomes a major bottleneck in clean technology manufacturing. Moreover, the high geographical concentration of today's production creates security of supply risks, making international collaboration and strategic partnerships crucial. Clear policy signals about future deployment are particularly important to de-risk investments in this sector, as companies developing new mining capacity need to be confident that clean energy technologies further down the supply chain will be successfully scaled up in time.

The majority of announced projects for the processing and refining of key critical minerals are set to be located in China. These midstream processes tend to be energy-intensive. China accounts for 80% of the announced additional production capacity to 2030 for copper and dominates announced refining capacity of key metals used in batteries (95% for cobalt, and around 60% for lithium and nickel). Currently planned expansions of mineral processing capacity worldwide fall well short of the volumes that will be needed for rapid deployment of clean energy technologies. Polysilicon for solar PV supply chains is the only area in which a surplus of capacity by 2030 can currently be expected.

Mitigating risks in critical mineral supplies requires a new, more diversified network of diverse international producer-consumer relationships. These will be based not only on mineral resources, but also on the environmental, social and governance standards for their production and processing. These new partnerships need to be balanced in ways that offer resource-rich producers, especially in developing economies, the opportunity to move beyond primary production. Stockpiling options can also provide safeguards against disruption, but

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a comprehensive suite of policies in support of minerals security needs to include attention on the demand side, notably via recycling programmes and support for technology innovation.

Countries' clean energy industrial strategies need to reflect their strengths and weaknesses

For most countries, it is not realistic to compete effectively across all parts of the relevant clean energy technology supply chains. They need not to do so. Competitive specialisms often arise from inherent geographic advantages, such as access to low-cost renewable energy or the presence of a mineral resource, which can lead to lower production costs for energy and material commodities. But they can also arise from other attributes, like a large domestic market, a high-skilled workforce or synergies and spillovers stemming from existing industries. Holistically assessing and nurturing these competitive advantages should form a central pillar of governments' industrial strategies, designed in accordance with international rules and complemented by strategic partnerships.

Energy costs will continue to be a major differentiator in the competitiveness of countries' energy-intensive industry sectors. Industrial competitiveness today is closely linked to energy costs, especially natural gas and electricity, which vary greatly between regions. This remains the case in the clean energy transition. For example, production costs of hydrogen from renewable electricity could be much lower in China and the United States (USD 3-4/kg) than in Japan and Western Europe (USD 5-7/kg) using the best resources in those countries today, translating into similar differences in production costs for derivative commodities, such as ammonia and steel. As countries make progress towards their climate pledges, with renewable electricity costs continuing their decline and electrolyser costs falling rapidly, the cost difference between regions is likely to shrink somewhat, but competitiveness gaps will remain. Carefully considering where in the supply chain to specialise domestically, and where it might be better to establish strategic partnerships or make direct investments in third countries, should form key considerations of countries' industrial strategies.

New infrastructure will form the backbone of the new energy economy in all countries. This covers areas such as the transportation, transmission, distribution or storage of electricity, hydrogen and CO2. Building clean energy infrastructure can take 10 years or more, typically involving large civil engineering projects that have to adhere to extensive local planning and environmental regulations. While construction is in most cases a relatively efficient process, taking 2-4 years on average, planning and permitting can cause delays and create bottlenecks, with

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the process taking 2-7 years, depending on the jurisdiction and type of infrastructure. Lead times for infrastructure projects are usually much longer than for the power plants and industrial facilities that connect to them.

The story of the new energy economy is still being written – supply chains are central to the narrative

Industrial strategies for clean energy technology manufac turing require an all-of-government approach, closely coordinating climate and energy security imperatives with economic opportunities. This will mean identifying and fostering domestic competitive advantages; carrying out comprehensive risk assessments of supply chains; reducing permitting times, including for large infrastructure projects; mobilising investment and financing for key supply chain elements; developing workforce skills in anticipation of future needs; and accelerating innovation in early-stage technologies. Every country has a different starting point and different strengths, so every country will need to develop its own specific strategy. And no country can go it alone. Even as countries build their domestic capabilities and strengthen their places in the new global energy economy, there remain huge gains to be had from international co-operation as part of efforts to build a resilient foundation for the industries of tomorrow.

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Introduction

Purpose of this report

The International Energy Agency (IEA) Energy Technology Perspectives (ETP) technology flagship series of reports has been providing critical insights into key technological aspects of the energy sector since 2006. Clean energy technologies and innovation are vital to meet the policy goals of energy security, economic development and environmental sustainability. Cost-effective energy and environmental policy making must be based on a clear understanding of the potential for deploying these technologies. ETP seeks to help achieve this goal by assessing the opportunities and challenges associated with existing, new and emerging energy technologies, and identifying how governments and other stakeholders can accelerate the global transition to a clean and sustainable energy system.

The Covid-19 pandemic and the Russian Federation's (hereafter, "Russia") invasion of Ukraine have critically disrupted global energy and technology supply chains, leading to soaring gas, oil and coal prices, as well as shortages of critical minerals, semiconductors and other materials and components needed to manufacture clean energy technologies. The current global energy crisis poses a threat to near-term economic prospects and is threatening to slow the rollout of some clean energy technologies, but it also strengthens the economic case for accelerating the shift away from fossil fuels by massively raising investments in renewables, energy efficiency and other clean energy technologies. The recent spate of extreme weather events across the planet reminds us of the urgent need for radical action to rein in emissions of greenhouse gases. As the IEA has repeatedly stressed, the world does not need to choose between tackling the energy crisis and the climate crisis. The social and economic benefits of accelerating clean energy transitions are as huge as the costs of inaction.

Secure, resilient and sustainable supply chains for manufacturing clean energy technologies and producing low-emission energy commodities are central to the global energy transition. These supply chains depend largely on minerals and on an array of materials and components derived from them, rather than on fossil fuel supplies. As a result, energy security considerations will increasingly be about access to those resources and goods. Important lessons can be drawn from established markets and technologies such as solar photovoltaics (PV) in shaping emerging markets for batteries, low-emission hydrogen and other technologies that are poised to play key roles in the clean energy transition.

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The primary purpose of this edition of ETP is to help government and industry decision makers overcome hurdles in developing and expanding the clean energy technology[1] supply chains the world needs to reach net zero emissions by mid-century. Through the lenses of energy security, resiliency and sustainability, ETP-2023 focuses throughout on the opportunities and risks involved in scaling up clean energy and technology supply chains in the years ahead. It sets out where key clean energy and technology supply chains stand today and assesses how quickly they need to expand for the world to be on track for net zero emissions, and it identifies vulnerabilities and risks in adapting them to a net zero world as well as emerging opportunities to establish the new global energy economy. It also examines how governments can design more effective policies and strategies to encourage greater supply chain security, resiliency and sustainability.

ETP-2023 builds on the 2020 revamp of this series, aimed at improving its usefulness and relevance for policy makers and other stakeholders. It draws on and updates the IEA's ongoing analysis of critical minerals and recent detailed assessments of technology supply chains for electric vehicle (EV) batteries and solar PV, as well as the IEA's extensive clean energy technology tracking and analytical activities. ETP analysis also benefits from IEA Technology Collaboration Programme expertise and research provided by experts around the world who support this work with technology data and analytical insights.

Clean energy and technology supply chains

Energy and technology supply chains refer to the sequences of steps, or stages, required to deliver a technology or an energy service to the market. They include extracting natural resources (such as minerals), producing materials and fuels, manufacturing components and assembling them into a technology or system, installing and operating that technology, and managing wastes generated during its operating lifetime and when it is being dismantled at the end of its lifespan. An energy technology comprises a combination of hardware, techniques, skills, methods and processes used to produce energy and provide energy services, i.e. energy production, transformation, storage, transportation and use.

In this report we distinguish between technology supply chains and energy supply chains, based on the final service delivered:

[1] Clean energy technology comprises those technologies that result in minimal or zero emissions of carbon dioxide (CO_2) and pollutants. For the purposes of this report, clean energy technology refers to low or near zero emissions technologies that do not involve the production or transformation of fossil fuels – coal, oil and natural gas – unless they are accompanied by carbon capture, utilisation and storage (CCUS) and other anti-pollution measures.

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- Technology supply chains refer to the different steps needed to install a technology, with inputs of materials, components and services involved at each stage. In the case of clean energy technologies, the main steps include the extraction of minerals; the processing of those minerals into usable materials; the manufacturing of components; their assembly into finished equipment; the installation of that equipment; its operation; and its decommissioning and reuse or recycling of certain components. These technologies include supply-side equipment, such as solar PV systems (ranging from household systems to large utility-scale plants) and electrolysers to produce hydrogen, as well as end-use equipment such as EVs, heat pumps and hydrogen-powered fuel cell vehicles.
- Energy supply chains refer to the different steps needed to supply a fuel or final energy service to end users, usually involving trade of that energy commodity along and across technology supply chains. Steps include power generation or fuel transformation, as well as their transportation, transmission, distribution and storage. Examples include the supply of renewable electricity (such as solar PV and wind power) and low-emission hydrogen and synthetic hydrocarbon fuels, such as synthetic kerosene.

Technology supply chains and energy supply chains are interrelated. Producing, generating, transporting and storing any form of energy requires technologies, which need to be manufactured and brought into service. In parallel, all the different steps along the technology supply chain consume energy and thus depend on energy supply chains.

Figure I.1 Steps and interdependencies of technology and energy supply chains

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Energy and technology supply chains are interdependent, as one is unable to operate without the other .

Recent trends in technology costs and energy prices illustrate the interlinkages between the two types of supply chains. The prices of many minerals and metals that are essential for some leading clean energy technologies have soared in the last few years, due to a combination of rising demand, disrupted supply chains,

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concerns about future supply and rising energy prices. For example, the price of lithium has nearly doubled since the beginning of 2022 (see Chapter 2). Cathode materials such as lithium, nickel, cobalt and manganese, which are essential for making lithium-ion batteries, accounted for less than 5% of battery pack costs in the middle of the last decade when there were only a handful of battery gigafactories; that share has risen to over 20% today.

Scope and analytical approach

Risk assessment framework for supply chains

Disruptions to clean energy technology supply chains could have a major impact on the world's ability to achieve climate and energy goals. Understanding the risk profile of each element of the supply chain is a key step in determining where to focus efforts to enhance security, resilience and sustainability, and in developing policies to address potential vulnerabilities. These profiles can look very different depending on the country, region and technology and will change over time as new technologies and materials emerge and mature, and as markets develop.

Making supply chains secure, resilient and sustainable can only be achieved through a comprehensive and co-ordinated approach. This means taking action to develop supply chains that can meet the needs of a net zero pathway and that can absorb, accommodate and recover from short-term shocks and adjust to long-term changes in supply, including periodic material shortages, the effects of climate change and natural disasters, and other potential market disruptions. The need to reduce the emissions intensity and environmental impact of clean energy technology supply chains themselves is particularly urgent.

The IEA has developed a risk assessment framework that both government and businesses can use to capture the risks and vulnerabilities of supply chains. It was first presented in Securing Clean Energy Technology Supply Chains, published in July 2022 (IEA, 2022a). For the purposes of ETP-2023, the analysis has been significantly expanded to provide a comprehensive risk-assessment framework for technology and energy supply chains based on the combined assessment of likelihood and impact metrics relevant to four identified potential risks: insufficient scaleup pace, and supply insecurity, inflexibility and unsustainability.

The framework is designed to be applied to current supply chain structures to assess how well they can adapt and respond in the short to medium term. This report uses it to provide a global perspective, but it can be applied at the national or regional level.

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Scenario analysis

Analysis in this report is underpinned by global projections of clean energy technologies derived from the IEA's Global Energy and Climate (GEC) model (IEA, 2022b), a detailed bottom-up modelling framework composed of several interlinked models covering energy supply and transformation, and energy use in the buildings, industry and transport sectors. The modelling framework includes 26 regions or countries covering the whole world (see Annex). The ETP-2023 projection period is 2021 to 2050. The most recent year of complete historical data is 2020, though preliminary data are available for some countries and sectors for parts of 2021 and have been used to adjust the projections.

We employ two scenarios to describe possible energy technology pathways:

- The Net Zero Emissi ons by 2050 (NZE) Scenario – the central scenario in this report – is a normative scenario that sets out a pathway to stabilise global average temperatures at 1.5°C above pre-industrial levels. The NZE Scenario achieves global net zero energy sector CO_2 emissions by 2050 without relying on emissions reductions from outside the energy sector. In doing so, advanced economies reach net zero emissions before developing economies do. The NZE Scenario also meets the key energy-related UN Sustainable Development Goals, achieving universal access to energy by 2030 and securing major improvements in air quality.
- The Announced Pledges Scenario (APS) assumes that governments will meet, in full and on time, all the climate-related commitments they have announced, including longer-term net zero emissions targets and Nationally Determined Contributions (NDCs), as well as commitments in related areas such as energy access. It does so irrespective of whether these commitments are underpinned by specific policies to secure their implementation. Pledges made in international fora and initiatives on the part of businesses and other non-governmental organisations are also taken into account wherever they add to the ambition of governments.

Neither scenario should be considered a prediction or forecast. Rather, they are intended to offer insights into the impacts and trade-offs of different technology choices and policy targets, and to provide a quantitative framework to support decision making in the energy sector and strategic guidance on technology choices for governments and other stakeholders. The focus of the analysis in ETP-2023 is on the technology requirements of the NZE Scenario; the APS is employed with a view to understanding geographical concentration and regional needs. The scenarios and results are consistent with those presented in the 2022 World Energy Outlook (IEA, 2022c).

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Selected energy and technology supply chains

This report analyses six clean energy and technology supply chains in detail (Figure I.2). They were selected based on their critical importance to the clean energy transition described in the NZE Scenario. Together, they contribute around half of the cumulative emissions reductions to 2050 in that scenario. Three are clean energy supply chains – for low-emission electricity (including solar PV and wind with their respective technology supply chains); low-emission hydrogen (including technology supply chains for electrolysers and natural gas-based plants with carbon capture and storage [CCS]); and low-emission synthetic hydrocarbon fuels (including technology supply chains for direct air capture [DAC] and bioenergy with carbon capture [BECC] to provide CO_2, connected to the low-emission hydrogen supply chain). The three others are clean technology supply chains – for electric cars (including the battery supply chain); fuel cell trucks (including the fuel cell supply chain); and heat pumps for buildings.

Figure I.2 Key elements for each step in selected clean energy and technology supply chains

LOW-EMISSION ELECTRICITY

LOW-EMISSION HYDROGEN

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LOW-EMISSION SYNTHETIC HYDROCARBON FUELS

BATTERY ELECTRIC VEHICLES

HEAT PUMPS

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FUEL CELL TRUCKS

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Notes: BECC = bioenergy with carbon capture. DAC = direct air capture. FT = Fischer-Tropsch.

ETP-2023 studies six selected clean energy and technology supply chains in detail .

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Report s tructure

Chapter 1 reviews the current status of the global clean energy transition and outlines the extent of the changes required to clean energy and technology supply chain to put the world on the NZE Scenario's net zero pathway, as well as some potential risks that could arise.

Chapter 2 assesses in detail how the key clean energy and technology supply chains function today and their vulnerabilities as clean energy transitions advance, focusing on the link between geographic concentration and security, resilience to market shocks and environmental performance.

Chapter 3 quantifies global mineral and material needs for the transition to net zero emissions and analyses the extent to which current expansion plans are compatible with that trajectory. It also discusses the policy and market factors driving investments in key regions and the main corporate strategies in this step of the supply chain.

Chapter 4 assess prospects for the supply of mass-manufactured and large-scale site-tailored clean energy technologies, focusing on the expansion of manufacturing and installation capacity based on current and announced construction activity. Like Chapter 3, Chapter 4 also discusses the policy and market factors driving investments in key regions and the main corporate strategies in this step of the supply chain.

Chapter 5 analyses how and at what pace energy and CO_2 infrastructure needs to be transformed to cost-effectively sustain the clean energy supply chains that will be needed for net zero emissions, focusing on electricity, hydrogen and CO_2 transportation, transmission, distribution and storage.

Chapters 6 sets out how policy makers can support the development and expansion of secure, resilient and sustainable supply chains, the tools at their disposal and how best to use them, drawing on recent experience around the world.

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Chapter 1. E nergy supply chains in transition

Highlights

- Momentum for clean energy transitions is accelerating, driven by increasingly ambitious energy and climate policies, technological progress and renewed energy security concerns following Russia's invasion of Ukraine. Clean energy investment reached USD 1.4 trillion in 2022, up 10% relative to 2021 and representing 70% of the growth in total energy sector investment. Despite this important progress, fossil fuels still account for 80% of the primary energy mix.
- Clean energy technology deployment must accelerate rapidly to meet climate goals. In the Net Zero Emissions by 2050 (NZE) Scenario, global production of electric cars increases six-fold by 2030; renewables account for over 60% of power generation (up from 30% today); and electricity demand increases by 25%, accounting for nearly 30% of total final consumption (up from 20% today). If delivered in full, announced projects to expand clean technology manufacturing capacity would meet the needs for 2030 in the NZE Scenario for solar PV modules and approach that required for EV batteries, but would fall short in other areas, leaving gaps of 40% for electrolysers and 60% for heat pumps.
- The transition to clean energy hinges on clean energy technology supply chains. USD 1.2 trillion of cumulative investment would be required to bring enough capacity online for the supply chains studied in ETP-2023 to be on track with the NZE Scenario's 2030 targets. Announced investments cover around60% of this total. Given project lead times, most investments are required during 2023-2025, at an average of USD 270 billion per year during that period, which is nearly seven times the average rate of investment over 2016-2021.
- Critical materials like copper, lithium, cobalt and nickel are changing the energy security paradigm. Manufacturing a typical-size electric car requires five times as much of these materials as a regular car. Anticipated supply expansion suggests that production could fall well short of NZE Scenario requirements for 2030, with deficits of up to 35% for lithium mining and 60% for nickel sulfate production.
- Lead times to establish new supply chains and expand existing ones can be long, requiring policy interventions today. Opening mines or deploying clean energy infrastructure can take more than a decade. Building a factory or ramping up operations for mass-manufactured technologies requires only around 1-3 years.
- Clean energy sector jobs in the NZE Scenario soar from 33 to 70 million over 2021-2030, offsetting the loss of 8.5 million in fossil fuel-related sectors. Building a large, skilled workforce is key to meeting net zero targets, but labour and skills shortages in expanding clean energy industries are already creating bottlenecks.

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The clean energy transition

Recent tr ends in energy technologies

The move to clean energy is accelerating

The global clean energy transition is accelerating, driven by a combination of policy, technological change and economics. The need to reduce greenhouse gas emissions drastically and urgently in the face of ever more startling evidence of global climate change is now widely accepted, reflected in increasingly ambitious national goals. The global energy crisis following the Russian Federation's (hereafter, "Russia") invasion of Ukraine has bolstered energy security concerns about supply of conventional fuels such as oil and gas, providing further impetus to the need and policy support for clean energy technologies. As of the end of November 2022, 87 countries and the European Union had announced pledges to reduce emissions to net zero this century, covering over 85% of the world's emissions and 85% of its gross domestic product. Notable announcements since 2021 include the People's Republic of China's (hereafter, "China") target of carbon neutrality by 2060 (IEA, 2021a), India's net zero emissions by 2070 goal (Government of India, 2022) and Indonesia's net zero emissions by 2060 target (IEA, 2022a). If all announcements and targets are met in full and on time, they will be enough to hold the rise in global temperatures to around 1.7°C in 2100 (IEA, 2022b; IEA, 2022c).

Over the last decade, the uptake of clean energy technologies and the supply of energy from non-fossil sources, notably renewables, has accelerated rapidly. In 2022, renewables accounted for 30% of global power generation, up from below 20% in 2010, with notable increases in solar PV, wind, hydropower and bioenergy output (IEA, 2022d). Electrification is accelerating across all end-use sectors. In transport, sales of electric cars exceeded 10 million in 2022, or 13% of the global car market, bringing their total number on the world's roads to over 25 million, up from practically zero in 2010 (IEA, 2022e). There were more than 1 000 gigawatts thermal (GW_{th}) of heat pump capacity operating worldwide in 2021, up from around 500 GW_{th} in 2010, with sales growing 13% relative to 2020.[2]

Investment in clean energy technology is increasing quickly and exceeded USD[3] 1.4 trillion in 2022, accounting for nearly 70% of year-on-year growth in overall energy investment, and up from about USD 1 trillion in 2015 (IEA, 2022f).

[2] Heat pumps included in this analysis are electric, and are those used primarily for heating (space and/or water) in buildings and the ones for which heating function is just as important as its cooling function, aiming to exclude to the extent possible air-air reversible heat pumps units bought primarily for space cooling. They include both centralised and decentralised units in buildings.

[3] All USD values in this report are expressed in real terms based 2021 prices.

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In the case of electric cars, global spending by governments and consumers doubled to about USD 280 billion in 2021, about ten times more than in 2015. This increase took place despite difficult market conditions and manufacturing constraints: the combined revenues of the world's 25 largest car manufacturers stagnated between 2015 and 2021, before rebounding in 2022. Renewables, power grids and energy storage in 2022 accounted for more than 80% of the nearly USD 1 trillion of total power sector investment, led by solar PV, up from 75% of the USD 800 billion invested in 2015, while the share of fossil fuel power fell from about 20% to 10% over the same period. Aggregate investment in oil, gas and coal supply amounted to just above USD 800 billion in 2022, down from over USD 1 trillion in 2015. Capital spending by oil and gas companies[4] on clean energy technologies has risen in recent years, expected to reach just over 5% of their total upstream investment in 2022, up from 0.5% in 2015.

The world still relies heavily on fossil fuels

Despite the rapid recent growth in clean energy technologies, the world still relies predominantly on fossil fuels for its energy supply (Figure 1.1). In fact, growth in clean energy supply since 2000 has been dwarfed by that of oil, gas and coal, especially in the emerging and developing economies. In those countries, the share of fossil fuels in total primary energy supply increased from 77% in 2000 to 80% in 2021, mainly due to a jump in coal, from 27% to 35%. In the advanced economies, the share dropped from 82% to 77% over the same period. As a result, the overall share of fossil energy in the global energy mix has remained almost constant at about 80%.

Oil remains the single largest source of primary energy, making up 29% of total energy supply in 2021 (down from 37% in 2000), followed by coal at 26% (up from 23%) and natural gas at 23% (up from 21%). Bioenergy is still the single largest source of non-fossil energy, accounting for around 10% of total primary energy use in 2021, though over one-third is in the form of traditional biomass, often used in unsustainable and polluting ways. Nuclear power makes up 5% of supply, hydropower around 2%, and solar and wind together a mere 2%. While electrification has accelerated over the last two decades, fossil fuels still dominate energy end use, accounting for around 35% of total energy use in buildings and 95% in transport.

[4] Includes the majors BP, Chevron, ConocoPhillips, Eni, ExxonMobil, Shell and TotalEnergies, as well as ADNOC (Abu Dhabi National Oil Company), CNPC (China National Petroleum Corporation), CNOOC (China National Offshore Oil Corporation), Equinor, Gazprom, Kuwait Petroleum Corporation, Lukoil, Petrobras, Repsol, Rosneft, Saudi Aramco, Sinopec and Sonatrach.

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Global mass -based resource flows into the energy system, 2021

IEA. CC BY 4.0.

Notes: Physical mass flows of fuels and materials in the energy system, in million tonnes. The “energy system” includes: devices that directly produce or consume energy (e.g. solar panels and motors); equipment and structures that house energy-consuming devices and in turn can passively have an impact on energy consumption (e.g. building envelopes and car bodies); infrastructure that directly transports energy or CO_2 (e.g. electricity grids and CO_2 pipelines); and infrastructure whose build-out could be directly affected by shifts in technology due to clean energy transitions (e.g. rail infrastructure and roads). Industry material demand includes that from equipment but not the plant shell. Region of production refers to region of extraction for fuels and minerals, and production for bulk materials (steel, cement, aluminium). For critical minerals (copper, lithium, nickel, cobalt and neodymium), volumes refer to the materials (metals) derived from them. A similar graph for the Net Zero Emissions by 2050 (NZE) Scenario for 2050 is in Chapter 3.

Sources: IEA analysis based on IEA data; USGS (2022).

Despite the rapid recent growth in clean energy technologies and demand for metals critical to them, the world still relies primarily on coal, oil and gas to meet its energy needs.

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In addition to the direct use of energy, end-use sectors consume large amounts of energy embedded in materials, such as cement for infrastructure and buildings, steel for vehicles and manufacturing goods, and chemicals for fertilisers and consumer goods. The production of these bulk materials today also relies mainly on fossil fuels, either for combustion or as feedstock. In 2021, coal made up around 75% of the energy used in global steel production and more than half of that used to make cement, while about 70% of chemicals production was based on oil or natural gas. The demand for so-called "critical minerals",[5] from which metals such as copper, nickel and cobalt are produced, has been increasing briskly in recent years, driven by the deployment of clean energy technologies such as batteries, yet their combined production by mass represents just 0.3% of that of coal today. The extraction and processing of critical minerals typically relies on fossil fuels at present.

Much of the momentum for clean energy is recent and has thus yet to translate into major change in global energy supply (IEA, 2022g). Most countries have been strengthening policy support for clean energy since the Paris Agreement in 2015, and even more so since 2020 as part of Covid-19 economic recovery packages. For example, the United States passed the Inflation Reduction Act in 2022, authorising USD 370 billion in spending on energy and climate change (US Congress, 2022). In the wake of Russia's invasion of Ukraine, the European Union adopted the REPowerEU plan, which is expected to mobilise an additional EUR 210 billion in clean energy technology investment over five years and support the Fit for 55 package – a set of proposals to revise and update EU legislation and to put in place new initiatives with the aim of reducing EU emissions by at least 55% by 2030 (EC, 2022; European Council, 2022). At the Global Clean Energy Action Forum co-organised by Mission Innovation and the Clean Energy Ministerial, 16 countries collectively announced USD 94 billion in spending for clean technology demonstration projects by 2026, following IEA analysis of global needs for net zero (US Department of Energy, 2022; IEA, 2022h). Japan has established a roadmap to reach net zero by 2050 with support for developing emerging technologies through the JPY 2 trillion Green Innovation Fund (Japan, METI, 2021; NEDO, 2021). China's 14th Five-Year Plan contains action plans for technology development aimed at achieving a peak in CO_2 emissions by 2030 (China, NEA, 2022; China, NDRC, 2021). India is increasing supply chain investments to boost domestic manufacturing in strategic industries including batteries (over USD 2 billion), cars (over USD 3 billion), solar PV (nearly USD 600 million) and steel (USD 800 million) through the Production Linked Incentive scheme over the 2022-2027 period (India, MCI, 2021a and

[5] In this report, five main critical minerals are analysed: copper, lithium, cobalt, nickel and neodymium. They were selected based on their use in key clean energy technologies, potential constraints in their supply and risks relative to the geographical concentration of their production.

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2021b; India, MHI, 2022a and 2022b; India, MNRE, 2022; India, Union Cabinet, 2020).

Clean energy technology needs for net zero

Net zero calls for a deep transformation of the energy sector

Achieving global net zero emissions of CO_2 by 2050 requires curbing the growth in energy demand alongside a radical change in the energy mix, involving a wholesale shift to renewable and other clean energy sources and technologies (Figure 1.2). In the NZE Scenario, behavioural changes, improvements in energy efficiency, and switching to renewables enable a fall in total primary energy supply by 10% between 2021 and 2030, despite the global economy growing by nearly a third. Total final consumption falls by 9% over the same period. The annual rate of energy intensity improvement nearly triples to more than 4% per year compared with the previous decade. Between 2030 and 2050, global demand falls more slowly, by just 15% in total, as the scope for further energy conservation efforts and efficiency improvements diminishes, and growing population and economic activity continue to drive up underlying demand for energy services.

Renewables – led by solar PV and wind – see the biggest increase in supply to 2050 in the NZE Scenario, complemented by significant increases in nuclear. Solar output jumps 23-fold and that of wind 13-fold, while nuclear power doubles between 2021 and 2050. By 2050, solar and wind together make up about 40% of total primary energy supply and nuclear 12%. Total capacity additions of renewables quadruple from 300 GW in 2021 to nearly 1 200 GW in 2030, their share of total power generation reaching over 60%; additions slow to about 1 100 GW by 2050 as the need to replace existing fossil fuel-based capacity diminishes, with renewables accounting for about 90% of generation by then.

Unabated fossil fuels provided around 65% of total final consumption in 2021, excluding fossil fuel use for non-energy purposes such as chemical feedstock. In the NZE Scenario, this share falls to around 55% in 2030 and to 15% by 2050. In absolute terms, the consumption of bioenergy in end-use sectors rises modestly over 2021-2050, but this masks a shift in its composition: the use of modern bioenergy rises sharply while its traditional use is phased out completely by 2030 as full access to modern energy is achieved in all countries.

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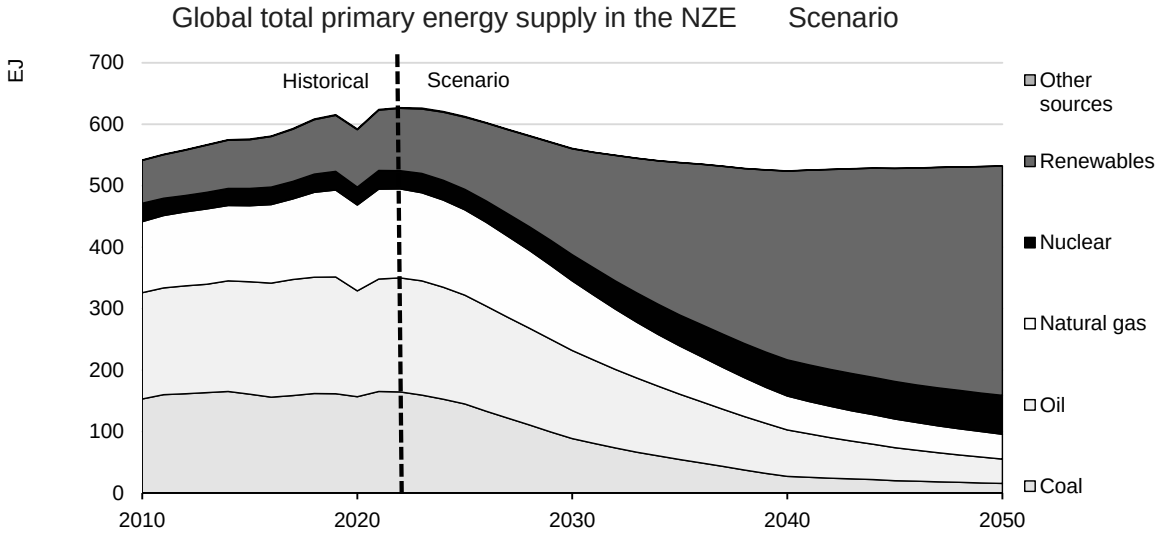

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Renewables and nuclear displace most fossil fuel use in the NZE Scenario , with the share of fossil fuels plunging from almost 80% in 2021 to less than 20% in 2050.

Electricity becomes the largest energy vector, with demand more than doubling between 2021 and 2050, by which time it meets more than half of total final consumption (Figure 1.3). Total electricity generation grows by 3.5% per year to 2050 to meet that demand. Hydrogen and hydrogen-based fuels emerge as significant end-use forms of energy, especially after 2030, being deployed mainly in heavy industry and long-distance transport; their share of total final consumption reaches nearly 10% in 2050. The share of bioenergy reaches around 15% in 2050. Carbon capture, utilisation and storage (CCUS) plays an increasingly important role: CO_2 capture grows from around 0.04 Gt in 2021 to 1.2 Gt in 2030 and 6.2 Gt in 2050, with industry and fuel transformation sectors accounting for more than 40%, direct air capture (DAC) for around 5%, and power and heat generation for the rest by then.

The transformation of the global energy system described in the NZE Scenario results in a rapid decline in energy sector CO_2 emissions (energy-related and from industrial processes), falling by about 30% by 2030 and by 95% by 2050 relative to 2021. Residual emissions in 2050 from sectors where reducing them is technically difficult and costly, such as aviation, shipping, road freight and heavy industry, are entirely compensated by carbon removal from bioenergy with carbon capture and storage, which removes CO_2 from the atmosphere indirectly, and direct air capture with storage, resulting in overall net zero emissions.

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Global energy flows in the NZE Scenario

2021

IEA. CC BY 4.0.

2050

IEA. CC BY 4.0.

Notes: Some electricity is used to generate hydrogen from water electrolysis, while some hydrogen (and hydrogen-based fuels such as ammonia) is in turn used for power generation in 2050. Losses include fuel, heat and power distribution losses, as well as transformation process conversion losses and own use.

Electricity becomes the largest energy vector in the NZE Scenario , with demand more than doubling between 2021 and 2050 .

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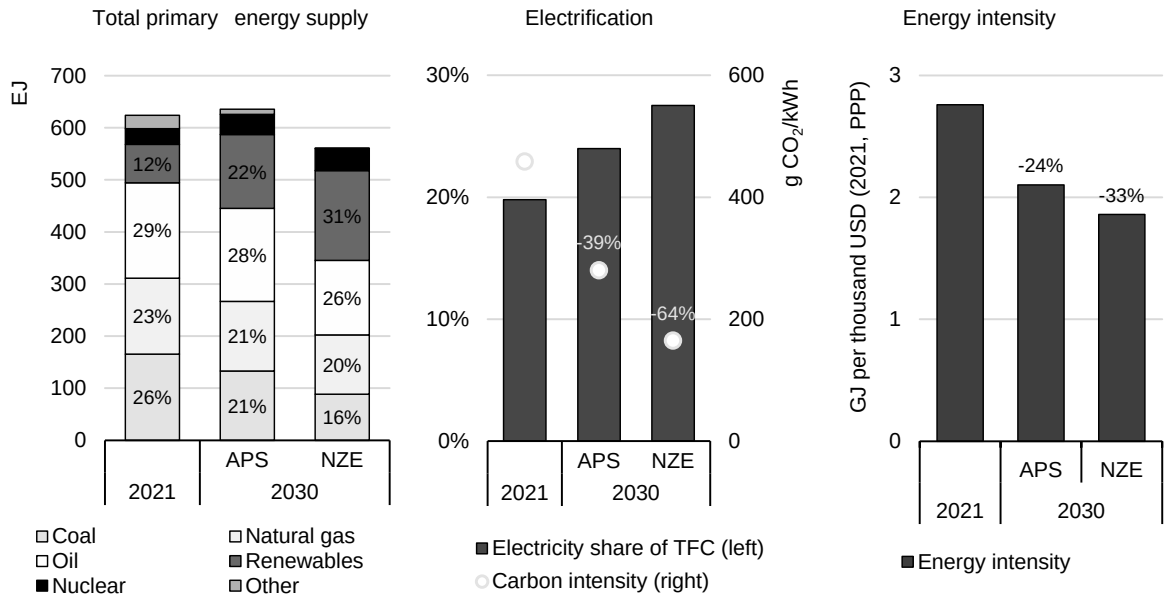
Announced pledges fall short of net zero, but still require major shifts in the energy sector

Despite strong progress, current pledges by governments and companies as reflected in the Announced Pledges Scenario (APS) are not enough to put the world on track to achieve net zero emissions by 2050. In 2050, energy-related CO_2 emissions in the APS amount to about 11 Gt CO_2. Nevertheless, achieving those pledges will still require quick decarbonisation this decade. Emissions fall by about 15% over 2021-2030 in the APS (40% in the NZE Scenario), which calls for major shifts in the energy sector.

In the APS, renewables overtake coal and account for over a fifth of total primary energy supply in 2030, while the share of fossil fuels drops from 80% today to 70% (Figure 1.4). Electrification accelerates – 25% of total final consumption in 2030 – and the carbon intensity of power simultaneously drops by about 40%. Growth decorrelates from emissions, and the energy intensity of the global economy falls by a quarter over 2021-2030. Clean energy technologies are deployed quickly: in 2030, sales of electric cars exceed 40 million (up from 10 million today), 320 GW_{th} of heat pumps are installed (up from 100 GW_{th}), and 30 Mt of low-emission hydrogen are produced (up from less than one).

Total primary energy supply, electrification rates and energy intensity in 2030 in the APS and NZE Scenario



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Note: TFC = total final consumption; PPP = purchasing power parity. NZE = Net Zero Emissions by 2050 Scenario. APS = Announced Pledges Scenario. In the middle graph on electrification, carbon intensity labels (%) refer to the decrease in electricity carbon intensity in APS and NZE in 2030 relative to 2021. In the right-hand side graph on energy intensity, labels (%) refer to the decrease in energy intensity in APS and NZE in 2030 relative to 2021.

While current pledges as reflected in the APS fall short of net zero pathways, they still require major transformation of the energy sector.

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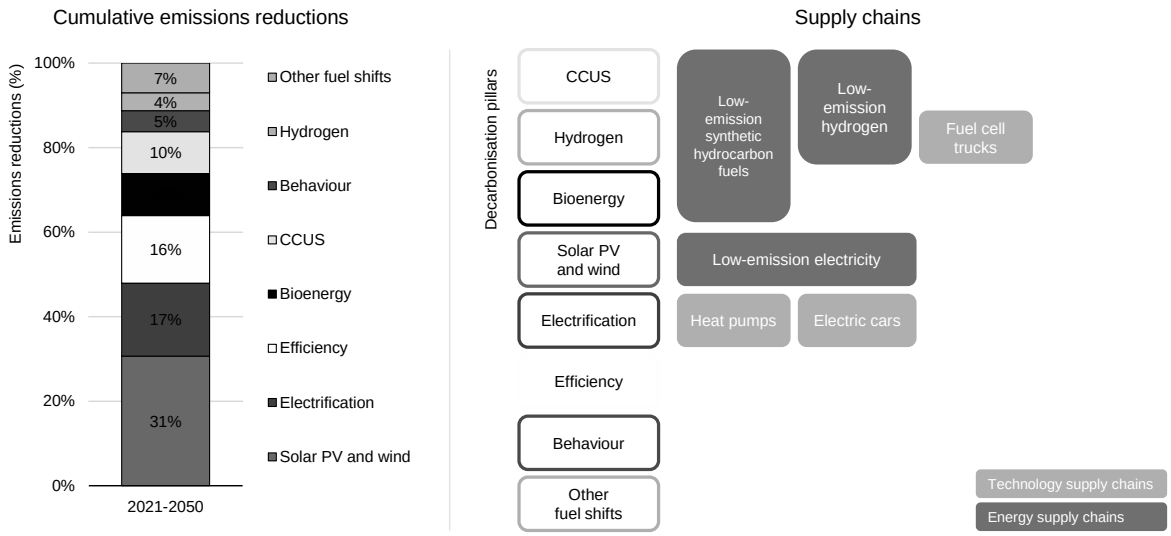
Massive deployment of clean energy technologies is needed

The decarbonisation of the energy system envisioned in the NZE Scenario rests on eight main pillars: behavioural change and avoided demand, energy efficiency, hydrogen, electrification, bioenergy, wind and solar, CCUS, and other fuel shifts (e.g. switching from coal and oil to natural gas, nuclear, hydropower, geothermal, concentrating solar power and marine energy). Behavioural change and energy efficiency gains do not require fundamental changes to existing energy systems, but the other pillars, which account for over 70% of total cumulative emissions reductions over 2021-2050, require the massive deployment of new types of equipment and infrastructure.

For the purpose of ETP-2023, we select key energy technologies and enabling infrastructure across the major decarbonisation pillars from the NZE Scenario to assess and illustrate the implications for supply chains of the clean energy transition (Figure 1.5). Taken together, they account for nearly 50% of total cumulative emissions reductions over 2021-50. Some selected energy and technology supply chains are specific to a particular pillar, such as electric cars and heat pumps for electrification, fuel cell trucks for hydrogen, or solar PV and wind. Some are more cross-cutting in nature, such as low-emission hydrogen and low-emission synthetic hydrocarbon fuels.

Global cumulative energy sector CO_2 emissions reductions by decarbonisation pillar and clean energy and technology supply chains studied in ETP-2023, 2021-2050



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Notes: "Other fuel shifts" include other renewables, nuclear, and switching from coal and oil to natural gas. "Behaviour" includes energy service demand changes from user decisions (e.g. changing heating temperature), as well as avoided demand, which refers to energy service demand changes from technology developments (e.g. digitalisation). The technologies featured in the right-hand side diagram are those selected for study in ETP-2023.

Six clean energy and technology supply chains hold the potential to unlock around 50% of cumulative emissions reductions to 2050 in the NZE Scenario.

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The scale and speed of the required deployment of clean energy technologies needs to increase dramatically to meet the needs of the NZE Scenario (Figure 1.6). Global production of electric vehicles (EVs) (excluding two- and three-wheelers) increases 15-fold to 2050, while the deployment of renewables nearly quadruples. Low-emission synthetic hydrocarbon fuels (primarily jet kerosene), production of which is minimal today as most technologies are still under development, reach 2.4 billion litres in 2030 (more than the oil consumption of domestic aviation in Japan in 2021) and over 105 billion litres by 2050 (equivalent to the total oil consumption of domestic and international aviation in the United States and the European Union combined in 2021). Production of low-emission hydrogen from electrolysis or natural gas-based hydrogen with carbon capture and storage (CCS) jumps from around 0.5 Mt in 2021 to 450 Mt in 2050 – equal in energy equivalent terms to about half of the world's energy consumption in the transport sector in 2021.

In many cases, available clean energy technologies on the market today are not yet competitive with existing fossil fuel-based ones, despite recent cost reductions. The former are generally more capital-intensive, i.e. the upfront cost of purchasing or installing them is higher per unit of capacity as they tend to involve more extensive and costly inputs, though their running and maintenance costs are typically lower. For some technologies, higher upfront costs are outweighed by savings during use, though this varies by region. In general, costs in real terms are expected to continue to decline over time as deployment increases and with innovation.

EVs are a case in point. The price gap between electric and internal combustion engine (ICE) cars has been shrinking, thanks mainly to major reductions in the cost of making batteries, helping to stimulate EV demand. Improvements in performance and recent fuel price hikes are also boosting their attractiveness. Yet electric cars remain more expensive and offer shorter driving ranges in most cases. For a medium-sized car, a battery EV typically costs around USD 10 000 (or roughly 40%) more than a conventional alternative (before taxes and subsidies). The price premium is generally smaller in China, averaging about 10%, due to smaller vehicle size and greater competition among carmakers, while it has been rising recently in Europe following large investments aimed at improving vehicle performance.

Heat pumps – a technology that efficiently provides heating and cooling to buildings and industry – also have an upfront price premium when compared with fossil fuel heating equipment, though heat pumps pay back over their lifetime in many regions today. The total cost of purchasing and installing a heat pump ranges from USD 1 500 to USD 10 000 for most homes, but varies substantially depending on the region and the type of unit installed (Figure 1.7). Installation can add substantially to total cost; especially if the energy distribution system needs

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to be upgraded to accommodate heat pumps (i.e. enlarging radiators or underfloor exchangers), this can add cost. This matters substantially for more efficient ground-source heat pumps, where installation can take up to several weeks and requires drilling and underground piping, making their total cost much higher than other options. Installation time and costs could decline as heat pumps become more common, and offer greater opportunities than in manufacturing. The most expensive components in heat pumps (e.g. heat exchangers, compressors) have already been mass manufactured for a long time, making further manufacturing cost reductions more limited than for other clean energy technologies.

Global deployment of selected clean energy technologies in the NZE Scenario

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Notes: HF = hydrocarbon fuels

The scale and speed of deployment of clean energy technologies and their associated supply chains accelerate dramatically in the NZE Scenario .

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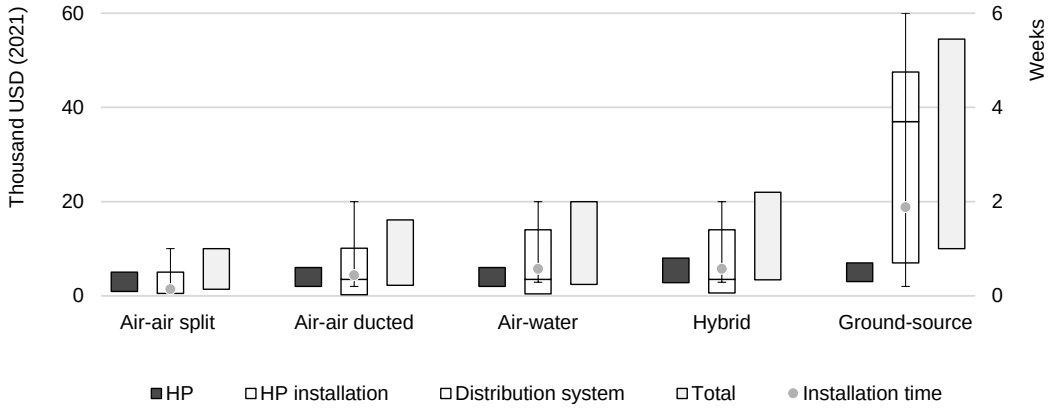
Heat pumps and heating distribution system market price and installation time for a typical household by type of equipment, 2021



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Notes: HP = heat pumps. For ground-source heat pumps, the installation costs include drilling costs and underground pipes. HP installation cost includes labour and balance of plant. Distribution system costs include labour and materials. The uncertainty line refers to installation time.

The market price of heat pumps significantly depends on installation costs, where the biggest potential for lowering costs lies.

Many supply-side clean energy technologies also involve higher capital costs than their fossil fuel equivalents. The main exception is solar PV, which is already cheaper in most locations, not accounting for the additional costs associated with its intermittency and variability. The capital cost of solar PV currently ranges from USD 600 per kilowatt to USD 1 000/kW depending on the region, and up to USD 1 800/kW including battery storage. By comparison, the cost of a conventional coal-fired power plant varies between USD 600/kW and USD 2 100/kW depending on the efficiency of the plant and flue gas treatment as well as the region. Equipping the plant with CCUS can push the cost up to between USD 1 800/kW and USD 6 600/kW.

Hydrogen capital costs are also very high. The cost of a conventional natural gas reformer plant sits at USD 780 per kW of hydrogen output (USD 1 470 per kW of hydrogen output if equipped with CCUS), while the capital cost for an installed electrolyser ranges from USD 1 400 per kilowatt electrical (kW_e) to USE 1 770/kW_e (USD 2 150-2 720 per kW of hydrogen output). Capital cost is an important cost component for hydrogen production cost, especially in the case of electrolysers. Natural gas prices affect the economics of producing hydrogen from natural gas reforming, with or without CCUS, making the electrolysis a cheaper production route when gas prices are high (see Chapter 2). At the prices of USD 25 per million British thermal units to USD 45/MBtu that prevailed in Europe during 2022, hydrogen production costs were USD 4.8/kg to USD 8.6/kg, almost 80% of which was due to the fuel cost. In the same region, hydrogen produced with renewables can cost as low as USD 4/kg (IEA, 2022i).

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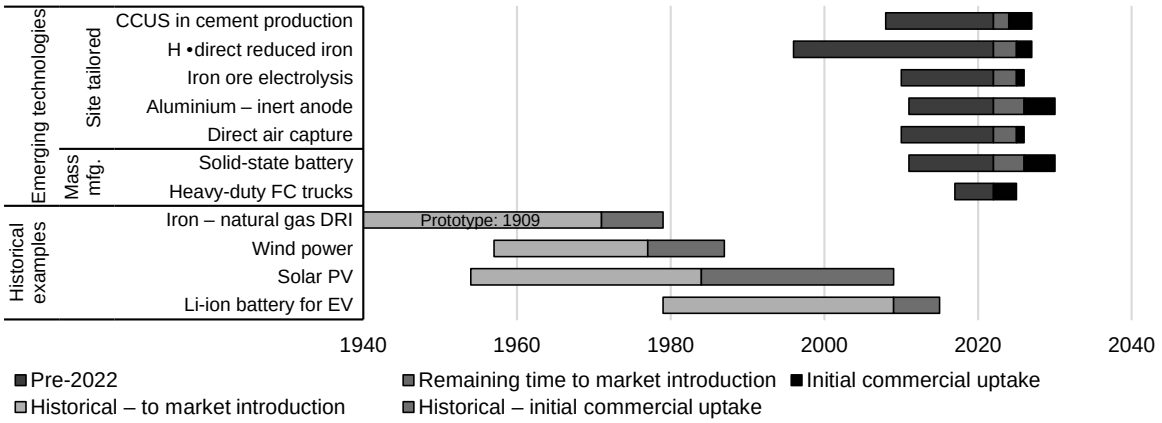
Getting to net zero is not possible without more innovation

Many of the clean energy technologies required to get to net zero by mid-century are not available at scale today. While the emissions reductions to 2030 in the NZE Scenario can be achieved with existing technologies, about half of the emissions reductions in 2050 come from technologies at prototype or demonstration stages today. This includes key technologies, such as cement, steel and aluminium production with CCUS; hydrogen-based steel making; and DAC.

Bringing new technologies and solutions to market takes time. Experience shows that the innovation process usually takes 20 to 70 years from prototype to commercialisation, with large-scale process technologies taking typically longer than small modular technologies (Figure 1.8). The NZE Scenario requires a shortening of innovation cycles, which can be partially achieved by improving the commercial advantage of clean energy technologies. There are several promising projects seeking to address pressing innovation gaps in a broad range of technology areas, but they need to progress quickly to play a major role in the next three decades. Global co-operation and international knowledge transfer, as well as tracking progress, such as in the ETP Clean Energy Technology Guide and the IEA Clean Energy Demonstration Projects Database, will be vital in this regard (IEA, 2022h; IEA, 2022j).

Time frame for prototype to market introduction and early adoption for selected clean energy technologies in the past and the NZE Scenario



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Notes: mfg. = manufacturing; DRI = direct reduced iron; H_2 = hydrogen; FC = fuel cell; Li-ion = lithium-ion. Initial commercial uptake is defined as the time until take-up in 1% of the market and market introduction as when the first commercial model is available on the market. Direct air capture is assumed to reach initial commercial scale at 1 Mt of CO_2 per year and market introduction at 1% of the market. Historical figures are calculated for selected market-leading countries (Norway for Li-ion batteries; Germany for solar PV; Denmark for wind power; and the United States for natural gas DRI).

Sources: IEA analysis based on Gross et al. (2018); Worldsteel Association (2020); Comin & Hohjin (2004). Also see IEA (2020a).

The time to bring emerging clean technologies to market is generally shorter in the NZE Scenario than was the case for existing technologies.

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Implications of net zero for supply chains

Expanding existing chains and setting up new ones

The transition to clean energy hinges on supply chains

Achieving net zero would have far-reaching implications for the supply chains of both clean energy and fossil fuels, with profound changes to the current energy system. Existing supply chains would need to be expanded and modified, while new ones for emerging technologies would need to be created. The clean energy transition is already triggering shifts in global supply chains delivering energy technologies, including mining, material production, technology manufacturing, energy transmission and distribution systems, and other enabling infrastructure. It is helping to cut reliance on fossil fuels and the need to invest in their associated supply chains, but it is increasing the need to put in place new supply chains for manufacturing clean energy technology equipment; produce and deliver clean fuels; and expand, upgrade and develop new electricity transmission and distribution systems that can handle flexibly changing loads and sources of generation.

The energy transition is taking place in a context of globally interconnected supply chains. Most existing technologies are produced and traded around the world. Today, 70% of global trade is in intermediate parts, components and services, the rest being finished goods and services (OECD, 2022a). Manufacturing is spread across many countries, often based on where skills and materials are available at the lowest cost. In many countries, a large share of domestic employment is sustained by trade, ranging from about 10% in the United States to 20% in France and 30% in Germany (OECD, 2022b).

In many emerging and developing economies that are less integrated into today's global energy supply chains, there is considerable potential for establishing new ones that leapfrog fossil-based options. In those with a more established presence in energy supply chains, opportunities are emerging for them to move quickly to develop clean energy alternatives, on the condition that the market power of incumbent suppliers does not constitute a barrier to investment and that incentives for clean energy are high enough.

Critical minerals are changing the energy security paradigm

Until recently, discussions about energy security were largely focused on the supply of fossil fuels, particularly oil. The IEA itself was created in the wake of the 1973-1974 oil crisis. Half a century later, fossil fuels are once again at the heart of an energy crisis, providing a stark reminder of the continuing importance of the

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security of supply of traditional fuels on the road to net zero. But energy security in the future will be concerned increasingly with the reliability of clean energy supply chains.

The raw materials, equipment and components involved in clean energy supply chains differ markedly from those needed for fossil fuels. In particular, there is a much greater reliance on a wide variety of critical minerals (Figure 1.9). They include the rare earth elements (REEs) and other metals such as copper, nickel, lithium, cobalt, manganese, graphite, silicon and platinum group elements. The types of mineral resources needed vary by technology. Batteries make use of lithium, cobalt, manganese and nickel. The magnets in some wind turbines and electric engines require REEs. Electricity networks and electric appliances, equipment and EVs require copper. Electrolysers and fuel cells require nickel or platinum group metals, depending on the technology type.

The quantities of critical minerals and other raw materials needed for clean energy technologies can be large. For example, making a 55 kWh battery and associated systems for a small electric car typically requires over 200 kg of critical minerals, including copper, lithium, nickel, manganese, cobalt and graphite, compared with just 35 kg of copper for the powertrain of a comparable ICE. Solar and wind also generally require more steel, aluminium and, in some cases, cement per unit of capacity than fossil fuel-based generating technologies. For example, an onshore wind plant requires nine times more mineral resources than a gas-fired plant with the same capacity.

The deployment of clean energy technologies is already pushing up overall demand for critical minerals. In aggregate, the use of critical minerals solely for those technologies increased by around 20% between 2016 and 2021. In volume terms, copper is the leading critical mineral, accounting for 70% of the total consumption of critical minerals for clean energy in 2021, though the use of lithium and cobalt has increased more in percentage terms since 2016. Demand for minerals in other industrial sectors has also increased in recent years (e.g. lithium and cobalt for batteries in electronics, copper in cars and buildings, nickel in alloys), but it is growing much more quickly in the clean energy sector. While there may be scope to reduce the amount of such minerals and other materials needed through innovation, global demand for them is set to soar as clean energy transitions accelerate.

The increasing reliance on critical minerals is changing the traditional energy security paradigm, which focused on fossil fuel supply, and particularly oil. Setting up secure – that is, reliable and affordable – global supply chains for critical minerals is crucial, not only to accelerate deployment of clean energy technologies to meet net zero, but also to ensure that the future energy system in a net zero world is secure (also see Chapters 2 and 3).

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Global average raw material requirements for selected energy technologies, 2021

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Notes: PEM = polymer electrolyte membrane; gas-CCS H_2 = natural gas-based hydrogen production with CCS; HV-DC = high-voltage direct current; AC = alternating current. “Other critical” includes zinc, tin, silver, lead, graphite, boron, chromium and molybdenum. For infrastructure, only copper, steel and aluminium components are taken into account. The steel in overhead transmissions includes the material needs for the conductor and the towers. For EV batteries, the current mix of battery chemistry is used (see IEA [2022e] for more details). The mass of fuel such as oil, coal or uranium is not included.

Sources: IEA analysis based on IEA (2021b); IEA (2022e); IEA (2022k); Greening & Azapagic (2012); Saoud, Harajli, & Manneh (2021); Violante et al. (2022).

The raw materials and equipment involved in clean energy supply chains differ markedly from those for fossil fuels, with much greater reliance on a variety of “critical minerals ”.

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Near-term prospects

The world is not yet on track for secure, resilient and sustainable supply chains

It is far from certain that the global supply chains needed to support the deployment of clean energy technologies projected in the NZE Scenario will be able to expand at the required rates. Moving quickly this decade is vital: any delay means that achieving net zero by mid-century will be out of reach or achievable only at greater cost. This calls for an immediate acceleration in the pace of clean energy deployment and the requisite expansion of their supply chains.

For the purposes of ETP-2023, we examine the current status and expansion plans for a number of clean energy and technology supply chains, based on public announcements and industry data, to assess whether they are in line with the trajectories of the NZE Scenario, in terms of the pace of scale-up required, and their level of security, resilience and sustainability. Three metrics are used:

- Production capacity gap: We assess whether specific technologies or elements in energy supply chains are on track to reach the required levels of deployment by 2030 in the NZE Scenario. For minerals extraction/mining and material production, we rely primarily on third-party estimates of likely supply availability in the coming years, which are based on projects that are under development/construction or at the late planning stage and are expected to be online before the end of the decade. For technology manufacturing, we rely on both third-party and in-house assessments of announced future production capacity plans.[6] The supply gap – defined as the difference between what is required in the NZE Scenario by 2030 and what is currently announced, as a share of the former – is used as a proxy for the additional efforts needed. We also calculate the investment needed to fill each of these gaps.
- Geographical and corporate concentration (see also Chapter 2 for furt her analysis) : The energy supply chains required in the NZE Scenario need to be secure and resilient to ensure a smooth transition and functioning of global energy systems. If a given step of the supply chain is heavily concentrated in one region or among a small number of companies, the risk of a supply disruption is likely to be greater. We assessed, therefore, whether announced investment plans imply a more concentrated or a more diverse supply chain for each of the main technologies.
- Energy needs and CO_2 emission s (see also Chapter 2) : Not all steps of the supply chains of clean energy technologies are compatible with net zero at present. Mining extraction and processing, material production and technology

[6] Based on announcements up to November 2022.

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manufacturing currently give rise to large CO_2 emissions. The expansion of these supply chains would need to be accompanied by a drastic reduction in their CO_2 footprint. We assess for each step the impact of scaling up production on global energy demand and CO_2 emissions.

The rest of this section provides an overview of the prospects to 2030 for each step of clean energy and technology supply chains based on the three metrics described above. Chapters 3-5 delve more deeply into their implications and provide more details for each step across different regions (Chapter 3 for mineral extraction and material production; Chapter 4 for manufacturing and installation; and Chapter 5 for infrastructure).

Supply gaps vary by technology and supply chain step

For the extraction of critical minerals, the gap between projected needs in the NZE Scenario and expected supply in 2030 is above 25% for lithium and nickel, and nearly 20% for copper (Figure 1.10). The gap, at 35%, is largest in percentage terms for lithium, while the shortfall in supply in absolute terms, at 6 Mt, is largest for copper. Overall, the extraction of critical minerals remains heavily concentrated in resource-rich countries in 2030, with cobalt remaining the most concentrated.

For critical material production , the supply gap in 2030 is generally similar to that for mining, with some exceptions. At 60%, the gap for nickel sulfate production is much higher than for nickel mining, and the gap for cobalt processing as well, at 40%. In the case of bulk materials , demand does not increase significantly in the NZE Scenario, in part thanks to measures to enhance material efficiency, and the supply gap is close to zero as a result. The expected geographic concentration of the production of critical materials by 2030 is just as high as for minerals mining, with China remaining the dominant producer. In the NZE Scenario, geographic concentration of bulk material production decreases gradually, primarily due to decreasing volumes in China and increased output in India, Southeast Asia and Africa. See Chapter 3 for further details on minerals and materials supply gaps and how to overcome them.

The picture for technology manufacturing is much more diverse. For a few clean energy technologies, especially those related to solar PV, current announcements concerning manufacturing capacity point to an increase in global capacity that is more than sufficient to meet projected demand in 2030 in the NZE Scenario. For EV battery manufacturing, the supply gap is relatively small. For both technology groups, manufacturing remains highly concentrated in China. The supply gap is significantly higher for electrolysers at about 50%, and up to over 60% for heat pumps and bioenergy with carbon capture (BECC). Expected production capacity is more evenly distributed geographically for electrolysers and heat pumps, but highly concentrated for BECC. See Chapter 4 for further details on technology manufacturing supply gaps and how to overcome them.

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Global supply gap with the NZE Scenario and geographic concentration by stage and technology based on expansion announcements, 2030

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Notes: The gap is defined as the difference between required production in the NZE Scenario and projected production taking into account current production and announced expansion plans, expressed as a share of the former. The regions/countries included in this analysis are Africa, Other Asia Pacific, China, Europe, Eurasia, North America, Central and South America, and the Middle East. Gas-CCS H_2 = natural gas-based hydrogen production with carbon capture and storage. Synthetic HC fuels = low-emission synthetic hydrocarbon fuels.

Sources: IEA analysis based on company announcement. IEA (2021b); USGS (2022); S&P Global (2022a); S&P Global (2022b); S&P Global (2022c); S&P Global (2022d); EC (2020); Fraser et al. (2021); InfoLink (2022); BNEF (2022); BNEF (2020). Also see the Annexes to this report.

Current expansion announcements point to large production gaps for some clean energy supply elements, notably lithium and nickel mining and processing.

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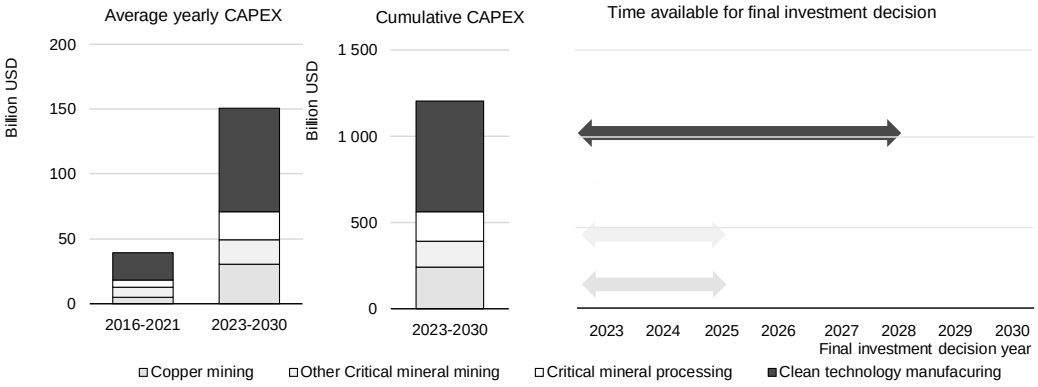
More investments are needed urgently to avoid bottlenecks

Bridging the production gaps described above would require enormous additional investments in the coming years. The total cumulative investment in mining, critical material production and manufacturing of the clean energy technologies selected in this report required to bring the necessary capacity online by 2030 amounts to around USD 1.2 trillion,[7] in 2021 dollars (Figure 1.11). Investments associated with projects already announced reach around60% of this, with large gaps in critical mineral mining and for some technology manufacturing.

While mobilising such levels of investment is achievable, the timeline is extremely tight, especially given the long lead times to bring production to market. Most of the investment (including for projects already announced) needs to occur over 2023-2025, implying an average of more than USD 270 billion per year over the period. To compare, this is about two-thirds of current annual capital spending of the oil and gas industry, and nearly seven times higher than the average annual investment seen in clean energy supply chains over 2016-2021.

Global investment in selected clean energy supply chains needed to bring online enough capacity in 2030 in the NZE Scenario, by supply chain step



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Notes: CAPEX = capital expenditures. Only refers to the investments needed to bring online enough capacity in 2030 – not counting what would be needed to further scale up in subsequent years – for the subset of clean energy technologies selected in ETP-2023. Assuming construction times of five years for mining, three for processing plants and two for technology manufacturing. Investments are assumed uniform over the available period. Excludes site-tailored technology installation.

Sources: IEA analysis based on company announcement; Bartholomeusz (2022); S&P Capital (2022).

Most of the supply chain investments needed to meet NZE Scenario targets in 2030 are made over 2023- 2025, at an annual average seven times higher than over 2016- 2021.

[7] This refers only to the investments needed to bring enough capacity online in 2030 for the technologies selected in ETP-2023, excluding the investments that would also be needed by 2030 to further scale up deployment in subsequent years.

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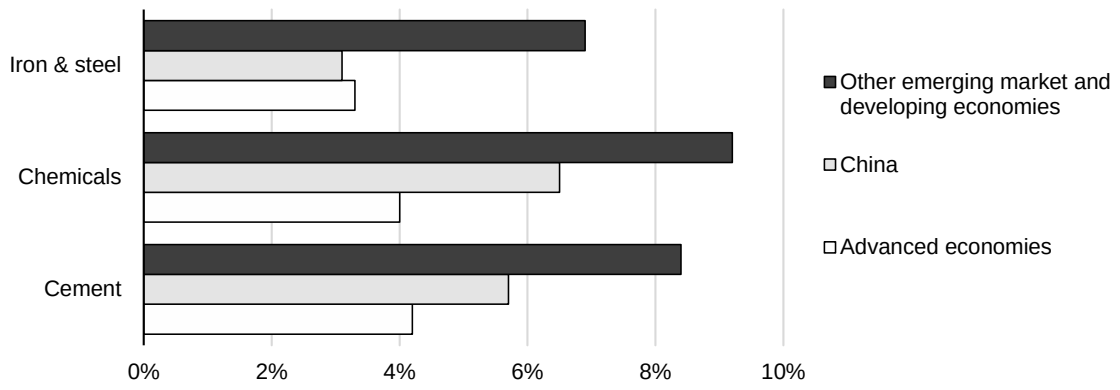
For the mining of copper, lithium, nickel and cobalt alone, investment of around USD 130 billion per year over 2023-2025 is required, which would be directed to any mining project already in the permitting pipeline. This is equivalent to the entire metal mining industry investments of 2021 (S&P Global, 2022e), implying a doubling of overall investments in the sector in 2023. The copper mining market, which accounts for over half of the required mining investments, may be in part balanced through demand reduction in other sectors and recycling. For the refining of those minerals, announced projects cover about 80% of investment needs for copper, but only over 40% for other metals. In terms of clean technology manufacturing capacity, announced projects cover two-thirds of investment needs to 2030.

The overall investment needed in clean energy supply chains is much higher than the investment required to develop those under study in ETP-2023 and bring sufficient capacity online by 2030. In total, investment in clean energy technologies and infrastructure reaches over USD 4.5 trillion in 2030 in the NZE Scenario (IEA, 2022f). This scale of investment is unprecedented. Mobilising it across all regions, technologies and supply chains is an enormous task. Bottlenecks can occur as a result of policy and regulatory risks, a lack of confidence in demonstration and first-of-a-kind projects, uncertainty about project pipelines, wider macroeconomic factors such as currency stability, and geopolitical events.

The risk of underinvestment in clean energy and supply bottlenecks is particularly acute in the emerging economies. One hurdle to investment in those countries is their higher cost of capital, which has a significant impact on the financial viability of clean energy projects. For example, financing costs for material production projects can be more than twice that in the advanced economies, due a greater perception of risk (Figure 1.12). Costs in China tend to be lower due to the importance of state-owned enterprises and their ability to raise cheap public finance.

Cost of capital for bulk material production industries by country/regional grouping, 2020



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Source: Adapted from IEA (2021c).

Financing costs for bulk material production in the emerging economies can be more than twice those in advanced economies, driven by a greater perception of risk .

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Each step of the supply chain must be decarbonised

Each step of the supply chain of all types of clean energy and technology is decarbonised in the NZE Scenario, their total associated CO_2 emissions falling by 95% between 2021 and 2050. Manufacturing is almost completely decarbonised by 2050, while there are some residual emissions in bulk material production and mineral processing (offset by negative emissions elsewhere in the energy system). The decarbonisation pathways vary across sectors and supply chain steps. They involve mainly electrification in mining and manufacturing, and the use of low-emission hydrogen and CCUS in material production.

Important progress is made in decarbonising the mining of critical minerals over the rest of the current decade in the NZE Scenario. The current energy and CO_2 emissions intensities of mining operations for critical minerals are higher than for more commonly used minerals due to the lower concentration of the minerals in the ores. With rising demand and declining ore grades, global CO_2 emissions from mining critical minerals could double over 2021-2030 to 30 Mt (see Chapter 3). Emissions from material production, which are currently the largest of all supply chain steps, decrease quickly in the NZE Scenario, down 40% for cement and 25% for iron and steel over 2021-2030. Emissions from technology manufacturing are typically smaller than other steps, and fall steadily mainly thanks to electrification (see Chapter 2).

Decarbonising supply chains would come at a cost, although the impact on final consumers would, in most cases, be marginal. Producing low-emission bulk materials, notably steel, cement and aluminium, results in significant additional costs compared with conventional production routes (Figure 1.13). Cost premiums for low-emission alternatives today vary based on different technology options, with some claiming near cost equivalence (e.g. smelting reduction with CCUS), while others are likely to command a significant premium (e.g. hydrogen direct reduction). Cost estimates warrant further analysis as the first set of plants are built over the 2020s.

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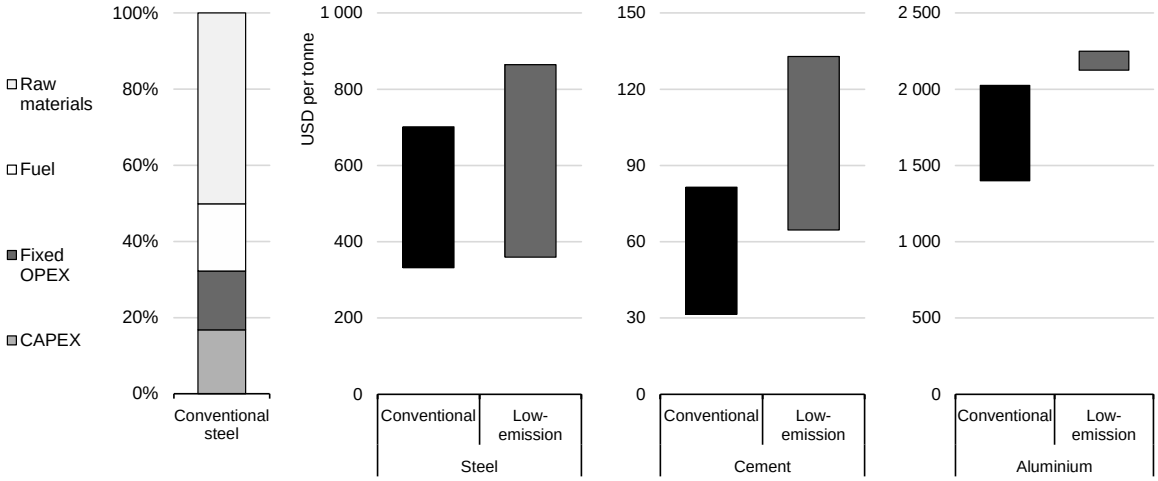
Indicative levelised cost of production for selected bulk materials



IEA. CC BY 4.0.

Notes: OPEX = operational expenditures. Levelised cost is a proxy for production costs, calculated as the average net present financial cost of producing a good, accounting for total costs and output over the lifetime of the factory or plant. Estimated costs in a range of typical price contexts since 2019. On the left-hand side for steel, the cost breakdown is for a conventional blast furnace-basic oxygen furnace. The ranges on the right hand side represent different production routes. Low-emission estimates are based on plants that have reached commercial scale.

Sources: IEA analysis based on IEA (2020b); MPP (2022).

Cost premiums of low-emission alternative routes for producing bulk materials vary significantly by material and technology.

Although the cost of producing bulk materials using low-emission technologies is generally significantly higher than using conventional ones, the estimated impact on final prices for clean energy products is typically small, as bulk material costs represent a relatively small share of their total production cost. For example, a 50% increase in the cost of steel at 2021 prices would result in an increase of only around 0.5% in the final average cost of an electric car, 0.2% for a residential heat pump, 1% for an offshore wind farm and 1.5% for utility-scale solar PV. Based on 2021 costs, fully decarbonising production for these bulk materials would push up the cost of making an electric car by 0.7%, a heat pump less than 0.3%, an offshore wind farm by 0.6%, utility-scale solar PV over 2% and a typical house by 1.4% (Figure 1.14).

Manufacturers' ability to pass on cost increases to consumers depends on the magnitude of the increase and on competition with conventional products. For example, vehicle and home heating system markets are particularly competitive, potentially making it more difficult for EV and heat pump manufacturers to pass on cost increases. Producers of wind turbines and solar PV modules are currently better placed to pass on higher costs thanks to surging wholesale power prices in most regions. Nonetheless, some companies or consumers may be willing to pay a premium for clean products. For example, at least ten companies in the automotive sector have committed themselves to using "green steel" from 2025 (H2 Green Steel, 2022; SteelZero, 2022; First Movers Coalition, 2022).

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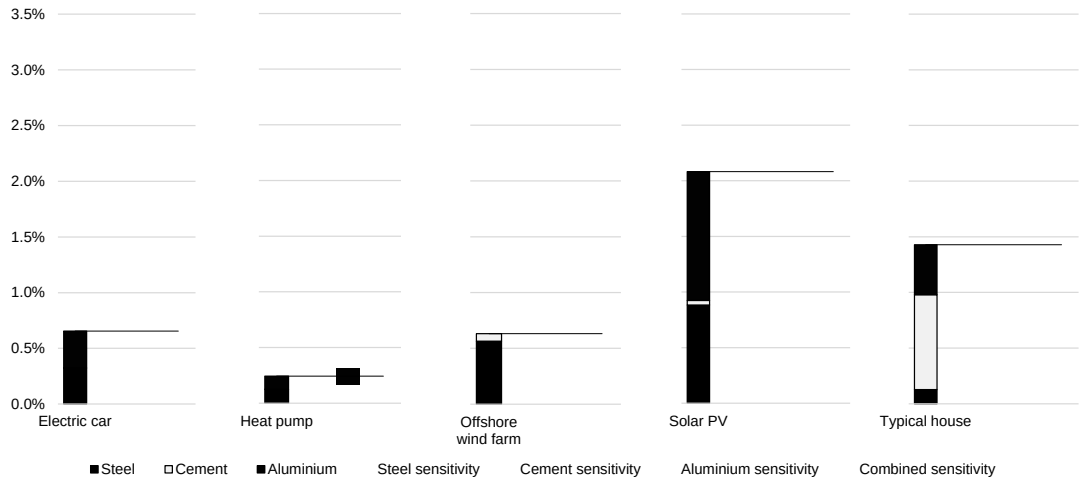
Increase in the global average prices of selected clean energy products from switching to low-emission bulk material production



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Notes: Based on 2021 costs of typical products: USD 36 000 for an electric car; USD 11 000 for a heat pump, USD 2 860/kW for an offshore wind farm, USD 880/kW for solar PV and USD 300 000 for a single-family home. The assumed cost premiums for low-emission materials are 10-50% for steel; 60-110% for cement and 10-50% for aluminium, with these cost ranges informing the sensitivities for each material.

Sources: IEA analysis based on IEA (2020b); MPP (2022).

Decarbonising clean energy supply chains would come at a cost, although the impact on buyers would, in most cases, be marginal.

Supply chain lead times and product durability

Building mines and factories and ramping up output takes time

The time needed to put in place and expand supply chains is a major constraint on how quickly the clean energy transition can be achieved. The industries and infrastructure that underpin the world's existing energy supply chains took decades to develop – fossil and clean technologies alike. Building a new factory, mine, road or pipeline takes time, as does expanding production from existing factories and facilities. In addition to lead times – defined as the time that passes from when a project is announced (i.e. a company states the intent to build a given facility) to when the project begins commercial operation – there are production ramp-up times: once a new production facility is established, some time is needed before the machinery is able to produce at its full nominal capacity.

Lead times are important as they have an impact on the speed at which supply can react to demand. The inability to expand supply quickly, especially when spare production capacity is tight, can hinder the ability to meet a rapid increase in demand, such as that of solar PV and EVs. The result is bottlenecks in supply and higher prices, as has been the case with semiconductors and EV supply chains since 2020 (see Chapter 2) (IEA, 2022l). A failure to anticipate future demand alongside barriers to investment could hinder global decarbonisation efforts and hold back progress towards a clean energy future.

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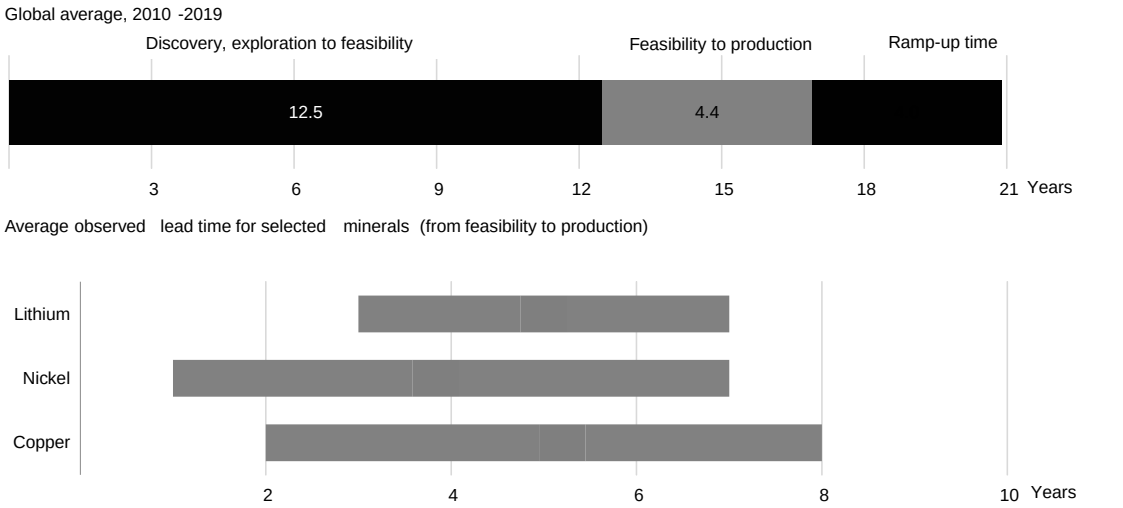
The longer the lead time for a given supply chain component, the greater the risk of underinvestment, co-ordination and sequencing issues with other steps of the supply chain, and future bottlenecks in supply. If projects at a given step of the supply chain are undertaken sequentially, long lead times increase the time between the first and second generations of plants. If projects are carried out in parallel, long lead times may reduce the opportunity to learn from each other. Long lead times also increase investment risk and, therefore, the cost of capital, components and final products: investing in a project that is due to start generating revenues within a year is inherently less risky and easier to finance than one starting to pay back in several years. Long lead times also imply greater exposure to regulatory, political and market changes.

Some of the longest lead times in clean energy supply chains are in the upstream, i.e. mining of raw minerals (Figure 1.15). In some cases, the entire process can take more than two decades. This comprises the time needed for exploration (to identify an economically extractable resource) and construction (building the mine and starting commercial operation). Exploration often takes a long time (usually more than a decade) and does not always result in a development project. The fastest mining operations have a lead time of under five years, but ramping up production to full capacity typically takes almost as much time. For established mining techniques, ramping up production can take up to three to four years. In cases where more complex operations are involved, ramp-up times can be much longer. For example, most high-pressure acid leaching nickel production projects in Indonesia have required five years to reach nominal production (IEA, 2021b).

Lead times for mining of selected minerals



IEA. CC BY 4.0.

Note: Lead time averages are based on the top 35 mining projects that came online between 2010 and 2019.
Sources: IEA analysis based on S&P Global (2020); S&P Global (2019); Fraser et al. (2021); Heijlen et al. (2021).

Exploration takes the most time in bringing new mines into operation, while construction and ramping up production to full capacity typically take almost a decade.

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There are several reasons for these long lead times. Exploration and resource appraisal carry substantial risk, making it difficult for mining companies to obtain financing from lenders. As a result, they often use their own cash flows to pay for investment. Financing mining operations can also be difficult, largely because of uncertainty about future market demand and commodity prices – especially if supply chains are nascent. The financial structure of mining projects is usually a highly leveraged mix of debt and equity, with the goal of generating as much cash and as little balance sheet profit as possible.

Mine engineering and construction also take time due to their large scale and complexity, as well as the need to make use of other infrastructure such as ports, roads and power plants before operations can start. Large amounts of earth and rock need to be displaced before reaching the ore-containing layers. Permitting is also a very time-consuming step, primarily because of the importance of carrying out rigorous impact and environmental assessments and legal procedures, and ensuring local community acceptance and equity. This is particularly true of heavily contested projects such as those in areas with indigenous populations or of significant environmental concern.

Material production projects generally take less time to complete than mining projects, but can still take several years. Like other heavy industrial projects, time is needed to procure the necessary machinery and to obtain the required environmental permits to build and operate plants.

Commissioning manufacturing facilities for components used in making clean energy products can take up to five years (Figure 1.16). In addition to the construction work, additional time is needed to hone the manufacturing process, which can take up to a year depending on the complexity of the process and the company's experience. For example, building a completely new polysilicon factory can take 12 to 42 months and ramping up production another 6 months, while building new production lines for wafers, cells and modules at existing factories can take as little as 4 months, once the go-ahead has been given.

Factories to assemble final clean energy technologies can generally be built relatively quickly. For EVs, the excess production capacity of existing automotive factories means that it is often sufficient to retool an existing factory to be able to ramp up production in the near term. Vehicle assembly technology is mature and there are a lot of machinery suppliers available, so raising capacity can be very quick. Similarly, for PV module assembly, standard machinery is often used, resulting in relatively short lead times. For both component manufacturing and final assembly, ramp-up times can be similar to construction times. For example, construction of Tesla's first gigafactory in Nevada in the United States started in 2014 and came online in 2017, but reached its nominal capacity of 35 GWh only in 2021.

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Building and expanding enabling infrastructure such as pipelines, CO_2 storage facilities and electricity grids also involve long lead times, in some cases over a decade (Figure 1.16). These projects have similar characteristics to mining projects, including their large scale, high capital requirements and vast land coverage, sometimes across different jurisdictions. As a result, they face similar obstacles, including permitting and approval processes, financing, and public acceptance. Limited availability of specialist equipment and skills can also cause bottlenecks, particularly for offshore projects.

Developing supply chains for emerging clean energy technologies as they become available are unsurprisingly likely to take much longer than for existing ones. Many of the technologies needed in the NZE Scenario, including DAC, low-emission synthetic hydrocarbon fuels and some low-emission technologies in heavy industry, are still at the prototype or demonstration stages today and are not yet commercially available at scale. They first need to be demonstrated in real operating conditions, probably requiring several “first-of-a-kind” facilities at different sizes or in different regions, before they can be deployed successfully on a commercial scale. In parallel, fully fledged supply chains would need to be established and expanded progressively. Permitting is likely to take more time for plants that make use of novel technologies.

For small, modular or standardised technologies such as solar PV, batteries, heat pumps and fuel cells, lead times are generally much shorter than for large, more complex or specialised technologies such as those used in biorefineries, BECC and CCUS facilities, advanced nuclear reactors, and mines. This is especially true when technology designs depend on the specific use to which it is put and when it is linked to existing facilities, such as retrofitting CCUS to an existing power plant, which can increase the time needed for testing to make sure the impact on the operations of the existing plant is minimised. For complex and novel technologies, shortages of skilled labour can lengthen lead times and require extra planning. For example, biorefinery shutdowns for upgrades can be planned together with other refineries in the region to optimise the use of scarce labour.

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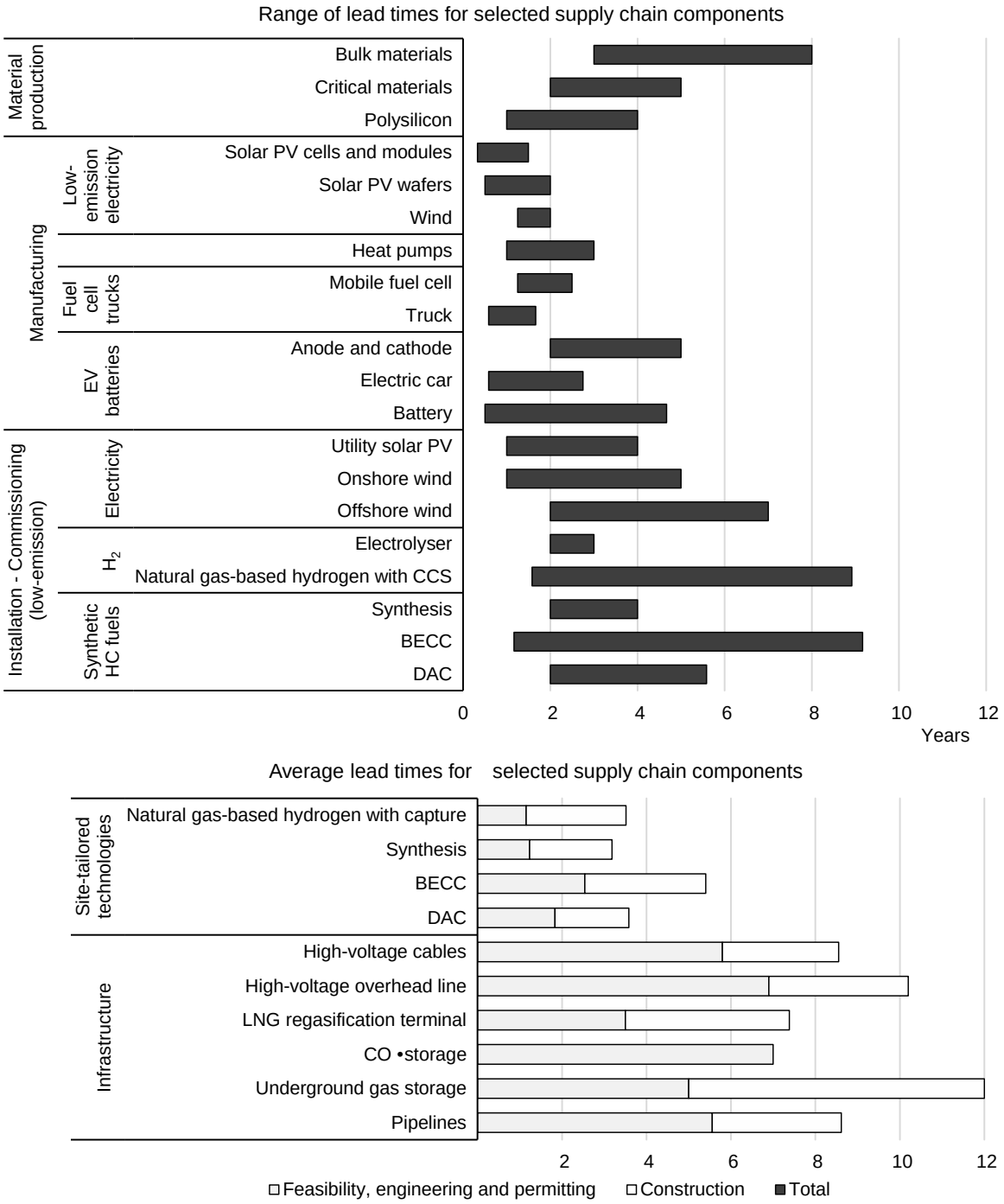
Range of (top) and average (bottom) global l ead times for selected clean energy technology supply chains



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Notes: Construction for CO_2 storage often occurs during detailed engineering and ahead of permitting since wells are usually drilled during site characterisation to acquire the data needed for permitting. As a result, construction time has been combined with feasibility, detailed engineering, and permitting. LNG = Liquefied natural gas.

Sources: IEA analysis based on company announcements; IEA (2021b); IEA (2022m); United Kingdom, Department for Business, Energy & Industrial Strategy (2020); IEA (2022e).

Some of the longest lead times in clean energy supply chains are in material production and enabling infrastructure, such as power transmission or CO_2 managem ent.

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Accelerating deployment calls for shorter lead times

Shorter lead times would help facilitate an acceleration in the deployment of clean energy technologies. For minerals extraction, lead times to open new mines and expand existing ones are reduced substantially in the NZE Scenario, including a cut in permitting times to just one year – the minimum time required to prepare a thorough environmental assessment and ensure adequate safeguards. In addition, policy support, the prospect of long-term demand growth and high mineral prices can give more confidence to investors, shortening the period needed to secure financing for mining projects.

There are several historical examples of the rapid deployment of new technologies, notably modular and mass-manufactured technologies, being achieved by compressing lead times, which suggest that the rapid rates of deployment of clean energy technologies in the NZE Scenario are achievable in a similar way. For example, the urgent production of aircraft during World War II and the recent launch of Covid-19 vaccine manufacturing involved compressing lead times drastically, in both cases to less than one year compared with several years previously (Figure 1.17). Their success was due in part to relatively mature processes for developing the products and building factories, as well as the critical circumstances, which ensured massive demand directly from governments and enabled them to appropriate swathes of existing industrial capacity for emergency retrofitting and reuse. For certain mass manufactured clean energy technologies such as EVs, global deployment is still growing rapidly, approaching the rates required in the NZE Scenario, implying that lead times should not be a cause of supply bottlenecks.

For technologies and projects with inherently longer lead times, such as mining projects and nuclear power plants, there are also historic examples suggesting industry could sustain fast growth rates. In the 2000s, iron ore mining grew at a 10% annual rate, an expansion which was mainly driven by surging demand in China and a tenfold increase in iron ore prices between 2000 and 2010 (IMF, 2022). In the NZE Scenario, lithium mining expands much more quickly at an annual rate of 25% over 2021-2030, after which growth slows down and peak production is reached in 2040. Basic oxygen furnaces were deployed very quickly in the 1960s at an average annual growth rate of over 35%. Once the technology reaches commercial scale by the 2030s in the NZE Scenario, hydrogen-based steel production grows on average by only 17% per year; however, getting the first commercial-scale plants in the late 2020s is the main challenge. For this to happen, producers need a fundamental cost advantage and clear financial incentive to lower lead times and encourage investment and innovation as commercial deployment begins.

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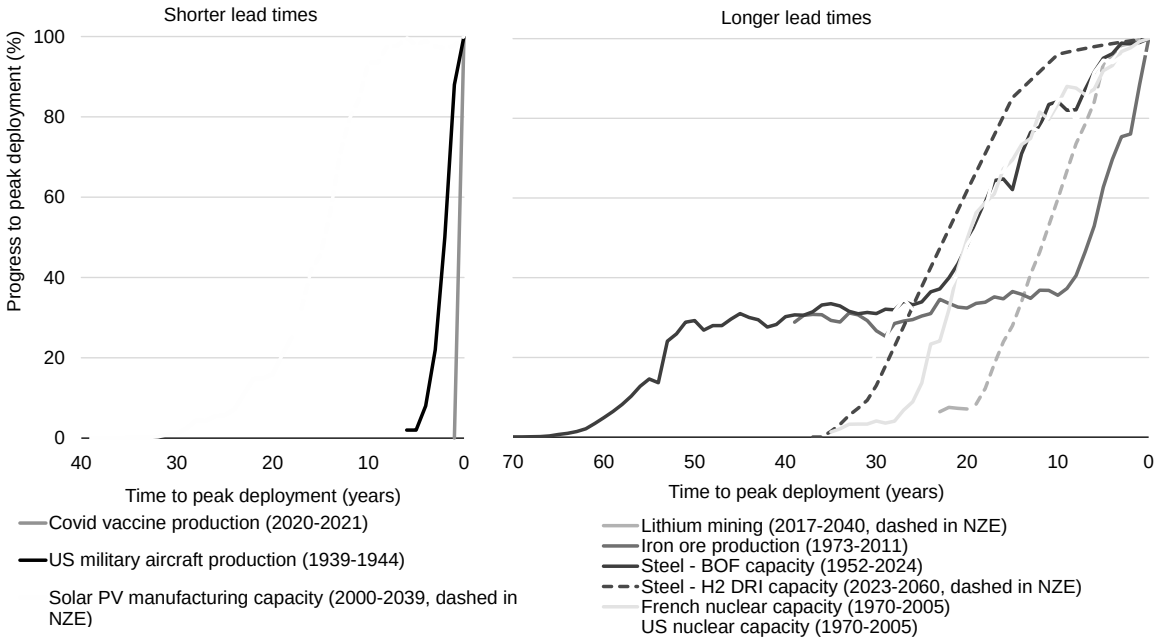
Global scaling -up of selected energy and other supply chains by lead time in the past (solid) and the NZE Scenario (dashed)



IEA. CC BY 4.0.

Notes: BOF = basic oxygen furnace steel making; H_2 DRI = hydrogen direct reduction based steel making; NZE = Net Zero Emissions by 2050 Scenario. Historic solar PV manufacturing capacity uses additions to world's grids as a proxy for manufacturing capacity. Data are global averages except for US military aircraft production and French and US nuclear capacity. US nuclear capacity is plotted for the same time period as French nuclear capacity, though the historic peak was in 2019, as US nuclear capacity saw little variation between 2005 and 2019.

Sources: IEA analysis based on USGS (2022); Comin & Hohjin (2004); Richter (2022).

Historic examples suggest that rapid deployment of clean energy by compressing lead times is technically possible, especially modular and mass -manufactured technologie s.

Shortening lead times should not be taken for granted: there are several examples of lead times for energy projects increasing, which serve as a cautionary tale. The rapid slowdown in the rate of growth in nuclear power generation in France, from around 85 TWh per year over 1978-1986 to around 15 TWh per year over 1990-2005, was in part due to a substantial increase in lead times from about five years in 1980 to ten years in 2000 (Berthélemy & Rangel, 2013).

Clean energy technologies need to be made more durable

Differences in the durability of clean energy technologies relative to conventional fossil fuel ones have important implications for both their competitiveness and sustainability. For example, the operational performance of renewables such as solar PV and wind can drop after a decade, with most having a lifetime of around 25-years. In contrast, coal- and gas-fired power plants can operate for 30 to 40 years or more, though intermittent large-scale refurbishment may be needed (Figure 1.18). Some ICE cars can be used for several decades, especially second-hand ones that are sold to emerging economies at low prices, while EV batteries

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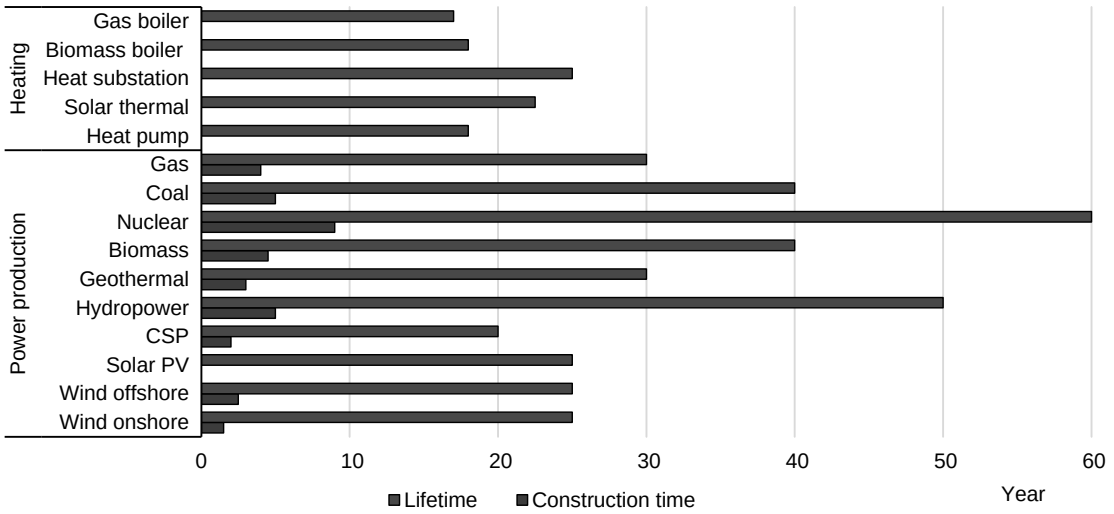
tend to degrade by up to 30% after 8 years and are typically retired within 15 years (UNECE, 2022). Technological advances are likely to improve battery durability, such that EVs could ultimately match the durability of ICE vehicles as they are based on simpler transmissions and powertrains. Regular maintenance and end-of-life management play a considerable role in ensuring the sustainability of clean technologies.

In some cases, clean energy technologies can already be more durable than their more carbon-intensive alternatives. One example is LED technologies for lighting, which last much longer than tungsten-filament light sources and compact fluorescent lamps. Recycling and refurbishing obsolete equipment can greatly reduce the energy and emissions intensity of clean technology supply chains.

Typical operating lifetime of selected energy technologies



IEA. CC BY 4.0.

Notes: CSP = concentrating solar power. Biomass in power production refers to dedicated biomass; biomass in heating refers to modern biomass. Heat pumps in this example are air-to-water units. Heat substation refers to heat exchangers (district heating).

Source: IEA analysis based on Schlömer et al. (2014).

Some clean energy technologies are less durable than existing fossil fuel ones, increasing the need for recycling and refurbishing obsolete equipment to limit environmental effects .

Employment along clean energy supply chains

Clean energy employment today

Labour markets worldwide have experienced major upheavals since the start of the Covid-19 pandemic, due to the economic disruption caused by restrictions on the movement of people and commercial activity. Energy sector employment has not been immune from these shocks and has also been affected by the recent energy crisis in the wake of Russia's invasion of Ukraine. While higher energy

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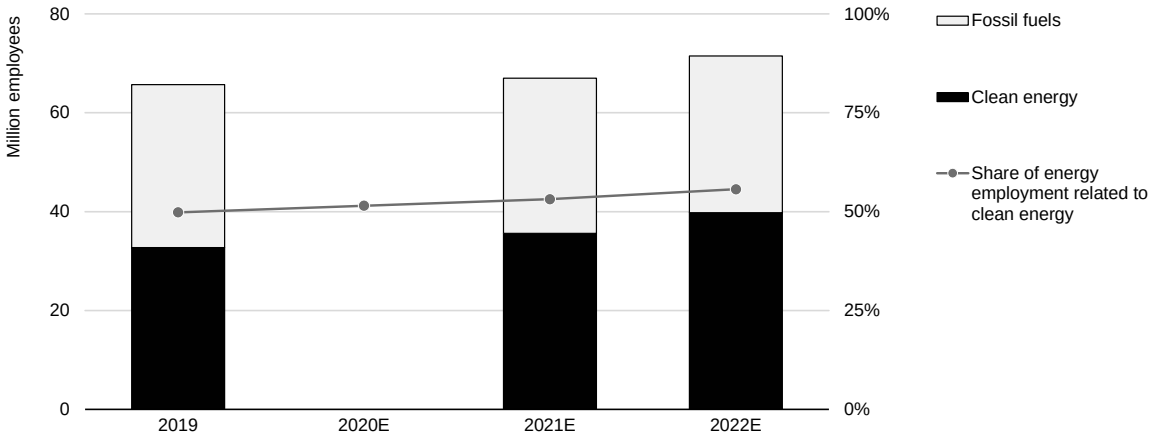
prices have, in many cases, boosted the demand for workers in the oil, gas and coal industries, the growing attractiveness of clean energy technologies and their increasing deployment is pushing up demand for workers in those sectors as well. Stronger policy responses to the climate and energy crises are expected to continue to drive a shift in employment away from the fossil energy industries to clean energy sectors in the coming years and decades. Overall energy sector employment is set to grow steadily through 2030 as demand for energy services continues to expand and supply shifts to more labour-intensive activities (Figure 1.19).

Global energy sector employment by technology



IEA. CC BY 4.0.

Note: Clean energy employment includes workers in bioenergy supply (including farmers), nuclear and renewables for power generation, grids and storage, EV manufacturing, and energy efficiency (such as building retrofits, heat pump manufacturing, and ventilation and air-conditioning installations). Labour market disruptions associated with the Covid-19 pandemic made 2020 employment difficult to assess, so 2020 estimates are indicative. Estimates for 2020-2022 are modelled based on latest IEA energy balances and investment data, under the assumption that labour intensity and the job creation potential of new investment remain constant across years; for more details please refer to the World Energy Employment report methodology.

Sources: IEA analysis based on IEA (2022n).

The total number of jobs in clean energy supply and use, and their share of total energy employment, has grown in recent years despite the Covid-19 pandemic.

Over 65 million people are employed worldwide in the energy sector, including direct jobs in energy supply industries as well as indirect jobs in manufacturing essential components of energy technologies such as the manufacturing of vehicles or heat pumps (Figure 1.19). Around two-thirds of energy workers are engaged in the development of new projects or equipment, while the other third are involved in operating or maintaining existing assets. Energy workers are spread across economic sectors: over 14 million employees work at utilities and firms providing professional services, approximately 22 million in manufacturing of equipment, 16 million in construction of energy facilities, 9 million in the raw materials sector, and 9 million in related activities such as wholesale trade and energy transport.

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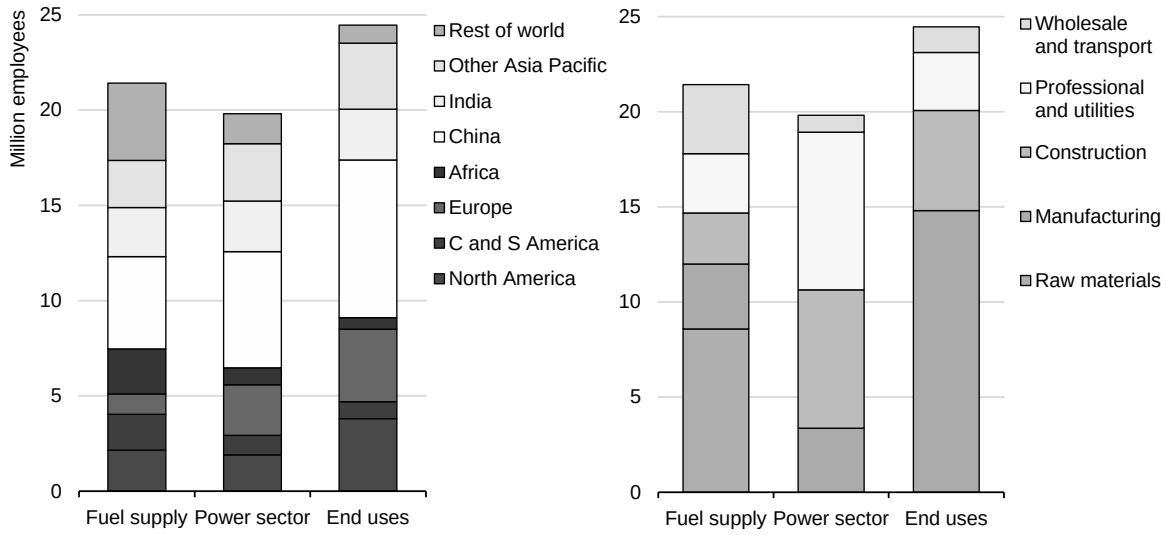
Overall energy employment is concentrated in countries with major manufacturing hubs and large energy production industries, especially where new energy facilities are being built. As a result, almost three-fifths of all energy employment is in the Asia Pacific region, with China alone accounting for almost 30% of the global energy workforce with nearly 20 million energy workers (Figure 1.20). Clean energy employment now accounts for just over half of the global energy workforce. This is in large part due to the continued growth in new projects, which generate the most jobs (construction and installation activities are highly labour-intensive). Most new energy projects today involve clean energy supply or end-use activities. Eurasia and the Middle East are now the only regions where the share of clean energy employment does not exceed half.

Low-emission power generation currently employs an estimated 7.8 million workers worldwide, with over 4.2 million in solar and wind alone. Fossil fuel-based power generation employs just 3.4 million (Figure 1.21). There are roughly the same number of workers in low-emission power generation as in the oil supply industry, which employs the most people among the three fossil fuel supply sectors. In vehicle manufacturing, 10% of the almost 14 million workers worldwide are already involved in making EVs, their batteries and related components.

Energy employment by region and supply chain step, 2019



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Notes: C and S America = Central and South America. Value chain steps and economic sectors for employment are aligned with International Standard Industrial Classification (ISIC) rev.4 (a standard classification of economic activities). “Raw materials” includes agriculture (ISIC code A) for bioenergy production, as well as mining and quarrying (ISIC code B) for fossil fuels (excludes critical minerals mining). “Manufacturing” (ISIC code C) includes both traditional manufacturing and material processing such as the manufacture of refined petroleum products. “Construction” (ISIC code F) indicates installation, while “Professionals and utilities” encompasses the supply of electricity, gas, steam and air conditioning (ISIC code D), as well as professional, scientific and technical activities (ISIC code M). "Wholesale and transport” refers to wholesale and retail trade (ISIC code G), and transportation and storage (ISIC code H). End uses refers to jobs in vehicles manufacturing (including related batteries), energy efficiency for industry, and buildings (retrofits and efficient heating and cooling).

Sources: IEA analysis based on IEA (2022n).

The manufacturing and construction of new projects dominates energy employment today.

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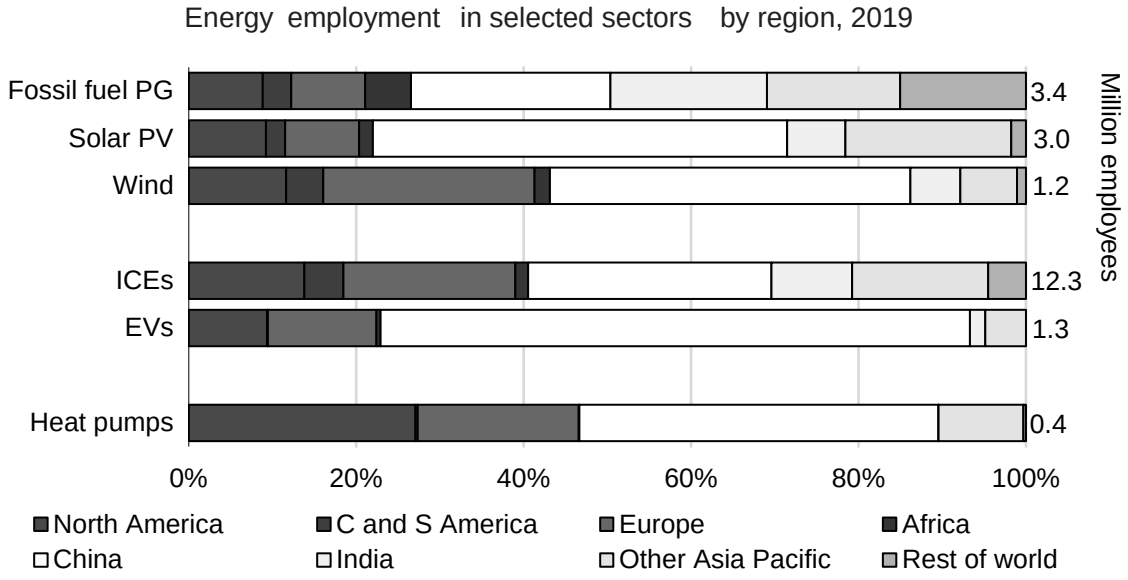

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Notes: Fossil fuel PG = fossil fuel power generation. EV employment includes manufacturing of EV batteries and other related components.

Sources: IEA analysis based on IEA (2022n).

Low-emission energy technology sectors already employ large numbers of workers, though their share of total energy employment varies markedly across regions.

Labour shortages and skills gaps

An adequately skilled and sufficiently large workforce will be central to the energy transition. But shortages of skilled labour in emerging clean energy sectors, coupled with broader labour market difficulties, are already limiting the pace and extent of new projects in several key regions, raising doubts about the speed of the transition in the near to medium term. In China, for example, manufacturers are struggling to fill positions in factories in the face of a declining working population, with young people and college graduates generally more attracted by white-collar jobs (Nulimaimaiti, 2022). The Ministry of Education has estimated that there will be a shortage of almost 30 million workers in China's manufacturing sector by 2025, including talent gaps of over 9 million in power equipment, over 1 million in new energy vehicles and over a quarter of a million in offshore engineering equipment (Government of China, 2017). Meanwhile, a dearth of tradesmen, such as plumbers, pipefitters, electricians, heating technicians and construction workers, is already restricting the pace of installations of clean energy technologies in Europe and the United States, including solar PV, wind turbines and heat pumps (McGrath, 2021; SEIA, 2021b; Weise, 2022; Hovnanian, Luby & Peloquin, 2022).

Some fast-growing clean energy sectors are also facing a shortage of the requisite skills needed to scale up output. In the wind sector, insufficient training capacity and differences in certification requirements across countries are contributing to

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bottlenecks in new installations. The Global Wind Organisation and the Global Wind Energy Council estimate that 480 000 trained workers will be needed to build, install and operate the wind capacity that is planned to come online between 2021 and 2025, but only 150 000 workers had been able to be trained by the end of 2021 (GWO and GWEC, 2021). Offshore wind projects require better trained workers and more labour input per megawatt than onshore projects over their lifetime. There are growing concerns that shortages of trained personnel in the offshore wind sector could delay installations in the coming years (GWEC, 2021).

In the EV sector, skills shortages are already emerging in both production and maintenance. Battery producers are struggling to hire enough research and engineering specialists (Heekyong Yang, 2021), while vehicle technicians and mechanics are unprepared for the impending expansion of EV fleets as ICE bans and EV target deadlines approach (Automotive Management, 2021). Several countries with major hydrogen ambitions, including Canada and the Netherlands, are facing difficulties in finding qualified personnel (Hufnagel-Smith, 2022; CE Delft, 2021). In addition, heat pump manufacturers have flagged a lack of trained labour to install new units as a potential bottleneck for wider deployment.

Millions of jobs will need filling to realise energy transitions

The clean energy transition will involve a massive change in energy sector employment, with many jobs set to be lost in traditional activities in producing and supplying fossil fuels, but many more created in clean energy sectors, including in their supply chains. Filling those new jobs will be key to avoiding bottlenecks and speeding up transitions around the world.

Global energy sector employment grows from around 65 million today to almost 90 million in 2030 in the NZE Scenario. Nearly all of the new jobs are in clean energy sectors. Employment in oil, gas and coal fuel supply and at power plants that are not equipped with carbon capture facilities declines by around 8.5 million to 13 million over the same period (Figure 1.22). The deployment of clean technologies in the NZE Scenario implies a need to recruit a large number of workers in those sectors. For example, jobs in wind and solar PV increase by almost 10% per year on average over 2021-2030 as capacity additions continue to grow. With the share of EVs in total car sales reaching over 60% in 2030, more people work in manufacturing EVs, including their batteries, than in making ICE vehicles.

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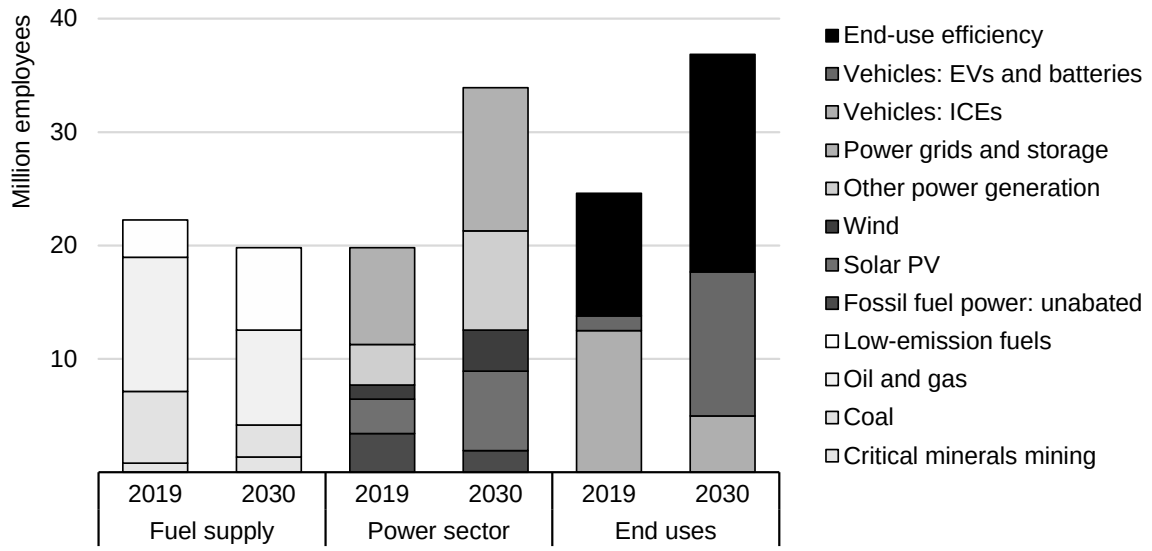
Global e nergy sector employment by technology in the NZE Scenario



IEA. CC BY 4.0.

Note: End-use efficiency employment refers to employment in efficiency improvements for buildings and industry; for more details please refer to the World Energy Employment report methodology.

Sources: IEA analysis based on IEA (2022n).

Clean energy sector employment soars in the NZE, from 32 million in 2019 to 70 million in 2030, more than offsetting the loss of 8.5 million jobs in fossil fuel and related industries.

More skilled workers are needed in the clean energy sector

Overall, the energy sector employs more highly skilled workers than other industries, with 45% of the workforce requiring some degree of tertiary education, from university degrees to vocational certifications, compared with the economy-wide average of 24% (Figure 1.23). Many energy firms are already facing a very competitive environment for hiring candidates with the needed skill sets, particularly for positions in the field of science, technology, engineering and mathematics (STEM), followed by project managers and other technical roles (IEA, 2022n). The biggest hiring gaps globally at present are in project management and information technology (IT) (Global Energy Talent Index, 2022). The continuing shift in employment to clean energy jobs could exacerbate these skill shortages.

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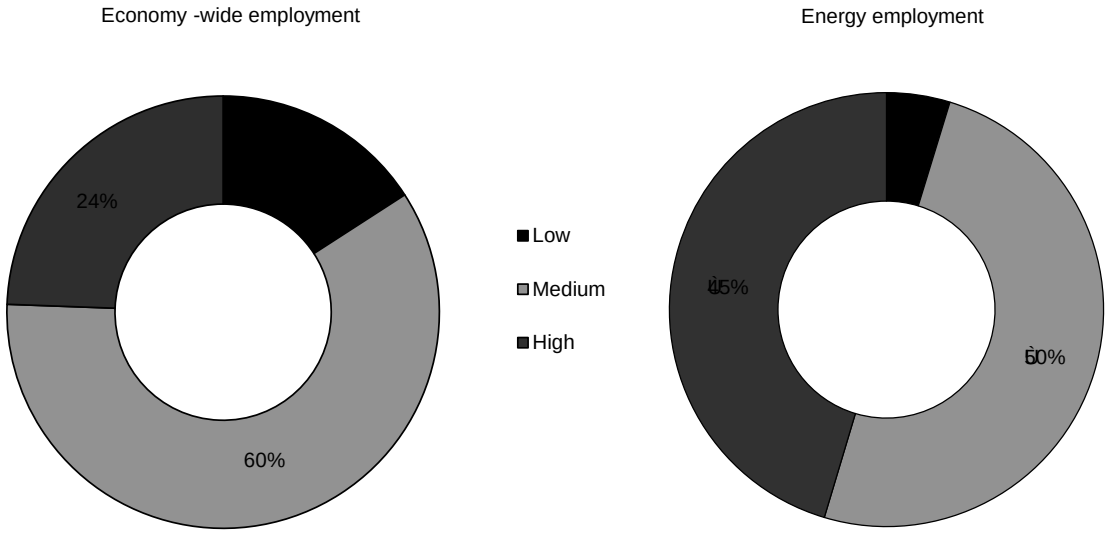
Global employment by skill le vel, 2019



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Note: High skill level refers to ISCO-08 skill levels 3 and 4, medium to ISCO-08 skill level 2 and low to ISCO-08 skill level 1.
Sources: IEA analysis based on IEA (2022n); International Labour Organization (2022).

The energy sector demands more highly skilled workers than other industries, with 45% of the workforce having some form of tertiary education .

The specific skills required in the supply of clean energy and the current labour shortages vary considerably according to the type of technology. In the power sector, safety experts, construction managers, cybersecurity professionals and software developers, as well as skilled middle-management project engineers, are already difficult to recruit (Naschert, 2022). The broader dearth of construction workers and tradespeople is starting to limit solar and wind power capacity additions in some locations. There is also a widespread shortage of electricians who require multi-year training (SEIA, 2021a). In the case of renewables, around two-thirds of solar PV and onshore wind jobs require minimal formal training, whereas 30% of jobs require STEM degrees and 5% of jobs are for highly qualified non-STEM professionals such as lawyers and regulation experts (IRENA, 2021). In power grids, increased digitalisation of networks is boosting the need for IT skills. The biggest skills shortages today in renewables are in construction and engineering; followed by planning, organising and scheduling; project development; and on-site construction and fabrication (Global Energy Talent Index, 2022). In hydrogen production, there is strong demand for engineering skills, as well as those in designing, operating and maintaining hydrogen infrastructure and vehicles.

Skills shortages are less of a constraint to expanding capacity in some other areas. In the case of EVs, many manufacturing-related skills can generally be transferred from ICEs. In addition, EVs tend to have fewer components than ICEs, simplifying the assembly process. However, for the maintenance and repair of EVs, more

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mechanics will need to receive electrical training to handle high-voltage batteries (Institute of the Motor Industry, 2021). EV battery producers have also been facing shortages in research and development (Heekyong Yang, 2021).

Some fossil fuel workers have skills that can be transferred to clean energy sectors, which will help alleviate shortages and provide them with new opportunities. For example, coal miners have skills that can be used in mining critical minerals. Based on new geospatial analysis carried out by the IEA, an estimated 40% of coal workers worldwide are employed within 200 km of a critical mineral reserve. Nonetheless, opportunities for shifting mining and related jobs will be limited, especially as the volumes of critical minerals needing to be mined is small when compared with the volume of coal mined today.

It may also be possible to transfer some marine-based technical skills from the offshore oil and gas industry to the offshore wind sector, including hydrodynamics, shipping operations and the application of health and safety rules (C&S Partners, 2021). Oil and gas engineering skills are highly applicable to CCUS and geothermal including seismic interpretation, drilling and well completions, reservoir mapping, and flow assurance. The Integrated People and Skills Strategy of the United Kingdom's North Sea Transition Deal estimates that 90% of the existing UK oil and gas workforce have medium to high skills transferability, with over half of the existing oil and gas workforce open to considering a move into offshore wind or renewables generally (Energy Skills Alliance, 2022). Chemical engineers in refineries have skills that are useful in the production of biofuels and hydrogen and raw materials extraction.

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Chapter 2. Mapping out clean energy supply chains

Highlights

- The production of critical minerals is highly concentrated geographically, raising concerns about security of supplies. The Democratic Republic of Congo supplies 70% of cobalt today; China 60% of rare earth elements (REEs); and Indonesia 40% of nickel. Australia accounts for 55% of lithium mining and Chile for 25%. Processing of these minerals is also highly concentrated, with China being responsible for the refining of 90% of REEs and 60-70% of lithium and cobalt. China also dominates bulk material supply, accounting for around half of global crude steel, cement and aluminium output, though most is used domestically.
- China is the leading global supplier of clean energy technologies today and a net exporter for many of them. China holds at least 60% of the world's manufacturing capacity for most mass-manufactured technologies (e.g. solar PV, wind systems and batteries), and 40% of electrolyser manufacturing. Europe is generally a net importer, with the exception of wind turbine components; about one-quarter of electric cars and batteries, and nearly all solar PV modules and fuel cells are imported, mostly from China. For solar PV, China supplies equipment directly to all markets except North America. The United States imports two-thirds of its PV modules, primarily from Southeast Asia, where Chinese companies have been actively investing.
- Recent supply chain disruptions resulting from the Covid-19 pandemic and Russia's invasion of Ukraine, combined with rapidly growing demand, have dramatically increased the cost of materials and energy. The average price of lithium was nearly four times higher in 2022 than in 2019, and twice for cobalt and nickel. Batterymetal price hikes in early 2022 led to increasing battery prices – up nearly 10% globally relative to 2021 – after years of continuous decline. The price of solar PV-grade polysilicon, copper and steel all roughly doubled between the first half of 2020 and that of 2022. These increases contributed to pushing up the price of PV modules rising by 25% and that of wind turbines outside China rising by up to 20%.
- Clean energy technologies have far lower life-cycle CO_2 intensities than their fossil counterparts, but their supply chains are still an important source of CO_2 emissions and other pollutants. Material production and technology manufacturing typically account for over 90% of the emissions for the clean energy technology supply chains analysed. Reducing emissions from these steps is challenging, given the current lack of commercially available low-emission technologies in many cases, but an important undertaking in the transition to net zero emissions.

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Assessing vulnerabilities in supply chains

Understanding the functioning of clean energy supply chains today and their vulnerabilities is crucial to lay the foundations for expanding them as the clean energy transition advances (Table 2.1). The goal must be to ensure that both energy and technology supply chains are secure, resilient and sustainable. This chapter assesses those vulnerabilities in detail for selected clean energy supply chains, focusing on the link between geographic concentration and security, resilience to market shocks, and environmental performance.

The clean energy transition is affecting the nature of energy security, which depends on adequate and timely investments to ensure supply stays in line with demand. The move to clean energy is shifting the focus from fossil fuels to critical minerals, though the former will remain important to energy security during the transition, especially at its early stages. Compared with fossil fuel supply, the supply chains for clean energy technologies today are generally more geographically concentrated. Global supply chains are not always more vulnerable than domestic ones and may be necessary due to a lack of economically viable domestic resources for individual steps of supply chains. However, some external sources of key materials and components may be considered insecure. This is a particular concern if a large share of supply comes from countries subject to acute geopolitical risks due to conflict, social instability, unfair trade practices or human rights issues. The global energy crisis has reinforced this concern. In the longer term, as countries approach net zero emissions, demand for primary inputs to clean energy supply chains should start to decline, as new capacity is required mainly to meet new energy demand rather than also replace existing fossil fuel incumbent technologies.

Building resilience to disruptions along supply chains is vital to mitigating emerging problems for energy systems. Most low-emission technologies rely on domestic energy resources, such as sunshine and wind, but the equipment, critical minerals, materials and components needed to exploit those and produce end-use equipment often rely on global supply chains. An oil supply crisis, when it happens, has broad repercussions across the economy. The supply of electricity, which is set to play an increasingly important role in meeting energy needs, low-emission hydrogen and derivative fuels (including ammonia), and bioenergy/biofuels will face similar threats in the future. A shortage or spike in the price of a raw material or component required for producing key clean energy technologies such as batteries, solar panels or electrolysers will affect their availability, which could lead to delays in decarbonising the energy system and increasing the overall costs of the energy transition.

The goal of sustainability concerns energy technology supply chains as well as the supply of energy itself. The use of clean energy technologies may involve

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fewer emissions, but their supply chains may result in significant emissions and other environmental impacts. Today, emissions from clean energy supply chains come mainly from bulk materials production. Reducing them will be tough, since many of the technologies required to do so are not yet commercially available. Mining and technology manufacturing are also responsible for a significant share of emissions, but reducing them should be easier since there is greater scope for switching to electricity. In any case, the emissions from supply chains and other environmental impacts should not be a reason to stall the rapid roll-out of clean technologies in the near term, since in most cases supply chain emissions are dwarfed by those that are saved as a result of their use.

Supply chains need to meet the needs of a net zero energy system while themselves being compatible with it, and be able to 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. The goal should be to achieve this while maintaining a commitment to the principles of open and transparent markets. Self-sufficiency is not always an option – particularly for some elements of the supply chain that are bound to the availability of certain natural resources that are geographically concentrated – nor necessarily an economically optimal approach. A combination of open markets within the rules of the World Trade Organization, strategic partnerships and diversity of supply sources will, in many cases, be a better approach (see Chapter 6).

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

Objective	Characteristics
Secure	Adequate, reliable and uninterrupted supply of inputs. Diversity in market, suppliers and technologies.
5 H V L O L H Q W ×	Able to respond and quickly adjust to sudden market shocks on prices or demand. Stable and affordable prices. Effective interconnection with other supply chains that can deliver an equivalent technology or service.
Sustainable	Greenhouse gas emissions as low as possible and consistent with climate objectives. True supply chain transparency and impact assessments (e.g. air and water pollution, biosphere protection) with strengthening environmental, social and governance measures (ESG) along the entire supply chain. Efficient and responsible use of natural resources, including through promotion of material efficiency and end-of-life stewardship.

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Box 2.1 Clean energy supply chains interdependencies

Supply chains link suppliers of inputs to consumers of outputs, often spanning multiple sectors and countries to form complex networks. These interdependencies are also vulnerabilities in terms of resilience. In the case of clean energy, certain technologies and technology or energy supply chains are “foundational”, i.e. without them, the superstructure of supply chains would not be able to function properly. For example, any disruption to low-emission electricity supply would directly affect low-emission hydrogen production, and in turn low-emission synthetic hydrocarbon fuels production (Figure 2.1).

Interconnections between selected energy and technology supply chains

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Notes: DAC = direct air capture. BECC = bioenergy with carbon capture.

The use of cross-cutting technologies can also expose the clean energy system and supply chains to new vulnerabilities. These technologies are typically deployed in different sectors and supply chain steps, hence have broad impacts in case of disruption. For example, carbon capture, utilisation and storage (CCUS) can contribute to decarbonising industry, power and fossil-based hydrogen production, as well as provide carbon dioxide removal and CO_2 for synthetic fuel production. As a result, disruptions in the supply of CO_2 capture components or along the CO_2 transport and storage infrastructure could have an impact on clean energy supply across several sectors.

It is crucial that industry and policy makers assess these vulnerabilities at the system level and reduce them through targeted measures, such as by deliberately building redundancy into the system in the form of overcapacity or alternative supply or production routes.

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Geographic diversity and energy security

Extraction of critical minerals

The shift from fossil energy to less emissions-intensive technologies and fuels will fundamentally change global energy supply chains, including the types of natural resources needed. In particular, clean technologies depend much more on critical minerals. While the world's resources of these minerals are very large and unlikely to constrain supply in the long term, 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 export restrictions. In general, the supply of critical minerals is more geographically concentrated than that of oil, gas and coal.

Regional shares of global fossil fuel and uranium production and resources, 2021

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Notes: CSA = Central and South America. Uranium resources are identified uranium resources assuming an international market price of USD 130/kg. Fossil fuel resources consider the remaining technically recoverable resources.
Sources: IEA analysis based on IEA data; WISE Uranium Project (2020).

Fossil fuel production today is concentrated in North America, the Middle East and China.

The countries that dominate minerals production today are generally very different to the leading producers of fossil fuels (Figure 2.2, Figure 2.3). The United States is currently the world's biggest producer of both oil and gas, but features prominently only in silver, copper and rare earth elements (REEs) mining. Although the People's Republic of China (hereafter, "China") is the world's leading producer of coal, it has relatively small resources of oil and gas. Yet it dominates production of REEs, accounting for 60% of global output, and is also a big

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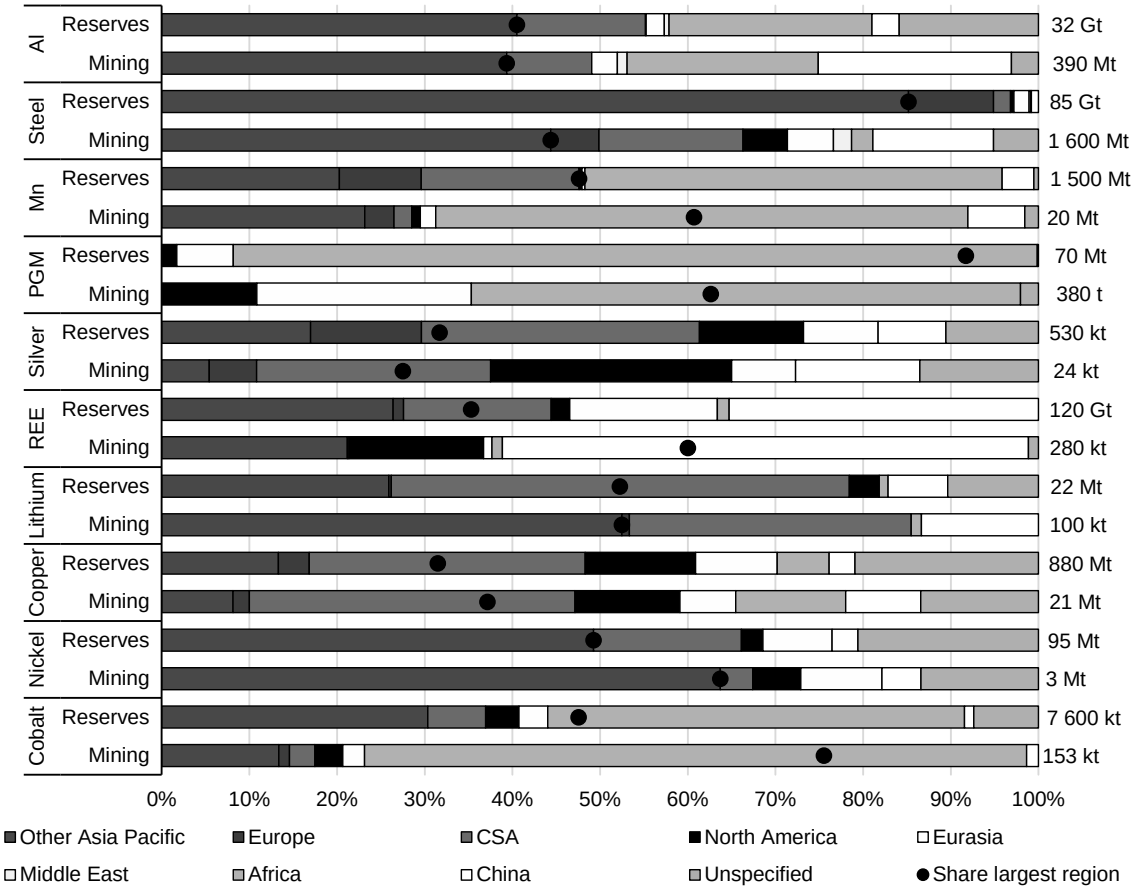
producer of iron ore, lithium and copper. While several countries in the Middle East are major oil and gas producers, they produce very few critical minerals. The mining of those minerals is concentrated in Africa, South America, Australia and Indonesia, while their processing is concentrated in China.

Global reserves and extraction of selected resources by region, 2021



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Notes: Al = aluminium; Mn = manganese; PGM = platinum group metals; REE = rare earth elements; CSA = Central and South America. PGM mining includes only platinum and iridium. Reserves data are uncertain as companies and countries do not always disclose their full reserves.

Sources: IEA analysis based on USGS (2022); S&P Global (2022a).

Leading countries in minerals extraction today are very different from fossil fuel producers, with mining concentrated in Africa, South America and Asia Pacific.

The degree of geographic concentration of critical minerals today varies significantly. For lithium, cobalt and REEs, the top three producing nations control three-quarters or more of global output. South Africa supplies more than 70% of the world's platinum needs for all uses – one of the highest concentrations of any mineral. Mining of ores of cobalt, which is a vital component of lithium-ion (Li-ion) batteries and superalloys used in turbines, nuclear reactors and sensors, is also highly concentrated, with the Democratic Republic of Congo holding 70% of global

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production, although the majority of those mines are owned by Chinese firms. Mining companies pay back the government with royalties at rates that are 4-8% of mining revenues. There are serious claims that corruption and other factors deprive communities of such benefits (Eurometaux, 2022). For lithium, Australia accounts for 55% of mining and Chile over 25%. Output of copper ores is the least concentrated of all the main critical minerals, with the three leading producers – Chile, Peru and China – accounting for less than half of global supply. Market concentration is also high. For instance, the top five lithium producing companies controlled almost 80% of global mining capacity in 2021 (BNEF, 2021a).

Proven reserves for most critical minerals are more geographically widespread than current production.[8] This suggests that there is considerable scope for increasing the diversity of the sources of these minerals and reducing over-reliance on a small number of major producers. For REEs, the distribution of reserves is very different to that of current mining, implying that many countries have considerable potential to boost output. Political, economic and environmental factors affect the extent to which each region may be willing to exploit its resources. For example, while Chinese reserves of REEs account for less than 40% of global reserves, about 60% of global REE extraction takes place in China, illustrating the government's strong support for critical mineral production.

Box 2.2 The different steps of metal production

Producing metals involves many steps and processes that cut across different elements of supply chains to convert the raw material, such as a metallic ore (a compound containing the metal), to a final form in which the metal can be used as an input to manufacturing. The principal steps are as follows:

- Exploration and mining of the ore, including the removal of soil and rock to gain access to it. Most ores are extracted form open-cast or underground mines, but a few metals, such as magnesium, are partly extracted from seawater using electrolysis (passing an electric current through a water solution of the compound). The energy intensity of this step is affected by the stripping ratio (of waste rock to ore) and the grade of ore. In this report, this step is simply referred to as mining.
- Transportation of the ore after crushing to a mill or processing plant, usually in bulk or in large bags.
- Purification of the ore, involving the separation of the metal from various impurities contained in the ore (usually through a combination of sieving and

[8] Reserves are defined as known resources and quantified deposits that can be economically extracted. Reserves are smaller than resources, which are the amount of both discovered and suspected undiscovered deposits. Geological discoveries and changes in technology and market prices can affect what are considered reserves.

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flotation methods using water and chemicals). Low ore grade minerals require more purification steps, resulting in higher energy and emissions intensities.

- Storage of tailings – leftover materials from the processing of mined ore – usually in the form of slurry in water-filled pools known as tailings dams to prevent tailing powder from blowing away and polluting the area surrounding the mine (see Box 2.6).
- Reduction of the ore (the conversion of the ore from its oxidised state to its pure form) through smelting to produce metals that can be used in manufacturing. For example, iron is currently mostly reduced by reacting iron oxide with carbon and carbon monoxide in a blast furnace. In this report, refining and reduction steps are simply referred to as materials production.

Critical and bulk materials production

Processing of critical minerals is more concentrated than reserves

After minerals are extracted from the ground, they first need to be processed and refined to reach the required level of purity for use. For example, EV battery manufacturing requires nickel sulfate, which can be produced from nickel sulfides and hydroxides or can be derived from refined nickel, which itself is produced through a purification of raw nickel ore (Le Gleuher, 2022). These steps involve advanced physical and chemical treatment techniques, which can be highly energy-, capital- and skills-intensive.

The degree of geographical concentration of critical materials production is even greater than that of minerals extraction (Figure 2.4). China dominates processing of several of them: it holds a share of around 30% of global processing for nickel (the figure is higher if the involvement of Chinese companies in Indonesian operations is included), 60-70% for lithium and cobalt, and as high as 90% for REEs (to convert them into oxides, metals and magnets). No other country controls more than a fifth of critical materials production, with the exception of Chile, which processes almost one-third of the world's lithium, and Indonesia, which does the same for nickel. China has built integrated supply chains from mining and processing of some critical minerals to manufacturing. This is the case for permanent magnets, which are used in wind turbines and EVs and are composed to a large extent of neodymium, an REE. In other cases, China imports ores and concentrates produced elsewhere for local processing and integration into domestic supply chains. For example, lithium is typically imported from Australia, refined and subsequently integrated into EV batteries for vehicles made domestically.

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Some countries have increased their processing of critical minerals in line with extraction. This is the case with nickel in Indonesia, the mining and processing of which has increased significantly over the last decade in line with rising EV battery demand. The country was the world's largest nickel miner in 2021 at nearly 40% of global output, having boosted extraction capacity twofold since 2012, and accounted for about 30% of global refined nickel production, up from just 1% in 2012. In contrast, the Democratic Republic of Congo produced less than 1% of refined cobalt although it accounted for over 70% of mining output.

In general, other steps along clean energy supply chains are more likely to experience bottlenecks than processing (see Chapter 1). However, there are exceptions. In the case of polysilicon production, bottlenecks are more likely at the processing stage, due to its complexity. Raw minerals must be of very high quality to yield metallurgical-grade silicon of above 98% purity, which then needs to undergo multiple refining steps to produce polycrystalline silicon with 99.9999% purity for solar PV applications. China currently controls about 70% of metallurgical-grade silicon production and 80% of the polysilicon production (USGS, 2022).

Regional shares of global production of selected critical materials, 2021

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Sources: IEA analysis based on BNEF (2020); S&P Global (2022a); WBMS (2022); Adamas Intelligence (2020).

The concentration of the processing and refining of minerals is greater than that of extraction, with China dominating the processing of several of them.

Bulk materials production is highly concentrated as well

Clean energy technologies and infrastructure are made from large amounts of bulk materials, notably steel, cement, aluminium and plastics. Solar PV plants and wind farms generally require more bulk materials per unit of capacity than fossil fuel-based power plants, with some exceptions (also see Chapter 1). The raw materials

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and fuels required for the production of bulk materials, including iron ore, limestone, bauxite, oil and natural gas, are widely available and there are few bottlenecks at present to increasing capacity in most parts of the world. Indeed, there is global overcapacity in the production of some bulk materials.

Bulk material needs vary enormously across energy end-use sectors. Steel and cement are vital for buildings and infrastructure, with demand generally highest in the emerging economies where economic development is fastest, notably China and Asia Pacific. Other end-use sectors, such as the manufacturing of consumer products, packaging, industrial and electrical equipment, and vehicles, also make use of large amounts of a wider range of bulk materials, including aluminium and plastics (Figure 2.5).

Estimated end -use shares of global consumption of selected bulk materials, 2021

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Notes: Energy infrastructure includes electricity grids and oil and gas pipelines. Industrial equipment does not include material demand from the plant shell. Transport includes vehicles and estimated material demand from road and rail infrastructure. Other includes non-energy infrastructure and miscellaneous uses.

Sources: IEA analysis based on Worldsteel (2022a); USGS (2022); IAI (2022); Platts (2022); Geyer, Jambeck & Law (2017).

Bulk materials are used in a diverse range of end uses, with the main drivers varying substantially by material.

Bulk materials production is relatively highly concentrated geographically, although not to the same extent as critical materials (Figure 2.6). China accounts for more than half of the world's production of crude steel, cement and alumina, and more than a quarter of primary chemical production. While some of this production is exported, China's development path has been especially material-intensive, with demand for cement and steel in particular being higher relative to the country's economic activity than in other major countries. Bulk materials are

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generally less globally traded than critical materials, as a result of their wider global availability and higher costs of transportation relative to their value, encouraging production close to demand centres.

Regional shares in global production of bulk materials and intermediate commodities, 2021

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Notes: Plastics includes resin identifier codes 01-07, which excludes fibres. Iron includes pig iron and direct reduced iron. High-value chemicals include ethylene, propylene, benzene, toluene and mixed xylenes.

Sources: IEA analysis based on Worldsteel (2022a); USGS (2022); IAI (2022); Platts (2022); Geyer, Jambeck, & Law (2017).

China produces more than half of the world's crude steel and cement, and a large share of aluminium and primary chemicals, mostly for the domestic market.

Crude steel and iron

Steel is used in a wide range of end uses, with about half of demand coming from the buildings and transport sectors. Crude steel can be produced from scrap or iron, or more commonly a mixture of the two. Iron – made from iron ore – is virtually unlimited in its supply, whereas scrap availability is a function of past steel production and use. Countries with mature infrastructure and vehicle stocks tend to have ample domestic supplies of scrap, whereas emerging economies often need to produce more iron in order to increase their output of crude steel. Iron accounts for over 65% of the metallic inputs to crude steel production, with scrap accounting for the remainder. Globally, around 85% of available scrap is collected for recycling.

Around one-quarter of all the steel produced worldwide is traded internationally as intermediate steel products (finished and semi-finished), with the remainder being used by next-tier manufacturers in the country in which it was produced. The resulting products containing steel are also traded. Figures for the trade in volumes of steel contained in goods are much more uncertain; estimates from 2019 suggest that around 20% of this steel is exported, with almost 75% of the

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steel contained in goods used in the countries where the goods are produced (Worldsteel, 2022a). Though China uses around 95% of its production domestically, it is the largest net exporter of steel at 43 Mt in 2021 – or a third of global net exports. The other leading net exporters are the Russian Federation (hereafter, "Russia"), Japan, Korea and India, while the leading net importers are the United States, the European Union, Southeast Asia and the Middle East.

Cement and clinker

Cement, the primary ingredient for making concrete, is generally produced close to the point of use due to the high cost of transport as a heavy material and the widespread availability of limestone as an input. About half of global cement production is used for constructing buildings and the remainder for making a wide variety of other types of infrastructure, including for clean energy. China is both the biggest consumer and producer of cement, producing around 2.4 Gt in 2021 and accounting for around 55% of global production, followed by India (8%), the European Union (4%) and the United States (2%). The expectation of rising demand for cement to meet new construction needs generally leads to investment in local production, reducing the need for costly imports.

Aluminium and alumina

The use of aluminium is relatively evenly distributed around the world and across economic sectors, with the transport sector accounting for about 25% of global demand, and construction and packaging each for about 15%. Aluminium is an important input to the clean energy transition, with the production of several clean technologies, including solar PV installations and EVs, requiring significant amounts. Electricity networks alone account for about 8% of aluminium demand today.

Like steel, aluminium can be produced from virgin mineral inputs (bauxite) or from scrap. Bauxite is first transformed into alumina (aluminium oxide), which undergoes electrolysis in a smelter to produce aluminium. Around one-third of aluminium was produced from scrap (excluding that generated during aluminium production) in 2021, of which 60% was end-of-life scrap, with the remainder being sourced from the manufacturing of aluminium products.

China is the largest producer of aluminium, accounting for over 40% of global production. The United States accounts for around 5% and Canada for around 6% of global production, mostly using scrap and imported alumina. Approximately 40% of aluminium is traded internationally, with exports led by Russia (net exports accounting for 11% of total exports), Canada and the United Arab Emirates (9% each), and India (8%). China produces 55% of the world's alumina – an even larger share than aluminium, reflecting in part lower domestic scrap availability than that in many industrialised economies. Australia and Brazil are the world's

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largest alumina exporters, owing in part to their abundant bauxite reserves; together, they account for more than 20% of the world's alumina production, but just 4% of aluminium production.

Plastics and high value chemicals

The main thermoplastics – polyethylene, polypropylene, polyvinyl chloride, polyethylene terephthalate and polystyrene – are used primarily for packaging, which absorbs 36% of global supply, construction (16%), textiles (15%), automotive (7%) and consumer product (10%) applications. Some clean energy technologies make extensive use of plastics. For example, most wind turbine manufacturers use lightweight plastic composites to make blades, while solar panels often use various plastics to protect or connect some of the panels' parts.

Plastics are produced primarily from high-value chemicals – ethylene, propylene, benzene, toluene and mixed xylenes – which are in turn produced from oil products. Less than a fifth of plastic waste is currently collected for recycling, and less than a tenth of plastic production is based on post-consumer scrap material, reflecting the practical difficulties and cost of the recycling processes involved.

The geographic distribution of primary chemicals production reflects both regional demand and cost factors, especially the local availability and cost of oil feedstocks. Consequently, regions well-endowed with oil and gas resources, such as the Middle East and United States, are big producers. China is the world's leading producer of both high-value chemicals and key thermoplastics, accounting for around 25% of world output. The United States and Europe also hold strong positions in the global chemical and plastics industries, with the United States accounting for nearly 20% of combined production in these sectors and Europe for 10%. High-value chemical production and plastics production are generally located together. While plastic resins and derivative products are traded extensively, high-value chemicals are often gaseous (e.g. ethylene) and highly toxic (e.g. benzene), making transport cumbersome and expensive.

Technology manufacturing and installation

Technology manufacturing refers to the production of technologies using labour, tools and energy to transform materials into finished goods. In the case of the clean energy technologies covered in this report, these goods are categorised as follows:

- Mass-manufactured technologies , which are assembled in specialised factories in large volumes using several components and sub-assemblies, with the ready-to-use end product exiting the factory floor. Examples include solar PV modules, wind turbines components, EV batteries, fuel cells and fuel cell trucks, heat pumps, and electrolysers.

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- Large-scale site-tailored technologies, which are usually individually designed and sized to fit specific local conditions. Examples include most CCUS applications, synthetic hydrocarbon production and bioenergy-related technologies. These are effectively systems formed by components, some of which can be mass manufactured.

China dominates mass-manufactured clean technologies

China dominates the production of mass-manufactured technologies and components thanks to low manufacturing costs, a strong base in materials production and sustained policy support on these industry segments. It controls at least half of the output of most of the main such technologies, notably solar PV and EV batteries (Figure 2.7). The rest of the Asia Pacific region continues to manufacture technologies in which they hold strong intellectual property, such as batteries and fuel cells. As the markets for these technologies expand, capacity to produce these technologies can often exceed short-term production needs. Currently, manufacturing capacity exceeds production for most technologies in all regions, particularly electrolysers, EV batteries and fuel cell trucks (see respective sections below).

Solar PV and wind power

Solar PV and wind are the leading low-emission electricity generation technologies being deployed worldwide today. Over the last decade, China's dominance of manufacturing of solar PV equipment has grown, reducing the shares of Europe, Japan and the United States. Today, China's share in the manufacturing of silica-based solar PV modules exceeds 70% – almost double the country's share of global demand. The country is home to the world's top ten suppliers of solar PV manufacturing equipment. Asia Pacific (excluding China) hosts around one-fifth of module manufacturing, and the remaining capacity is located mostly in Europe and North America.

Manufacturing of wind turbines is also heavily concentrated geographically. The top 15 manufacturers accounted for almost 90% of the total capacity deployed in 2021. Among those, Chinese companies were the leaders, with more than 55% of the total, followed by European companies, with around 35%, and American ones, with less than 10%. The marketing strategies of these enterprises vary considerably across regions. In China, most of the wind farms that have been installed were built by Chinese manufacturers, accounting for more than 95% of the total capacity deployed domestically. European manufacturers have a much more international business, installing around 65% of their output in other regions, where they have built local manufacturing facilities.

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Regional shares of manufacturing capacity for selected mass-manufactured clean energy technologies and components, 2021

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Notes: FC = fuel cell. Heat pumps capacity refers to thermal output.

Sources: IEA analysis based on InfoLink (2022); BNEF (2022); BNEF (2021b); Benchmark Mineral Intelligence (2022); GRV (2022); UN (2022a); Wood Mackenzie (2022).

Around 90% of mass -manufa cturing capacity for several key clean energy technologies is concentrated in China and the Asia Pacific region.

EV batteries

The market for EVs is booming. Sales of EVs nearly doubled to 6.6 million in 2021 and exceeded 10 million sales in 2022. Of these, most were full battery EVs, accounting for over 70% of EVs sold, with the rest being plug-in hybrids.

EV manufacturing has certain synergies with other sectors, most obviously with the conventional internal combustion engine (ICE) vehicle industry. Though the production of EVs involves the manufacturing of specialty components not used for making ICE vehicles, with the battery being the most critical component. The rapid increase in EV sales and, more recently, Russia's invasion of Ukraine, have

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tested the resilience of battery supply chains, though output has to date managed to keep pace with demand. Global demand for automotive Li-ion batteries doubled to 340 GWh in 2021.

China dominates production at every stage of the EV battery supply chain, with the exception of the mining of metals needed to make cathode materials. Two-thirds of global battery cell production, as well as around 80% of the production of cathode and over 90% of anode material, is in China. Europe is responsible for over a quarter of EV production, but holds very little of the rest of the supply chain apart from cobalt processing, in which it has a share of around 16% (mostly in Belgium and Finland). The United States has a smaller stake in the global EV battery supply chain, with only around 10% of EV and battery production capacity. Both Korea and Japan have considerable shares of the supply chain downstream of raw material processing, particularly in cathode and anode material production. Korea holds 13% of global cathode and 3% of anode material production capacity while Japan accounts for 14% (cathode) and 10% (anode).

Both EVs and their batteries tend to be produced close to where they are sold. Only China exports significant amounts of both EVs and batteries over long distances. The top five battery manufacturers, headquartered in Korea, China or Japan, hold over 50% of global manufacturing capacity, with China's CATL – Contemporary Amperex Technology Co. Limited, the market leader – alone holding around 15%. EV battery production capacity currently exceeds demand, as factories have generally been deliberately oversized in anticipation of continuing strong growth in demand. In addition, some factories are still ramping up production to reach nameplate capacity, a process that can take from three to six years (Fleischmann et al., 2021). Overcapacity is nonetheless starting to fall: the global average utilisation rate for all types of battery factories was 43% of capacity in 2021, up from 33% in 2020.

Fuel cell trucks

Almost 900 heavy-duty fuel cell trucks[9] were sold worldwide in 2021, 90% of them in China. Switzerland was the second-largest market, with around 8% of sales. The production of fuel cell trucks involves the manufacturing of some specialty components not used for making conventional diesel-based ICE trucks. They include the hydrogen tanks for on-board storage and the fuel cell system. Currently, global fuel cell truck manufacturers' claimed nameplate capacity aggregates to over 13 000 trucks/year, implying significant idle capacity and

[9] Heavy-duty refers to trucks with a gross vehicle weight over 15 tonnes. We focus on this specific vehicle segment as it is the vehicle category that is projected to have the largest share of fuel cell vehicles in the Net Zero Emissions by 2050 Scenario. The global fleet of battery electric heavy-duty trucks was more than an order of magnitude bigger than that of fuel cell trucks in 2021. The former is projected to remain the dominant zero-emission powertrain in that scenario.

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enormous potential to increase near-term deployment with existing facilities concentrated in China, Korea, the United States and Europe.

The leading manufacturers of trucks are China's SAIC Hongyan, which can manufacture around 3 000 trucks/year, Korea's Hyundai (2 000 trucks/year), and the American companies Hyzon Motors (1 000 trucks/year in the Netherlands) and Nikola (2 500 trucks/year in the United States and 2 000 trucks/year in Germany). Many other established manufacturers are also well positioned to begin production of fuel cell trucks in the near future given the short lead times involved in retooling existing assembly plants and the large share of components common to fuel cell, battery electric and ICE trucks. Several fuel cell suppliers are collaborating with truck manufacturers, for example, Cummins with Daimler in the United States and Scania in Europe; Kenworth with Toyota in the United States under a long-standing deal; and Weichai Power and Sinotruck in China. All these manufacturers could quickly ramp-up production by leveraging their substantial existing capacity and supply chains.

Fuel cell trucks typically rely on proton-exchange membrane (PEM) technology that converts hydrogen to electricity, which is used to power the electric motor and charge the vehicle's battery. PEM fuel cell manufacturing capacity for all vehicles, including cars, vans, trucks and forklifts, totalled over 290 000 systems/year in 2021 and is thought to have reached over 330 000 systems/year in 2022. Around 65% of capacity in 2021 was in China, where the leading producers are Refire, SinoSynergy, Weichai and Wuhan HydraV Fuel Cell Technologies. Korea has over 15% of capacity, with Hyundai the largest manufacturer.

There is substantial existing manufacturing capacity for high-pressure on-board vehicle hydrogen storage tanks. The leading manufacturers have taken advantage of the knowledge and experience gained with other compressed gas storage, in particular natural gas. Many also supply equipment for hydrogen distribution via tube trailers and for stationary hydrogen storage such as at refuelling stations. High-pressure storage vessel manufacturing is already well-established in North America, Europe and Asia. A number of manufacturers of this type of equipment have either already entered the market for on-board hydrogen storage for heavy-duty vehicles or plan to do so. Luxfer, which has factories in Canada, China, the United Kingdom and the United States, provided tanks for the Hyundai heavy-duty trucks sold recently in Switzerland. Hexagon Purus, which has manufacturing facilities in Canada, Germany and the United States, has a contract to provide on-board storage tanks to Nikola. Toyota currently manufactures its own tanks and is also positioning itself as a supplier to other manufacturers.

Heat pumps

More than 1 000 gigawatts thermal (GW_{th}) of heat pump capacity was in operation in buildings worldwide at the end of 2021, meeting around 10% of the total building

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heating needs. Global heat pump sales increased by about 13% in 2021. The market grew quickest in the European Union, where sales rose 35%, the United States (15%), Japan (13%) and China (13% for air-source heat pumps). Air-source heat pumps (air-air and air-water) account for the majority of heat pump sales worldwide, making up over 80% of the market in 2021.

Global heat pump manufacturing capacity (excluding air conditioners) amounted to around 120 GW_{th} at the end of 2021. Manufacturing is dominated by China, with almost 40% of total capacity, North America (30%), Europe (15%) and other Asia Pacific (over 10%). While China and other Asia Pacific dominate the global heat pump market, in particular for split systems (with both indoor and outdoor units connected by a set of pipes), Europe is the leader in the market for hydronic systems (whereby heat is conveyed via hot water) and large-scale applications. The top four global manufacturers accounted for around 40% of total capacity in 2021.

Heat pump manufacturers mostly serve the local market, with only China exporting significant numbers of heat pumps. Several heat pump components such as fans, pumps, tanks, expansion valves, heat exchangers and compressors are also common to other heating equipment or other industries. In particular, space heating and water heating heat pumps share the same type of components with air-conditioning units and refrigerators, which makes the total demand for components of the refrigeration cycle much larger than the one from heat pumps alone. Nonetheless, these components are not always interchangeable across equipment. Their production is currently dominated by a small number of companies.

Some of the main heat pump manufacturers also make heat pump components such as heat pump compressors, which currently make up about one-quarter of the cost of a heat pump, and fans. Mitsubishi, Carrier and Daikin, which together accounted for over 30% of all the heat pumps produced in 2021, already produce their own compressors. While compressors are needed in many industries, the design and manufacturing of such a component is a specialised industry and some heat pump compressors might require specific designs for certain temperature ranges and refrigerants. The market is currently dominated by a few suppliers. Europe imports a large share of the compressors it needs to make air-air heat pumps, whereas the compressors it needs for air-water and ground-source heat pumps are typically manufactured within the region by companies such as Danfoss, Bitzer and Emerson Copeland (Lyons et al., 2022).

The global heat pump industry is facing some bottlenecks amid rapid growth, in part due to limited supplies of semiconductors, which are used in control panels, electric pumps and fans. However, some manufacturers in the heat pump industry are confident that current shortages can be overcome within the next 12-18

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months. If components become available, there may be potential to increase output at existing facilities by roughly 20%.[10] In some cases, there is also potential for assembly lines to switch between producing air conditioners and heat pumps, which use similar technology (reversible heat pumps can produce both heat and provide cooling). The scope for raising production at short notice varies among manufacturers. Some, particularly in Europe, are already operating at rates close to maximum capacity.

The manufacture of refrigerants used in heat pumps is concentrated in China and North America, with the former being the largest exporter (CEMAC, 2020; United Kingdom, Department for Business, Energy & Industrial Strategy, 2020). The location of manufacturing sites is driven primarily by the proximity of chemical feedstock and the availability of a cheap and specialised labour force. Key refrigerant manufacturers include Honeywell International and Chemours Company in the United States, Dongyue Group and Sinochem Group in China, and Daikin in Japan. Heat pumping technologies predominantly rely on hydrofluorocarbon refrigerants such as R410A, but the share of others with lower global warming potentials (GWPs), such as R32, and natural refrigerants (such as propane) is rapidly increasing (BSRIA, 2020).

Electrolysers

Technologies to produce low-emission hydrogen today include water electrolysis and fossil-based hydrogen with carbon capture and storage (CCS), generally using natural gas as the feedstock (see below). Water electrolysers, which can be mass produced, are currently based on a small number of technologies, including alkaline, polymer electrolyte membrane, solid oxide electrolyser cell (SOEC) and anion exchange membrane (AEM). Alkaline technologies dominate the market today, though polymer electrolyte membrane ones are also commercially available. SOEC and AEM electrolysers are under demonstration, with the former at a large scale, and are expected to be commercialised soon.

Alkaline electrolysers are extensively deployed in the chlor-alkali industry, which accounts for the majority of the current global installed electrolyser capacity of more than 20 GW. However, this capacity is dedicated to the production of chlorine, with hydrogen being a by-product of the process. Only around 500 MW of electrolysers had been deployed globally for the dedicated production of hydrogen as of the end of 2021, producing around 35 kt that year. There is a growing number of projects under development though and, if all were realised, global installed electrolyser capacity could reach 134 GW in 2030,[11] with Europe,

[10] IEA analysis based on research, industry consultation and data from Global Research View.
[11] This would increase to 240 GW if projects at very early stages of development (i.e. where only a co-operation agreement among stakeholders has been announced) are included.

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