BARRIERS TO CLEAN ELECTRIFICATION SERIES
SUPPLY CHAINS

Better, Faster, Cleaner: Securing clean energy technology supply chains

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Energy Transitions Commission

Insights Briefing

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner who works with the ETC team, led by Faustine Delasalle (Vice-Chair), Ita Kettleborough (Director), and Mike Hemsley (Deputy Director).

The ETC's *Better, Faster, Cleaner: Securing clean energy technology supply chains* was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ, and support from the European Climate Foundation (ECF). This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this publication but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse this briefing paper.

This report looks to build upon a substantial body of work in this area, including from the IEA and IRENA, and ETC knowledge partners BNEF.

The ETC team would like to thank the ETC members, member experts and the ETC's broader network of external experts for their active participation in the development of this report.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision-makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2°C. Many of the key actions to achieve these goals are clear and can be pursued without delay.

Learn more at:

www.energy-transitions.org
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Barriers to Clean Electrification Series

The ETC's Barriers to Clean Electrification series focuses on identifying the key challenges facing the transition to clean power systems globally and recommending a set of key actions to ensure the clean electricity scale-up is not derailed in the 2020s. This series of reports will develop a view on how to "risk manage" the transition – by anticipating the barriers that are likely to arise and outlining how to overcome them, providing counters to misleading claims, providing explainer content and key facts, and sharing recommendations that help manage risks.

An Insights Briefing will be developed for each barrier, covering the context and major challenges, and assessing the impact of deploying key solutions. These Insight Briefings will be accompanied by a series of Solution Toolkits, which lay out a set of key actions that need to be taken by the most important group of stakeholders (e.g., governments, renewables developers, grid operators, civil society) and outlines supporting case studies.

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Introduction

The path to a net-zero global economy will require huge growth in clean energy technology deployment, with rapid scaling required of both clean energy supply and end-use decarbonisation technologies. Despite positive recent progress, including widespread legislated national commitments to net-zero by mid-century, and some ambitious sector targets,[1] several barriers limit the pace and scale of the transition. These include overall uncertainty about the pace of clean tech deployment in some markets, where government-backed incentives or market design play a key role, and issues around execution – including planning and permitting delays, lack of infrastructure availability (e.g., grids), and supply chain volatility. If unresolved, these barriers risk delaying and/or increasing the costs of the energy transition, putting a global net-zero emissions trajectory by mid-century at risk.

As part of the ETC's *Barriers to Clean Electrification* series, this Insights Briefing focuses on the issue of supply chain risks.[2] The importance of supply chain issues for the energy transition has recently come to the fore in light of the Covid-19 pandemic and Russia's war in Ukraine. In 2021–2022, as the global economy re-started following the pandemic prices for commodities and raw materials (e.g., steel, copper), and shipping and freight rates shot up, leading to cost increases for wind turbines and batteries.[3] Furthermore, these dynamics have served to catalyse a series of policy choices to relocate the production of clean energy technologies – such as the US Inflation Reduction Act, and the European Union's Green Deal Industrial Plan – adding further complexity and new dynamics. Building resilience and managing risks to reduce potential bottlenecks as much as possible is therefore critical.

This Insights Briefing addresses two main questions:

- **Where – and to what extent – could there be bottlenecks to clean energy supply chains, looking out to 2030?**
- **What are the key actions that policymakers and industry can take to mitigate these?**

The scope of this Briefing covers:

Six major 'backbone' technologies for energy sector decarbonisation:

- solar photovoltaics (PV)
- wind
- lithium-ion batteries (for electric vehicles, and storage)
- large-scale grids
- domestic heat pumps
- electrolysers

Three major steps across supply chains:

- mining and processing of raw materials
- manufacture and assembly of key components
- major transport and logistics inputs

We do not cover issues relating to construction and installation, or related workforce skill issues (which are highly localised), but forthcoming ETC work will address these issues as they relate specifically to the expansion of the electricity grid.

Three major risk areas across supply chains:

- market tightness (i.e. the ability of supply to meet demand to 2030 for key materials and components)
- environmental and social concerns
- concentration of production across countries or companies

This Insights Briefing is accompanied by an *EU Policy Toolkit*, which summarises the EU's position across clean energy supply chains and major policy priorities.

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1 For example, commitments to power sector decarbonisation in the US and the UK by 2035.

2 Other insights in this series include: ETC (2023), *Streamlining Planning and Permitting to Accelerate Wind and Solar Deployment*; *Material and Resource Needs for the Energy Transition* (forthcoming), and *Grids* (forthcoming).

3 BNEF (2022), *Lithium-Ion Battery Price Survey*; BNEF (2022), *2H Global Wind Market Outlook*; BNEF (2022), *2H Wind Turbine Price Index*.

Context: Importance of supply chains for the energy transition

1

The significant transformation across the energy system required over the coming decades means that clean energy technologies need to scale rapidly. Globally, installed capacity of wind and solar will need to grow between 2.5–4 times by 2030, and electric vehicle (EV) sales six-fold, under a net-zero scenario [Exhibit 1.1].

The energy transition is already underway – in 2022, wind and solar annual capacity additions grew 25% on the previous year, setting a new record for annual deployment (350 GW combined).[4] Overall, the economics of clean energy technologies are becoming increasingly attractive.[5] In power generation, wind and solar are now cheaper than new fossil in countries representing over 95% of electricity generation, and cheaper than existing fossil in countries representing 60% of electricity generation.[6] Across the world, many countries such as the UK and the US have set clear decarbonisation targets supported by appropriate policies and implementation mechanisms, such as large-scale government auctions for renewable electricity backed by long-term contracts.[7]

However, the pace and scale required for the transition raises a number of challenges. As clean energy technology deployment scales, strengthening supply chains will be critical to ensuring low costs and avoiding disruptions. These supply chains demonstrate varying degrees of complexity, intensity of material use, exposure to international trade, and footprints across different countries. But in almost all cases, the rapid growth in deployment needed will require a large mobilisation of capital, resources and coordination across multiple players.

Global economic and geopolitical volatility has already led to some disruption, making it clear that the costs

The energy transition will require massive capacity additions of new technologies, by 2030 wind and solar grow 2.5–4x and EV sales ~6x from current levels

Exhibit 1.1

	Wind	Solar	Storage and EVs	T&D Grids	Electrolysers	Heat Pumps
Capacity in 2022	940 GW	1240 GW	10m EV sales, 90 GWh of stationary storage	70 million km	~0.2 MtH_2	~200m units
	x 2.5	x 4	x 6	x 1.5	x 100	x 3
Required size in 2030	2400–2600 GW	4900–5100 GW	60–80m EV sales, 1500 GWh of stationary storage	>100 million km	>20 MtH_2	~600m units

Source: Systemiq analysis for the ETC; BNEF (2023), *Interactive data tool – Power capacity*; ETC (2021) *Making clean electrification possible*; ETC (2021) *Making the hydrogen economy possible*.

4 BNEF (2023), *Interactive Data Tool – Capacity & Generation*.

5 Systemiq (2023), *The Breakthrough Effect: How to Trigger a Cascade of Tipping Points to Accelerate the Net Zero Transition*.

6 BNEF (2022), *2H 2022 LCOE Update*.

7 UK Government (October 2021), *Plans unveiled to decarbonise UK power system by 2035*; US Government (April 2021), *President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies*.

and pace of the energy transition are at stake. While some of these patterns are now easing, recent volatility has led to short-term increases in the price of wind turbines and batteries [Exhibit 1.2]; though the cost of equivalent fossil-fuelled technologies in these sectors has also increased.[8]

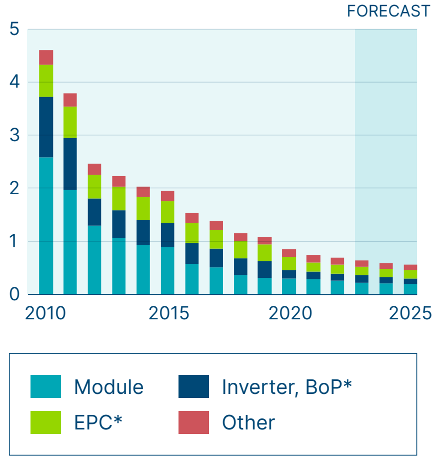
Supply chain shocks have the potential to derail the energy transition by increasing the costs of key technologies and, in worst-case scenarios, creating absolute shortages of key supplies; this in turn could slow down the pace of the overall transition.[9] As an example, a prolonged increase in the price of materials could significantly slow the pace of lithium-ion battery cost declines; given the importance of battery costs in total EV production costs (around 20–30%), this could lead to a later "cost parity" date between EV and Internal Combustion Engine (ICE) vehicles, pushing up consumer prices and slowing the uptake of EVs.[10]

Finally, it is interesting to note that the effects of supply chain "shocks" for clean energy technologies differ to those for fossil fuels. For current fossil use, the challenge around energy security requires ensuring the availability of fuel supply to keep the system running – avoiding queues at the pump, for example. Volatility and shocks to fossil fuel supply thus have strong, tangible impacts directly on consumers. Instead, for clean energy technologies, the current challenge is around barriers to building out the new low-carbon energy system at pace. A trend of increasing material prices would raise the cost of a new EV or a wind turbine, but it would not impact the ability or cost of current users to drive their EVs or power generation from wind turbines.

In recent years, disruption in global supply chains has led to price rises for wind and batteries

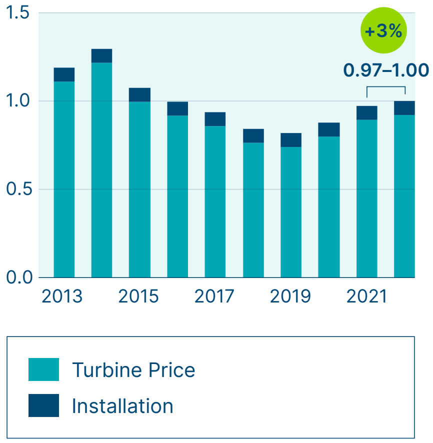
Exhibit 1.2

Solar PV capex benchmark
2022 $/W(DC)



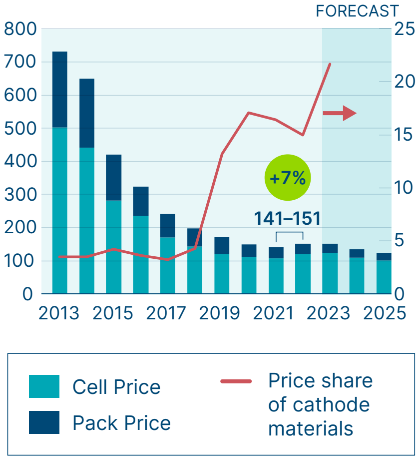
Solar: slowing of price reductions in 2022 due to tight supply for polysilicon and increased freight costs, alongside higher commodity prices, but expected to keep falling from 2023.

Wind turbine price by signing date
2022 $m/MW



Wind: cost increases driven by increasing prices of copper, aluminium and steel from 2020 onwards, alongside higher freight and shipping costs; however, **prices have been falling in China**.

Li-ion battery survey price
2022 $/kWh (LHS); % of total price (RHS)



Batteries: first-ever price rises in 2022 as prices of cathode materials (Li, Ni, Co) have risen sharply in past year; will take several years to recover to previous trend.

Note: *EPC = Engineering, procurement and construction. BoP = Balance of plant.

Source: BNEF (2022), *4Q Global PV Market Outlook*; BNEF (2022), *Lithium-Ion Battery Price Survey*; BNEF (2022), *1H Global Wind Market Outlook*; BNEF (2022), *1H Wind Turbine Price Index*.

8 E.g., LCOEs for gas turbines and coal rose by 19% and 9%, respectively, in the second half of 2022. BNEF (2022), *2H LCOE Update*.

9 Furthermore, supply chain risks could also lead to profitability concerns for major suppliers, therefore also contributing to bottlenecks. This issue is covered in Box A later in this Briefing.

10 Average battery pack prices rose by ~7% in 2022, driven by higher raw material costs. BNEF (2022), *Lithium-ion battery price survey*.

Current state

Today, clean energy supply chains are set within the context of an interdependent global economy, though with a large share of supply based predominantly in China, in particular for the production of mass-manufactured components and technologies (e.g., solar panels, batteries). China's leading role goes far beyond its sizable domestic needs and has been supported by a range of factors including: low manufacturing costs (including lower energy costs as well as – historically – labour costs), abundant supplier networks, significant domestic production of industrial materials, economies of scale, and clear domestic policy for clean energy sectors.[11] As with most global manufacturing around the world to date, particular stages in the production of clean energy technologies have been carbon intensive, although grid emissions intensities are declining or projected to decline by the end of this decade, including in China.[12]

Emerging dynamics

While the decade to 2020 saw a relatively stable economic environment within which several clean energy technologies experienced continual cost declines, several recent trends have combined to create a more challenging environment, in particular:

- The Covid-19 pandemic highlighted the fragility of global supply chains, as bottlenecks emerged in global trade due to shutdowns in key locations.
- Russia's invasion of Ukraine led to renewed focus on the issue of energy security, as Russia restrained gas exports to Europe, leading to a surge in energy prices.
- A major acceleration is now required in the pace of clean energy technology deployment to match the widespread adoption of net-zero emission targets.

This changing landscape is leading to new strategic priorities for countries and companies. Across the globe, a re-think is underway around how to reinforce both energy security and industrial competitiveness, in particular through the potential for "near-shoring" (and "friend-shoring"), defined as a transfer of business activity to within a domestic border. Several pieces of legislation stand out in this regard:

- In August 2022, the United States passed the Inflation Reduction Act (IRA), a historic bill for climate legislation which will allocate at least $369 billion in incentives for clean energy, and also includes many provisions for domestic production across multiple clean energy technology supply chains.[13] The IRA is part of a wider policy package, which together provides federal and state spending of nearly approximately $1 trillion over the next decade.[14]
- In response, the EU has set out a strategy to support its own domestic production; the recently announced Green Industrial Deal Plan, of which the Net Zero Industry Act (NZIA) is part, sets targets for increasing domestic supply across raw materials and clean energy technologies, along with supporting measures.[15] Currently, there is existing EU support for clean energy technology manufacturing in place (e.g., via EU Innovation Fund and European Investment Bank loans), which some estimate is broadly in line with IRA-level spending on manufacturing support; however, EU-level support remains fragmented across a number of instruments.[16] EU funding and policy approaches are discussed in more detail in the accompanying *EU Policy Toolkit*.
- India has also set out provisions across its trade and domestic manufacturing policy, which include Production Linked Incentive schemes to boost domestic manufacturing for EVs and solar PV modules, as well as import tariffs on solar modules manufactured in China.[17]

However, the growing global clean energy system means this is not a "zero-sum game", as this Insights Briefing will discuss further on. It is critical that national strategies for supply chains continue to foster stability at the global level, essential for a smooth transition. The final chapter of this Insights Briefing outlines key considerations for policymakers and industry that reflect both a set of beneficial actions at the global level for supply chains, as well as some considerations for domestic priorities.

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11 IEA (2023), *Energy Technology Perspectives*.

12 For example, the high carbon intensity of polysilicon production. See e.g., IEA (2022), *Special report on solar PV global supply chains*.

13 Bipartisan Policy Center (2022), *Inflation reduction act summary: Energy and climate provisions*.

14 Other packages include the IRA New Loan and Loan Guarantee Authority, the Infrastructure Investment and Jobs Act, and the CHIPS & Science Act. Kaya Advisory/Inevitable Policy Response (2022), *The US discovers its climate policy: A holistic assessment and implications*.

15 EU Commission (2023), *The green deal industrial plan: Putting Europe's net-zero industry in the lead*.

16 Bruegel (2023), *How Europe should answer the US Inflation Reduction Act*.

17 Note that there are also approved manufacturer lists and local content requirements – but these have been temporarily suspended. S&P Global (2022), *India's solar power prospects compromised by steep import duty, commodity hikes*; Indian Ministry of Heavy Industries (2022); PV Magazine (2022), *Indian government approves second phase of solar manufacturing incentive scheme*.

Mapping clean energy supply chains and assessing risks

2

This chapter provides a mapping of supply chains across selected key clean energy technologies and presents an overview of the key risks that could emerge across this landscape until 2030. It will cover in turn:

- A framework for assessing risks across supply chains.
- An overview of the supply chain structure and risk assessment for each technology.

Framework for assessing supply chain risks

The analysis in this report is based around three key dimensions for supply chain risks, all of which could lead to higher prices, shortages for key inputs, or delays in manufacturing and deployment.

1. **The risk of market tightness, resulting from an imbalance between supply and demand.**
2. **Environmental and social concerns.**
3. **The high concentration of production across geographies/companies.**

Across these dimensions, the analysis considers whether the risk is primarily a short-term phenomenon, likely to be disruptive in the next 1–3 years, or whether it could be a more sustained longer-term pressure point out to 2030. The analysis also specifically excludes supply chain risks arising from trade tensions,[18] which are often in themselves responses to perceived risks around high concentration of production.

1. Risk of market tightness

The issue of market tightness – or the inability of supply to keep pace with growing demand – can be present at different supply chain stages, from materials, to manufactured components, to transport markets. Three factors determine the severity of risk:

- **Demand:** What is the outlook for demand to 2030? Can material/component inputs be easily substituted in response to high prices or shortages? Can material intensity be reduced? Is the material/component used widely across energy transition technologies or the broader economy?
- **Supply:** What is the outlook to 2030? Are there any barriers to scaling up supply at pace, in terms of mines, factories for components, equipment, or transport inputs (e.g., vessels)? Have there been upward revisions to recent supply outlooks? Is there any evidence of the market showing long lags or unresponsiveness to price signals?
- **Timing:** How long are market imbalances expected to last for? Are these likely to be short-lived phenomena which are part of global supply chain volatility for any market, or are they likely to be protracted crunches over several years?

In turn, there are several features of supply chains which shape the ability of the market to respond more quickly or more slowly:

- **Lead times:** There is significant variation across lead times across stages of supply chains. Broadly, mining is the most supply-inelastic area, with timescales for new large-scale mining projects ranging between 5–20 years, depending on the material type and project location.[19] Lead times for building new factories for components and transport inputs are generally lower, under 5 years [Exhibit 2.1]. There may be scope to accelerate such timescales, and discussions in both the US and the EU may lead to provisions to speed up the planning and permitting of strategic projects – but this is still somewhat uncertain.[20]
- **Complexity of supply chains:** Within the component space, there is also significant variation across the complexity and barriers to entry for different supply chains, which will depend on factors such as a higher

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18 For example, the likelihood of one particular country introducing measures such as tariffs, export quotas or bans for materials, components or products.

19 IEA (2021), *The role of critical minerals in clean energy technologies*.

20 BNEF (2023), *Europe's Bid to Reshore Clean Tech Pulls its Punches*; Brookings (2023), *How to reform federal permitting to accelerate clean energy infrastructure*.

number of subcomponents, greater specialisation and specificity for components and transport inputs, and higher regulatory specificity (e.g., different efficiency standards for heat pumps across different geographies).[21] Broadly, across the technologies in the scope of this report, there are two different levels of complexity:

- **Lower complexity, mass-produced products**, such as solar PV modules and lithium-ion battery cells.
- **More complex products**, such as wind turbines, where specifications can be more tailored to specific needs and locations, and where the transport and logistics is more complex given the need to transport very large components; for example, some larger wind turbine components can no longer be transported via rail.[22]

2. Environmental and social concerns

Clean energy technology supply chains can be associated with several environmental and social impacts, including lifecycle carbon emissions, local environmental impacts, and incidences of child and forced labour, and low paid and/or artisan mining.

If not addressed, these could prevent mining and manufacturing from scaling as rapidly as is required. Key considerations to assess the level of risk include:

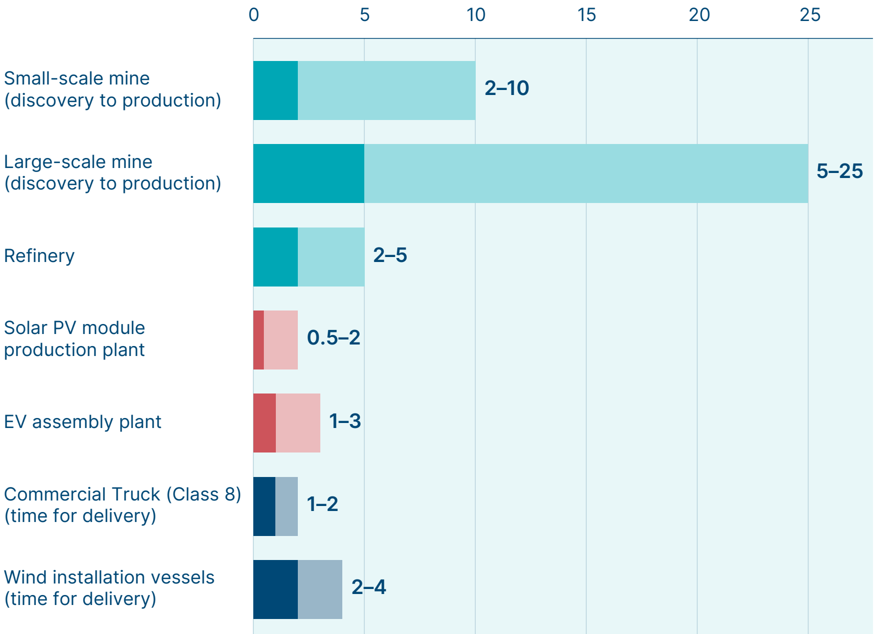
- **Carbon:** What are the embedded carbon emissions of production across materials, components, transport steps, and the final product? This can be best assessed using a lifecycle emissions intensity which compares to the technology it is displacing.[23]
- **Local pollution, nature, and biodiversity:** Is there significant local air or water pollution, tailings production, and how well are these managed in different locations? What are the requirements for natural resources (e.g., water), and does the land footprint of development have a significant impact on nature/biodiversity?
- **Human rights and social concerns:** Are there any concerns around the use of child labour, or forced low paid labour? Are the impacts on local communities being managed appropriately?

Many of these impacts are concentrated at the mining stage and the ETC is planning on addressing these in detail in an upcoming report on *Material and Resource Needs for the Energy Transition*.

Timescales for mining projects are longer than for manufacturing and transport

Exhibit 2.1

Average observed lead time for selected supply chain steps
Years (Min–Max)



Mining

Typical mine lead times range from 4–7 years for lithium or smaller-scale projects, but can be as high as 15–20 for large nickel and copper mines. Brownfield expansions can also be much faster.

Building new refining capacity is faster than new mines.

Manufacturing

Factory lead times depend on the components but are typically less than 5 years.

Transport and logistics

Typical lead times to build new transport inputs vary but are very short, except for shipping.

Source: IEA (2021), *The role of critical minerals in clean energy transitions*; IEA (2023), *Energy technology perspectives*; Petavratzi and Gunn (2022), *Decarbonising the automotive sector: a primary raw material perspective on targets and timescales.*

[21] Malhotra and Schmidt (2020), *Accelerating low-carbon innovation*.

[22] US DoE (2022), *Wind Energy Supply Chain Deep Dive Assessment*.

[23] See e.g., IEA (2023), *Energy technology perspectives*; PowerShift (2023), *Metals for the energy transition.*

3. High concentration of production across geographies/companies

The final risk dimension is whether there is excessive concentration of production at any stage in a specific geography, or across a small number of companies (e.g., a monopoly or oligopoly market structure). Key considerations for this risk include:

- **Single point of failure:** Is there a significant concentration of production in a single mine site, factory, country, or company that could lead to outsized disruption if there was a highly localised shock?
- **Market concentration in a small group of companies:** Is there a significantly high concentration of production in a limited number of companies that could lead to distortion on pricing?
- **Market concentration in one or a small group of countries:** From a global perspective, diversified supply chains are likely to be more resilient in the face of disruptive global geopolitical developments. High levels of concentration (e.g., around 75% or above of production) in one or few countries is assessed as a risk. However, these risks are balanced against considerations of energy security. What is defined as an "excessive" level of concentration will depend on a specific country perspective.

Critically, one dimension that is not considered a risk is a diversified base of producers whose ownership is concentrated within a small number of countries, within reasonable limits (e.g., a majority of battery manufacturers are headquartered in Asia but have operations globally). From a risk assessment perspective, as long as the location of production is diversified, concentrated ownership from a single country or small group of countries is unlikely to pose any major issues – so long as this position is not an overwhelming proportion of the overall market.

Box A **Profitability across clean energy supply chains**

Recently, there have also been concerns over the profitability of some manufacturers in clean energy sectors, for example in the European wind industry.[1] Supply chain dynamics can play a role in driving profitability concerns – for example, higher commodity prices in 2022 have lowered the margins of wind turbine manufacturers, unable to pass on higher costs to developers based on current contracts [Exhibit 2.2]. However, overall profitability depends on a wider number of factors, including revenue models and market design, market size, time taken from contract to payment, and the complexity of the product (e.g., a mass-produced product with lower barriers to entry could lead to lower margins).

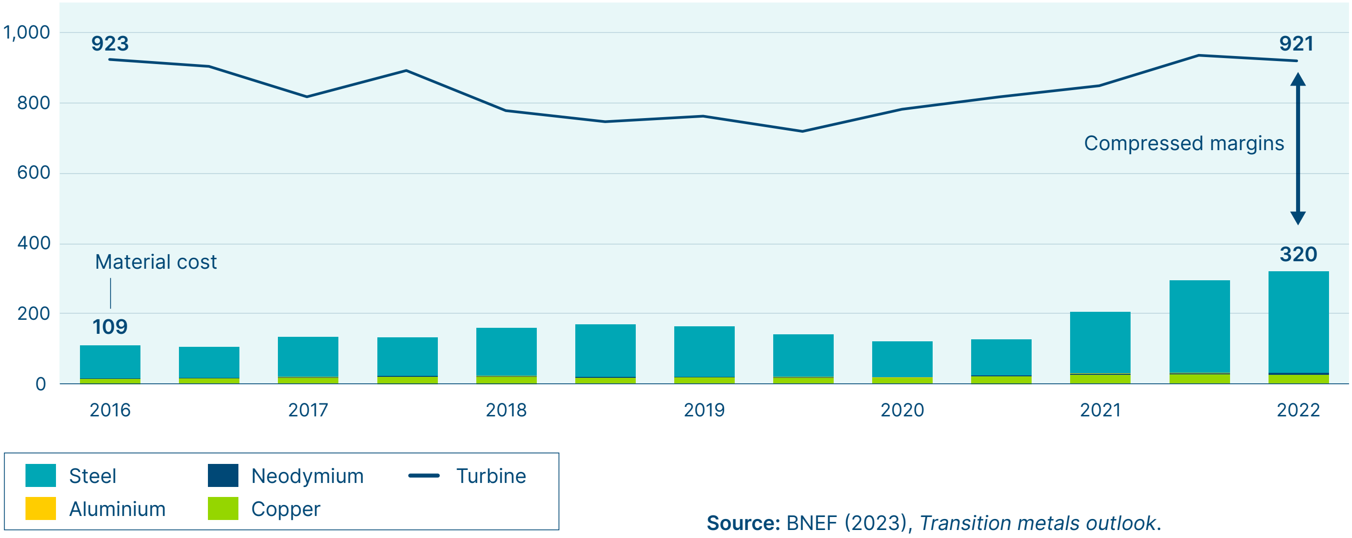
Concerns over profitability could also potentially impact supply chain stability in themselves if they were to lead to bankruptcies of major suppliers in this sector. Overall, this issue is a more complex risk and a systematic assessment of profitability prospects across clean energy supply chain players is outside the scope of this report.

[1] Financial Times (January 2023), *Europe's wind industry flags further weakness in 2023 despite energy demand.*

High exposure to commodity prices has helped drive up wind turbine prices in past few years and hit profitability

Exhibit 2.2

Metal and total wind turbine price
Thousand $/MW



Source: BNEF (2023), *Transition metals outlook.*

Mapping and risk assessment across technologies

Exhibit 2.3 presents an overview of supply chain structures across six key technologies and highlights trends that could influence the shape of these supply chains to 2030, including the composition of raw materials, components, and transport needs. The following sections cover conclusions from risk assessments across each technology.

Sources:

Solar PV: IRENA (2021), *Critical minerals for the energy transition*; IEA (2021), *The role of critical minerals in clean energy transitions*; Fraunhofer ISE (2022), *Photovoltaics Report*; BNEF (2023), *Transition metals outlook*; Hallam et al. (2022), *The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050*; IEA (2022), *Special report on solar PV global supply chains*; BNEF (2023), *1Q Global PV market outlook*; US DoE (2022), *Solar photovoltaics supply chain deep dive assessment*.

Wind: US DoE (2022), *Wind Energy Supply Chain Deep Dive Assessment*; BNEF (2021), *Wind Trade and Manufacturing: A Deep Dive*; BNEF (2022), *2H Wind turbine price index*; BNEF (2023), *Offshore wind expansion under threat from vessel shortage*; BNEF (2020), *35 MW Wind turbines to lower material demand*; BNEF (2023), *Transition metals outlook*.

Batteries: BNEF (2022), *Long-term electric vehicle outlook*; BNEF (2022), *Lithium-ion battery price survey*; BNEF (2023), *Sodium-ion batteries make inroads in passenger cars*; McKinsey & Co. (2022), *Lithium mining: How new production technologies could fuel the global EV revolution*; US DoE (2022), *Energy storage supply chains deep dive assessment*; He et al. (2021), *Considering critical factors of silicon/graphite anode materials for practical high-energy lithium-ion battery applications*; Nat Bullard (2023), *Decarbonization: The long view, trends and transience, net zero*.

Grids: BNEF (2023), *New energy outlook: Grids*; BNEF (2020), *Copper and Aluminium Compete to Build the Future Power Grid*; BNEF (2021), *Power grid long-term outlook*; US DoE (2022), *Electric grid supply chain review*; BEIS/National HVDC Centre (2021), *HVDC supply chain overview*; Alassi et al. (2019), *HVDC Transmission: Technology review, market trends and future outlook*.

Heat pumps: IEA (2022), *The Future of Heat Pumps*; BEIS (2020), *Heat Pump Manufacturing Supply Chain Research Project*.

Electrolysers: BNEF (2022), *Global electrolyzer outlook 2030*; BNEF (2022), *Electrolysis system CAPEX by 2050 – updated forecast*; EPO and IRENA (2022), *Patent insight report. Innovation trends in electrolysers for hydrogen production*; ITM-Power (2021), *Green Hydrogen: An Electrolyser Manufacturers Perspective*; Bristowe, G.; Smallbone, A. (2021), *The Key Techno-Economic and Manufacturing Drivers for Reducing the Cost of Power-to-Gas and a Hydrogen-Enabled Energy System*; Vattenfall (2022), *Vattenfall aims to build the world's first offshore hydrogen cluster in the Netherlands*.

Supply Chains Mapping Overview

Exhibit 2.3

	Major Raw Materials (Mined or Processed)		Major Components (Manufacturing)	Transport and Logistics	Final Product
Solar PV	• Steel • Aluminium • Glass • Copper • Quartz > metallurgical grade silicon (MGS)	• Silver • Polysilicon > Ingot • Ethylene vinyl acetate (EVA) • Fluorinated polymers (PVF, PVDF)	• Wafer • Cell • PV Module • Installation system: inverter and mounting system	• International shipping • Local trucking • Local mounting and installation	**Solar plant/ rooftop solar**

Major trends: Solar PV modules are designed to be highly mass-manufactured and can be easily stacked, trucked and shipped. Around half of all solar PV modules manufactured in 2021 were traded between countries.

Continuing efficiency increases at ~2% p.a., with absolute module efficiencies expected to reach 25% by 2030, drive continuous decreases in materials content per GW of solar capacity at wafer and module level, e.g., steel content expected to fall ~15% by 2030, silicon ~20%. Specific innovation to drive down both silicon usage and silver demand from solar is also taking place, helping reduce demand further.

Thin-film technologies likely to make up only <5% of solar PV market to 2030 – therefore any material supply issues for thin-film (e.g., tellurium, cadmium, indium) unlikely to significantly impact market.

	Major Raw Materials (Mined or Processed)		Major Components (Manufacturing)	Transport and Logistics	Final Product
Wind	• Concrete • Steel • Iron (cast) • Glass/carbon composites • Copper • Zinc	• Aluminium • Chromium • Manganese • Nickel • Rare Earth Elements (e.g., neodymium, dysprosium)	• Foundation • Tower • Rotor and Blades • Nacelle: Generator, Gearbox, Bearings, Semiconductors	• Rail • Truck • Foundation Installation Vessels (FIV); Wind Turbine Installation Vessels (WTIV); Cable Laying Vessels (CLV) • Heavy cranes	**Wind turbine / power plant**

Major trends: Overall trend towards larger wind turbines (particularly for offshore) is helping manufacturers drive down materials content for every MWh generated, but making manufacturing requirements more complex (e.g., some current factories no longer able to produce at these larger specifications), and changing logistics requirements (e.g., some transport by water, road/rail not possible, and with specific vessels and cranes).

Technologies for wind turbine rotation (e.g., gearboxes generators and direct-drive generators) exist that use fewer permanent magnets with REE but trend is not pushing in this direction.

Declining copper and aluminium usage in onshore wind turbines, but reverse trend in offshore as wind farms are located further away from shore and make use of higher-voltage transmission lines, driving up copper requirements.

	Major Raw Materials (Mined or Processed)		Major Components (Manufacturing)	Transport and Logistics	Final Product
Batteries	• Copper • Lithium • Graphite • Nickel • Cobalt • Manganese • Aluminium • Steel	• Lithium carbonate/ hydroxide • Nickel sulphate • Cobalt sulphate • Manganese sulphate • Electrolyte • Polyolefins	• Cell > Module > Pack: Cathode active materials, Anode active materials, Electrolyte, Separator, Casing • Battery management system: Electronics/ semiconductors, Sensors	• International shipping	**Battery with management system**

Major trends: Batteries are designed to be highly mass-manufactured and are typically produced close to electric vehicle assembly factories.

Battery chemistry choices and development key determinant of materials:

- Low-cobalt nickel-manganese-cobalt (NMC) batteries > reduces demand for cobalt, increases demand for nickel.
- Lithium-iron-phosphate (LFP) batteries > reduces demand for nickel and cobalt, increases demand for lithium.
- Development of sodium-ion batteries (commercially competitive by late 2020s) > reduces demand for lithium.
- Substitution of graphite with silicon > increases battery energy density and reduces demand for graphite.

Continuing battery energy density and packing efficiency improvements through to 2030 (reaching ~250 Wh/kg) help drive continuous decreases in materials needed to achieve a given vehicle range, driving down material content for EVs.*

Notes: *This can be achieved through a mix of battery cathode and anode chemistries, reduced voltage losses, or improving the packing efficiency of cells within a pack. BNEF estimate that battery energy density at the pack level doubled from 87 Wh/kg to 166 Wh/kg between 2010–20, and could reach over 240 Wh/kg by the end of this decade. CATL have recently announced a semi-solid state battery capable of reaching an energy density up to 500 Wh/kg – see PV Magazine (2023), *CATL launches 500 Wh/kg condensed matter battery*.

Supply Chains Mapping Overview

Exhibit 2.3

Grids

Major Raw Materials (Mined or Processed)

- Bauxite
- Copper
- Iron ore
- Lead
- Metal alloys: bronze, stainless steel, zinc
- Wood
- Aluminium
- Steel
- Concrete
- Polymers

Major Components (Manufacturing)

- Power lines: Conductors, Towers for transmission lines, poles for distribution lines, Insulators
- Substations: Transformers, Switchgears, Circuit breakers, Capacitor banks, Bus bars

Transport and Logistics

- Subsea Installation Vessels
- Truck
- Rail
- Heavy cranes

Final Product

Low/high voltage power lines; Distribution substations

Major trends: Grid supply chains are characterised by relative ease of global transport – substation equipment is easily stacked and transported; cables are easily wound into reels or drums. However, there is potentially constrained supply of subsea installation vessels for cabling (there are only seven in the world).

Aluminium and copper are substitutable in overhead lines (aluminium often favoured because lower cost and weight for same conductivity), but copper is better suited for underground and submarine lines due to higher intrinsic conductivity, higher strength, and better thermal resistance.

Technology evolution pointing to different impacts for materials intensity:

- Greater undergrounding and offshoring of power lines will result in an increase in average material intensity, due to needs for greater thickness for higher temperatures, and protective layers.
- Materials intensity may be mitigated by replacements of HVAC by HVDC lines (AC needs three conductors, DC two).
- Increased use of residential solar and storage could reduce overall pace and scale of grid expansion required.

Heat Pumps

Major Raw Materials (Mined or Processed)

- Steel
- Copper
- Nickel
- Aluminium
- Polymers
- Refrigerant
- Lubricating oil

Major Components (Manufacturing)

- Pump and/or fan
- Heat exchangers (evaporator, condenser)
- Compressor
- Expansive valve
- Wiring and chips
- Insulation
- Pipework
- Housing

Transport and Logistics

- International shipping
- Local trucking

Final Product

Heat pump

Major trends: Heat pumps can be easily mass-manufactured (similar to air-conditioning units) and currently have a lower level of international trade, due to the need to adapt to local laws with specifications on recycling, efficiency, voltage etc., as well as need for careful handling to avoid refrigerant leakage.

Some variation among material needs for different types of residential heat pumps, such as the most common type, air-source heat pumps (ASHPs) (over 80% of current market), and ground source heat pumps (GSHPs). ASHP require slightly more steel and copper than GSHPs, but less polymers and cement mortar for underground closed loop systems.

Natural refrigerants (e.g., propane, CO_2, ammonia) could replace synthetic working fluids with higher GWP intensity (F-gases).

Electrolysers

Major Raw Materials (Mined or Processed)

- Steel
- Nickel/Titanium
- Copper
- Aluminium
- Zirconium
- Graphite
- Platinum group metals (PGM)
- Polymers

Major Components (Manufacturing)

- Electrolyser stack: Cathode, Anode, Electrolytes, Separator, Membrane, Bipolar plates, Frames and sealing
- Other system components

Transport and Logistics

- International shipping
- Rail
- Truck

Final Product

Electrolytic H_2 plant

Major trends: Current electrolysers are modular and easily stackable, no issues for global trade. Plans for offshore electrolysers (e.g., by Vattenfall) would need to be manufactured for offshore use, transportable in containers.

Variation among material needs for Alkaline and Proton exchange membrane (PEM) technology (alkaline is ~80% of the market). Alkaline requires nickel, zirconium; PEM requires PGM titanium.

Ongoing innovation to reduce and adapt materials requirements:

- Development of hybrid anion exchange membrane (AEM) electrolysers without PGM and with higher performance than alkaline.
- Development of Solid Oxide Electrolyzers, requiring no copper, graphite, polymers, titanium or PGM, less nickel and more zirconium, scandium and yttrium. Might gain ~5% market share by 2030.

Solar

Solar PV supply chains are characterised by strong demand for four key materials (silicon, aluminium, copper, and silver), and a highly competitive manufacturing value chain with significant Chinese production at all stages. The current manufacturing pipeline could be sufficient to produce up to 1 TW of solar by 2030.[24] Solar panels are easily traded globally, with large volumes of imports from China to Europe and India, while the US mainly imports from other Southeast Asian countries, following a ban on Chinese imports.[25]

The following section presents conclusions from the risk assessment for solar across the three main dimensions:

1. **There could be possible market tightness across key materials (copper, silver), but the manufacture of solar components should be able to scale rapidly.**

There could be pressure leading to **high prices for silver** (as solar demand is >10% of the market, and this could increase as solar deployment rises rapidly) as well as **copper.**[26] The potential for high copper prices is discussed in more detail in the next chapter, as it affects all clean energy technologies.

Polysilicon shortages are not a concern. Supply of polysilicon (the high-purity version of silicon used in solar PV) has experienced two major boom-bust cycles in the past fifteen years, impacting the cost of solar PV modules.[27] The most recent price cycle, where prices rose five-fold between early 2021 to year-end 2022, led to a subsequent rapid expansion in polysilicon production capacity and an ensuing fall in prices throughout early 2023.[28] Although such price cycles have lead to a short-term slowing of price declines for solar PV modules, they have tended not to disrupt long-term cost declines [Exhibit 2.4].[29]

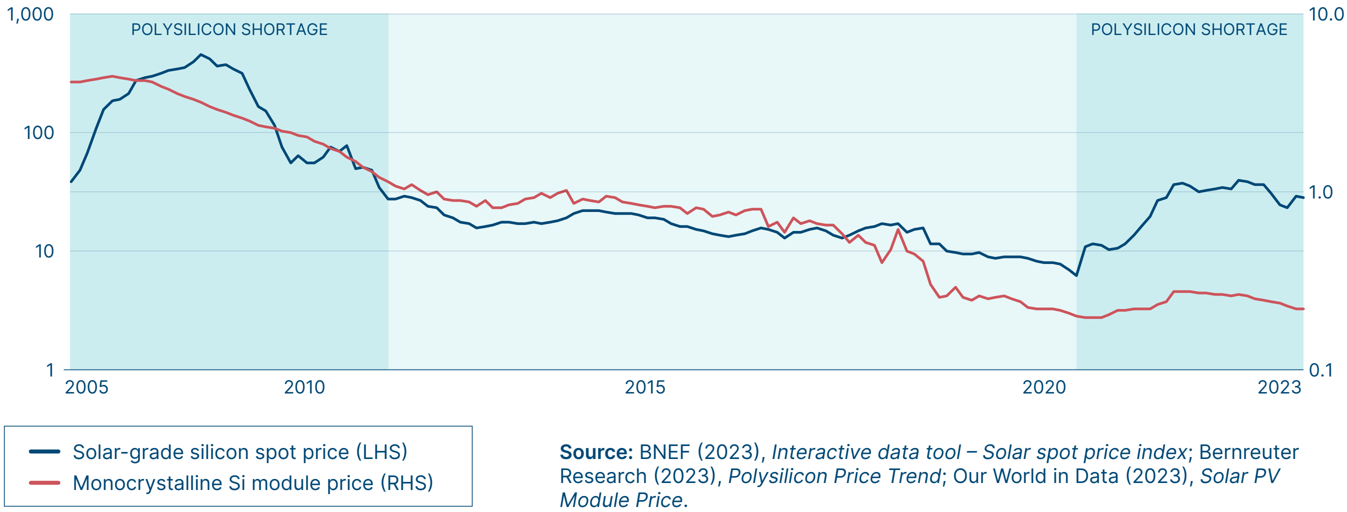
A key component of solar panels are the encapsulant and backsheet layers of a module, which rely on ethylene vinyl acetate (EVA) and fluorinated polymers such as Polyvinyl fluoride (PVF) or Polyvinylidene fluoride (PVDF).[30] Though there is **no shortage of these materials**, high natural gas prices (which lead to higher input costs) together with rapidly rising demand from solar could lead to **high prices** for both sets of materials – but these only make up a small fraction of overall solar module costs.[31]

Although **shipping and freight costs** rose sharply in 2021–22, these have now fallen back to pre-pandemic prices. Future blockages are also likely to **be short-term trends**, rather than longer term disruption.

Although polysilicon shortages lead to short-term price cycles, solar module prices keep falling regardless

Exhibit 2.4

Solar-grade silicon spot price (LHS); Solar module price (RHS)
LHS = $/kg, log scale; RHS = $/W, log scale



Source: BNEF (2023), *Interactive data tool – Solar spot price index*; Bernreuter Research (2023), *Polysilicon Price Trend*; Our World in Data (2023), *Solar PV Module Price*.

24 IEA (2023), *The state of clean technology manufacturing.*

25 IEA (2022), *Solar PV global supply chains*.

26 Hallam et al. (2022), *The silver learning curve for photovoltaics and projected silver demand for net-zero emissions by 2050*.

27 See e.g., Bernreuter Research (2023), *Polysilicon price trend*.

28 BNEF (2023), *1Q Global PV market outlook*.

29 BNEF (2022), *4Q Global PV market outlook*.

30 PVF and PVDF are polymers with high resilience which have a complex value chain, starting from fluorspar mining and hydrofluoric acid production. See e.g., ThunderSaidEnergy (2022), *Solar: capacity growth through 2030 and 2050?*

31 ThunderSaidEnergy (2022), *Ethylene vinyl acetate: Production costs?*; ThunderSaidEnergy (2022), *Solar: capacity growth through 2030 and 2050?*

2. **Environmental and social concerns are severe across the solar supply chain, particularly in relation to polysilicon.**

Polysilicon production in Xinjiang makes up around 30% of total supply, where there is currently very heavy use **of coal power**, leading to high life-cycle emissions for the production of solar PV modules (although rapid renewables deployment should decrease this in coming years).[32] Further, there have been allegations of the use of **forced labour and human rights abuses** in both the supply of coal power and the production of polysilicon in this region.[33] This issue is discussed in more detail in Chapter 3.

3. **The solar supply chain is highly geographically concentrated.**

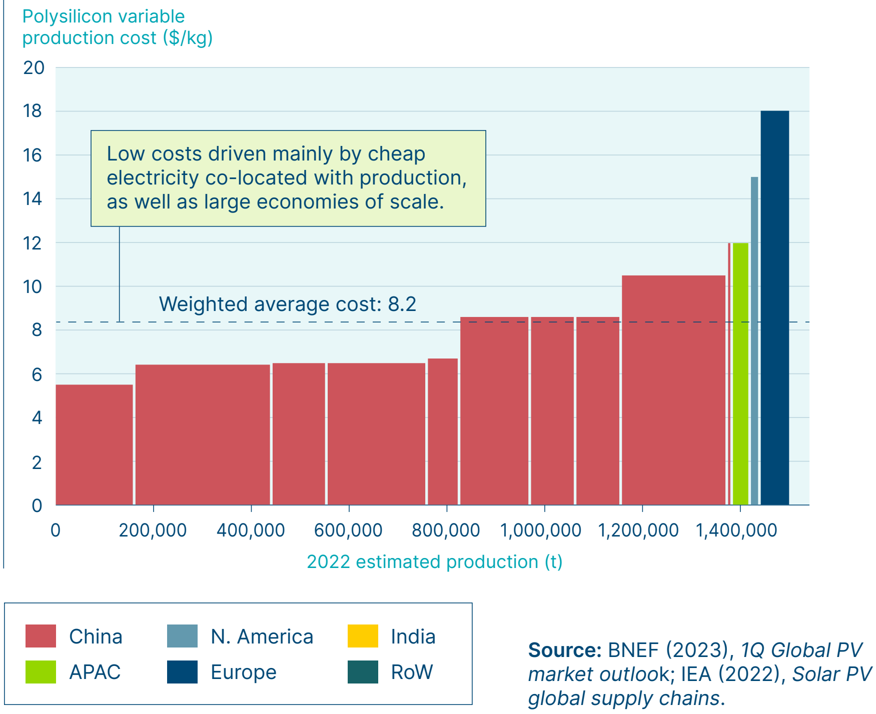
The solar supply chain is highly concentrated in China, from polysilicon production through to module assembly. The current wafer-to-module value chain is very highly concentrated in China, with over 70% of 2021 manufacturing capacity for wafers, cells and modules [Exhibit 2.5].[34] The past five years have seen some diversification to the rest of Southeast Asia, with increased production in Malaysia, Vietnam, and Thailand, but together these make up less than 10% of the market and are focused only on the simplest production stage of module assembly. Although a large fraction of Chinese production is to meet domestic demand,[35] the very high levels of concentration could be a cause for concern if trade tensions arise in coming years or if production comes under strain in key regions.[36]

From a company perspective, the manufacturing capacity of solar modules is quite diversified, with strong levels of competition throughout most of the value chain; the top-five module manufacturers controlled around 45% of total commissioned capacity in 2022.[37]

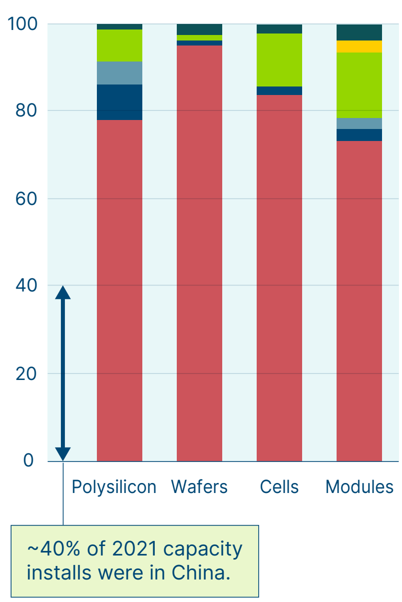
Thanks to higher economies of scale and lower costs, China has progressively grown its share in the PV module supply chain

Exhibit 2.5

Polysilicon: cost competitiveness of global manufacturing plants
Y axis: polysilicon variable production cost ($/kg); X axis: 2022 estimated production (t)



PV supply chain: share of global manufacturing capacity by geography and supply chain step
Share of global solar PV manufacturing capacity, 2021, %



Source: BNEF (2023), *1Q Global PV market outlook*; IEA (2022), *Solar PV global supply chains*.

32 IEA (2022), *Solar PV global supply chains*.

33 The Breakthrough Institute (2022), *Sins of a solar empire*; Murphy & Elimä/Sheffield Hallam University (2021), *In broad daylight*.

34 IEA (2022), *Solar PV global supply chains*.

35 Chinese domestic installations were approximately 70 GW in 2021, compared to approximately 180 GW of installations and 350 GW of manufacturing capacity. IEA (2023), *Energy technology perspectives*.

36 For example, in 2022 factory fires in Xinjiang, and droughts throughout Sichuan, both led to temporary decreases in production. See e.g., PV Magazine (2022), *China polysilicon producer shuts down factory due to fire*; Bloomberg (2022), *Power crunch in Sichuan adds to industry's woes in China*.

37 BNEF (2023), *Interactive data tool – Solar equipment manufacturers*.

Wind

Wind supply chains are characterised by strong demand for steel and aluminium, and a need for rare earth elements in permanent magnets. Crucial components are turbine blades and the nacelle, which houses the gearbox and generator. The production of wind turbines is fairly distributed geographically; for example, both European and Chinese domestic capacity is sufficient to meet their respective domestic demand.[38]

1. **Shorter-term periods of price volatility are more likely (as the global wind industry is current experiencing), driven by high exposure to commodity price volatility and a supply chain increasingly characterised by higher complexity components.**

Over 90% of total material mass for turbines is steel, where there are no availability or supply concerns,[39] though it can drive a large fraction of total costs and are exposed to commodity price volatility. The spike in steel prices throughout 2021–22 has contributed to a rise in input material costs for wind turbines and tighter margins for manufacturers [Box A].

Demand for rare earth elements from turbines is also expected to grow sharply, raising some scope for supply risks. Most wind turbines need significant amounts of neodymium (as well as dysprosium and praseodymium), with the highest demand arising in permanent magnet-based wind turbines – these materials are used in high-performance magnets that convert the rotation of turbine blades into electricity.[40] There is potential to shift to less rare earth-intensive turbine designs,[41] but other factors (e.g., performance) typically dominate design choice. Supply of rare earths from China can expand rapidly in response to high prices, and there is also new supply expected in Myanmar and the USA.[42]

Specialised wind turbines and vessels could be a bottleneck to offshore wind growth in the coming decade. The growing size of offshore wind turbines is causing fleet operators to hold back investing in new vessels, as they wait for certainty around what size and type will be required. BNEF currently expect shortages of foundation installation vessels from 2027 onwards, whereas there should be enough turbine installation vessels through to 2030.[43] This could hold back approximately 10 GW of installations in China by 2030, and approximately 25 GW across the rest of the world, equal to around 15% of expected offshore wind installations by 2030.[44]

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38 BNEF (2023), *Wind Data Hub*.

39 For example, wind power currently makes up approximately 1% of global steel demand and is expected to rise to 5–6% at most over coming decades. BNEF (2023), *Transition metals outlook*.

40 EU Commission Joint Research Centre (2020), *The role of rare earth elements in wind energy and electric mobility*.

41 For example, by using synchronous generators or induction-based generators. See e.g., IEA (2021), *The role of critical minerals in clean energy transitions*.

42 IEA (2023), *Energy technology perspectives*.

43 BNEF (2023), *Offshore wind expansion under threat from vessel shortage*; see also H-BLIX/Wind Europe/Polish Wind Energy Association (2022), *Offshore wind vessel availability until 2030: Baltic sea and Polish perspective*.

44 Ibid.

2. **Environmental and social concerns are low for wind power.**

Even though wind turbines use large amounts of concrete and steel, life-cycle emissions for wind power are very low (<5 gCO_2e/kWh),[45] with large power output of individual turbines, long operating lifetimes (>25 years), and rising capacity factors leading to very short carbon payback timescales.

Environmental concerns are mainly linked to the mining of rare earth elements. This was historically poorly regulated in China, and is linked to production of toxic waste and local air pollution,[46] but environmental standards in China have improved in recent years following tighter government regulation.[47]

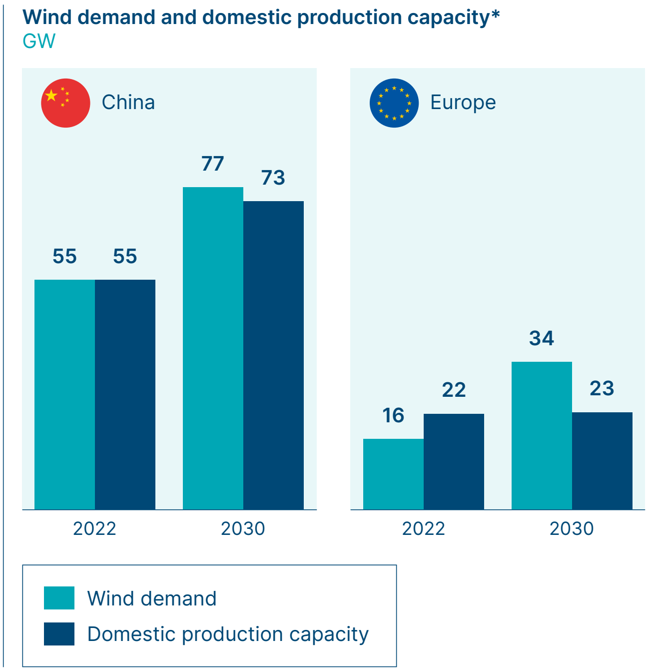
3. **Rare earth supply chains are highly concentrated in China, and while wind component manufacturing is diversified, all recent growth has been in China.**

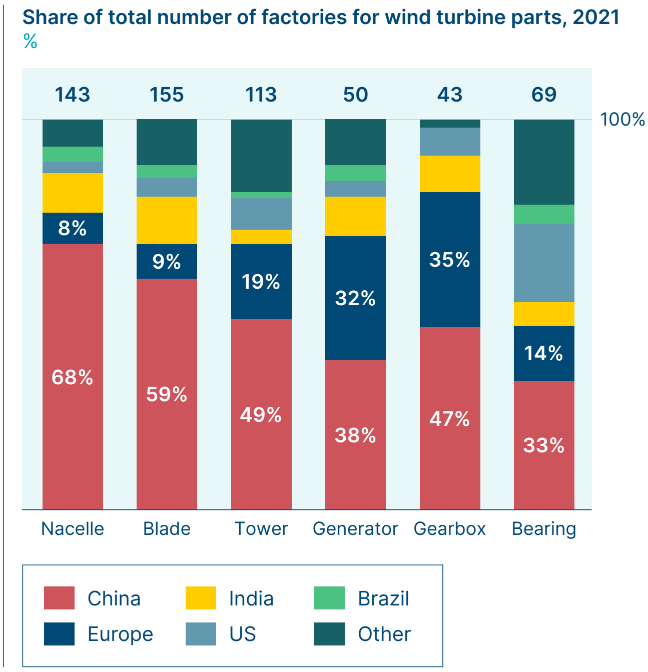
Mining and refining of rare earth elements is highly concentrated in China. China accounts for around 60% of the world's rare earth mining, 90% percent of rare earth processing, and 95% of high-strength rare earth permanent magnet production.[48]

Turbine production capacity in China and Europe is sufficient to meet domestic demand over coming years [Exhibit 2.6]. However, much of future manufacturing capacity is being built in China. According to BNEF, all new investment and announced investment in 2021 and 2022 for wind turbines came from the Asia-Pacific region.[49]

Wind turbine manufacturing tends to be regionally distributed, with Europe and China able to meet current domestic demand, but some concentration exists for key components

Exhibit 2.6





Note: *2030 capacity additions are taken from BNEF's short-term forecast; manufacturing capacity is taken from BNEF (2023), *Interactive data tool – Wind turbine market shares*, and is assumed to remain constant from 2025–30.

Source: BNEF (2023), *Interactive data tool – Wind turbine market shares*; BNEF (2021), *Wind Trade and Manufacturing: A Deep Dive.*

[45] UNECE (2021), *Lifecycle assessment of electricity generation options*; Pehl et al. (2017), *Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling*.

[46] See e.g., Ali (2014), *Social and environmental impact of the rare earth industries*; BBC Future/Tim Maughan (2015), *The dystopian lake filled by the world's tech lust*.

[47] Shen et al. (2020), *China's public policies toward rare earths, 1975–2018*.

[48] IEA (2023), *Energy technology perspectives*; Wood Mackenzie (2022), *Can the rest of the world repel China's magnetic pull over rare earth metals?*

[49] BNEF (2023), *Europe's Bid to Reshore Clean Tech Pulls its Punches*.

Batteries

Most future demand for batteries will come from electric vehicles, with a much smaller segment from stationary energy storage [Exhibit 2.7]. Batteries vary widely in terms of chemistries, with most currently relying on five key raw materials: lithium, graphite, nickel, cobalt, and manganese.[50] EVs also have high requirements for copper and rare earth elements, as well as semiconductor chips. Current battery manufacturing is concentrated in China, with EV assembly spread across China, the USA, and Europe.

Batteries face three significant challenges to scaling rapidly, alongside a range of more minor, specific risks:

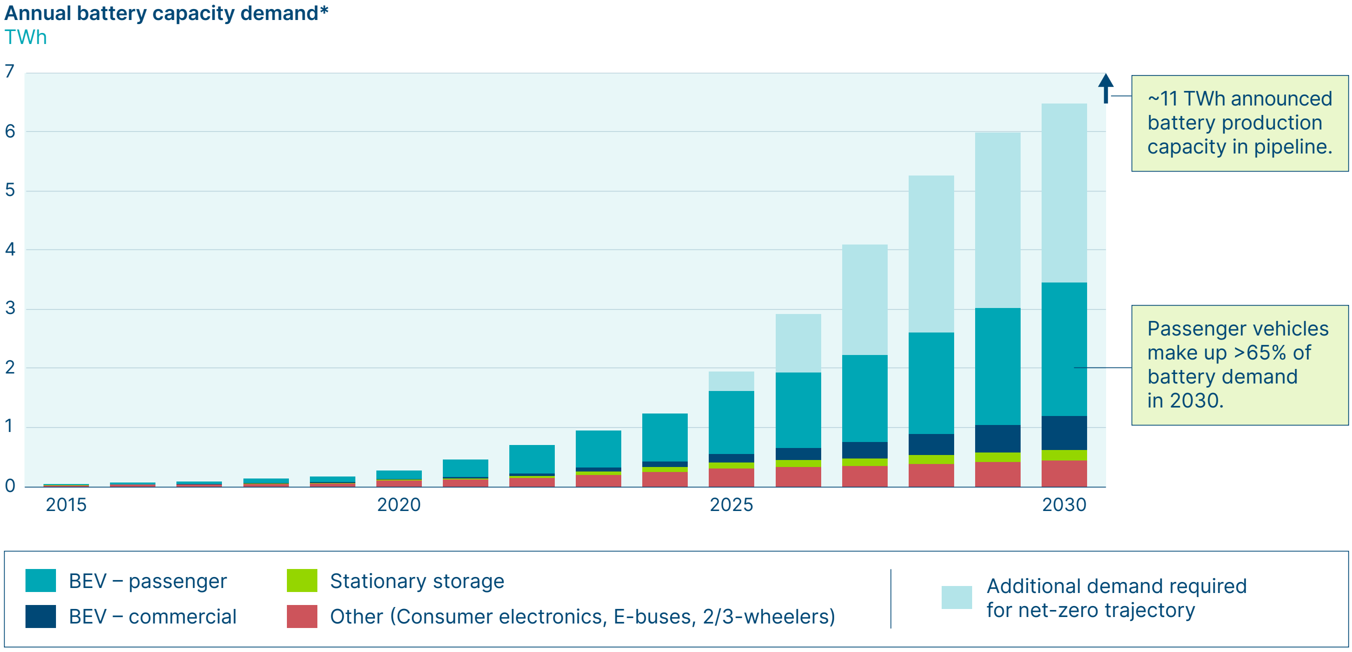
1. **Price spikes due to tight markets could be an issue for some key battery materials, although innovation is a driver in reducing requirements for some minerals; there are few concerns around scaling battery manufacturing.**

Mining: The lithium market could be tight through to 2030 – there may be shortages of high-purity refined nickel, but cobalt demand should not be a problem. Supply of both nickel and cobalt has expanded rapidly in the past few years, although supply of high-purity class 1 nickel could still be a blockage.[51] The rapid shift to low-cobalt NMC and cobalt- and nickel-free LFP batteries is reducing the scale of the challenge, especially for cobalt [Exhibit 2.8].[52] However, the risk of lithium shortages is high: demand is difficult to substitute (sodium-ion batteries will likely only have a significant market share post-2030, and even then may likely be limited to smaller vehicles) and supply needs to expand even more quickly than current pipelines suggest [see also detailed discussion in Chapter 3, and Exhibit 3.3].

Components: Expanding cathode material production at pace could prove challenging. Significant capacity expansions are planned: the IEA estimate around 14 Mt per annum of cathode production in 2030, and BNEF estimate a total pipeline of up to 24 Mt of announced projects – well in excess of potential demand of 10–12

Demand for batteries will grow ten-fold to 2030, driven by adoption of passenger battery electric vehicles, though this remains below net-zero trajectory

Exhibit 2.7



Note: *Demand forecast is for BNEF's Economic Transition Scenario, which is driven by techno-economics and current market trends.

Source: Systemiq analysis for the ETC; BNEF (2022), *Long-term electric vehicle outlook*; Benchmark Mineral Intelligence (2022), *Lithium ion battery gigafactory assessment – November*.

50 The scope of this analysis focuses on lithium-ion batteries as the dominant technology for clean energy (e.g., in EVs and stationary storage).

51 BNEF (2022), *2H Battery metals outlook*.

52 NMC = Nickel-Manganese-Cobalt; LFP = Lithium-Iron-Phosphate.

Mt in 2030.[53] However, new projects could be delayed due to the high complexity of engineering, production, procurement and construction, coupled with potential bottlenecks for key equipment such as kilns. These delays are most likely in Europe and North America, where a rapid expansion in capacity is planned over coming years, starting from a low base.

Manufacturing: There are very few concerns around scaling battery assembly. Announcements of planned production capacity for 2030 add up to over 10 TWh, which is well in excess of demand implied even by a net-zero pathway.[54] A significant proportion of this capacity may not be built, as some battery companies fail to gain EV manufacturer supply nominations and, as a result, cannot attract finance. However, given the intensity of competition, the need for EV manufacturers to secure supply, and the scale of public subsidies available, it is unlikely that battery production capacity will be a serious constraint on EV supply.

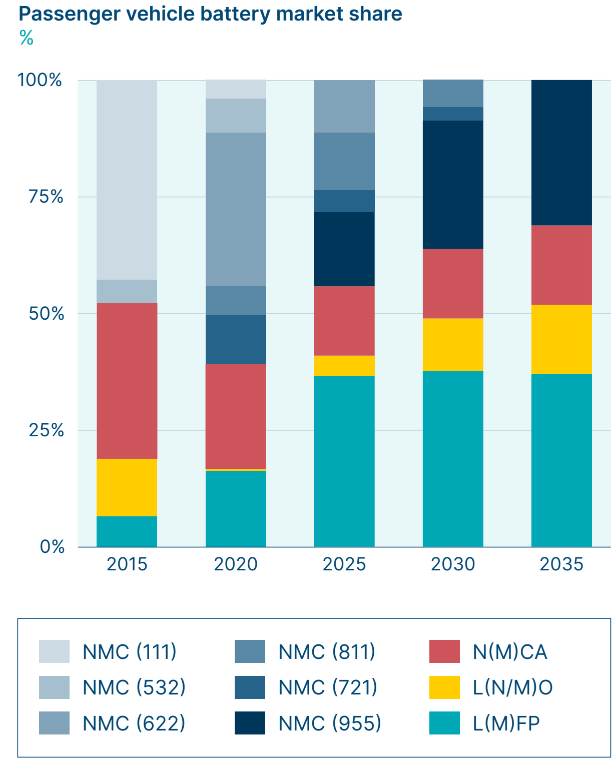
2. **Mining of battery materials has some environmental and social risks – but these are being addressed by manufacturers throughout the supply chain.**

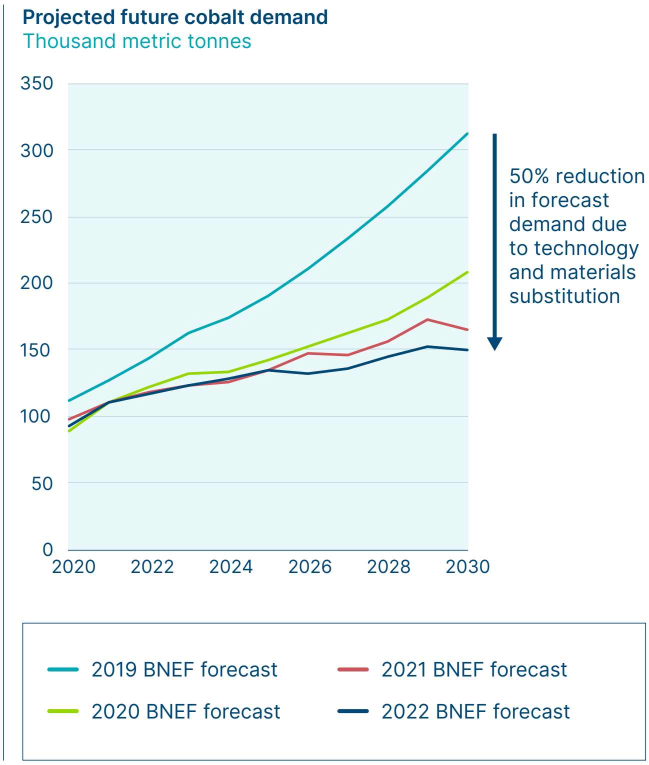
Each material has a particular set of challenges, including water use (for lithium), carbon intensity (lithium and nickel), and links to human rights abuses and child labour (cobalt). This is discussed in more detail in Chapter 3.

There are also **concerns around embodied carbon emissions** further down the supply chain, as the refining of materials into key precursors (e.g., lithium carbonate) often requires significant energy inputs and high temperatures above 800ºC, leading to high emissions in coal-intensive grids. Manufacturing of batteries is also currently emissions-intensive, partly due to heavy coal use in Chinese power grid.

Li-ion battery industry is shifting rapidly to lower cobalt and lower nickel chemistries, driving down demand projections

Exhibit 2.8





Note: N = Nickel, M = Manganese, C = Cobalt, F = Iron, P = Phosphate, O = Oxygen, A = Aluminium.

Source: BNEF (2022), *Long-term electric vehicle outlook.*

53 10–12 Mt assumes roughly 1.5 kg of cathode material per kWh of battery capacity, based on a maximum battery demand of ~7 TWh in 2030. See IEA (2023), *Energy technology perspectives*; BNEF (2023), *Interactive data tool – Equipment manufacturers*.

54 Benchmark Mineral Intelligence (2022), *Lithium ion battery gigafactory assessment – November*; BNEF (2023) *Interactive data tool – Battery cell manufacturers*.

It should be noted that electric vehicles already have lower life-cycle emissions than combustion vehicles, even when using emissions-intensive batteries and grids.[55] There is the potential to decarbonise production throughout the supply chain in coming decades, both from electrified high-temperature heat (for refining), and the decarbonisation of the power grid (for battery manufacturing). This is already occurring – including in China – but must happen faster. There is a clear opportunity for the coming generation of refining and manufacturing to set high standards for environmental and social performance whilst meeting growing demand.[56]

3. High concentration of supply chain in China across all stages.

There are risks around the concentration of raw material supply and processing: the mining of cobalt (70% DRC), nickel (45% Indonesia), lithium (50% Australia, 26% Chile) is heavily concentrated.[57] The same is true at the refining stage, where China dominates the supply of refined and processed forms of these materials.[58] Whilst the distribution of reserves is somewhat physically constrained due to resource endowments, there is a larger opportunity to re-balance the location of refining operations, for example as incentivised by recent policy announcements in the US and Europe.

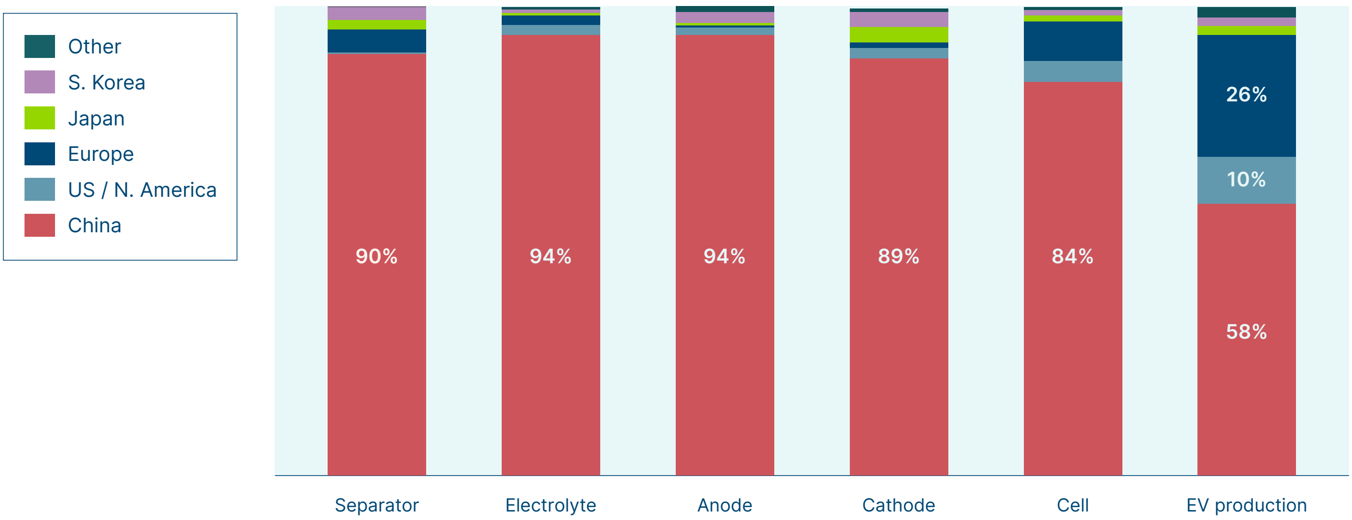
Furthermore, the downstream supply chain is also highly concentrated in China, which produces over 80% of the market for anodes, cathodes, electrolytes and battery cells [Exhibit 2.9].[59] Even though a large fraction of this production is to meet growing domestic demand, such a high level of concentration leaves individual companies and countries exposed to sole-supplier risks, and could lead to supply blockages if trade tensions worsen. It is worth noting that manufacturing of innovative cathode chemistries with lower critical metal requirements (notably, LFP and Na-ion) is currently almost entirely in China – meaning shifting production of these new technologies to the US or Europe could be even more challenging.[60]

Similar to the case for solar PV, there is **intense competition across companies** in the battery supply chain. The largest battery manufacturer is CATL, which controls around 18% of current global manufacturing capacity, and the ten largest manufacturers have around 60% of the total.[61]

China holds major share across EV supply chain

Exhibit 2.9

Country market share of production stage, 2022
%



Source: BNEF (2022), *Localizing clean energy supply chains comes at a cost*; BNEF (2023), *Interactive data tool.*

55 See e.g., Ricardo Energy (2020), *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*.

56 See e.g., Minviro (2021), *Shifting the lens*.

57 USGS (2023), *Mineral commodity summaries*.

58 IEA (2022), *Global supply chains of EV batteries*; IEA (2023), *Energy technology perspectives*.

59 BNEF (2023), *Interactive data tool – Battery equipment manufacturers*.

60 There are currently only two LFP cathode manufacturers in N. America, and one in Europe – BNEF (2023), *Interactive data tool – Battery equipment manufacturers*.

61 BNEF (2023), *Interactive data tool – Battery equipment manufacturers*.

Grids

Grid supply chains are characterised by high material needs for copper and aluminium, globally competitive markets for components, and relative ease of global transport.[62] Overall, grid supply chains are not expected to face any major impediments to scaling, though there could be a higher risk of bottlenecks in some specialised areas.

1. Some market tightness risks exist due to copper requirements and the need to rapidly scale more specialised components.

There could be constraints in copper supply; however, this is substitutable in overhead lines. For the more common overhead power lines (representing 70–80% of new power line additions to 2050[63]), aluminium has been favoured given its lower cost and lower weight for the same level of conductivity. For underground and submarine cables, which are growing in share, other properties of copper – higher intrinsic conductivity, higher strength, and better thermal resistance – make copper better suited.[64] The potential for high prices of copper is discussed in more detail in the next section.

The supply of large-scale transformers and subsea high-voltage cabling could slow down the expansion of power grids.

- High-power, large-scale transformers are seeing longer lead times and rising costs, especially in the United States – to the extent that these were included in the Defense Production Act passed by President Biden in 2022 to spur production of key technologies.[65] Manufacturing of this component requires labour-intensive specialised design, with a single unit costing at least $4 million, and a surge in demand is expected – in the United States, many of these units are operating past their technical deadlines.[66]
- For high-voltage subsea cabling, challenges arise both in the production of the cables, and low numbers of subsea cable installation vessels (there are only seven in the world).[67]

2. There are some concerns around the use of fluorinated gases (F-gases) in grid infrastructure, but regulation is already pushing for reduced use.

F-gases are widely used as insulation throughout the grid system, including in transformers, substations and switchgear. However, F-gases have a very strong impact as greenhouse gases if they leak.[68] Innovation is ongoing to develop equipment with lower-GWP gases,[69] and regulation is also being introduced to help the phase-out of F-gases.

3. There is some level of concentration across production of key grid equipment, but not at the level of other clean energy technologies.

Across conductors and transformers, China, Central and Eastern Europe, and Mexico are net exporters of key grid equipment, while Western Europe and North America are dependent on imports.[70]

As mentioned in the introduction, while out of scope for this report, there are important potential skill constraints in electricity grid expansion, which will be assessed in detail in our forthcoming work on issues relating to transmission and distribution grid development.

62 The scope of "grids" for this analysis covers major physical infrastructure for transmission and distribution infrastructure, including power lines (overhead/underground/submarine; low-voltage to high-voltage), mounting structures (towers and poles), and substations (e.g., transformers, switchgears, etc). Microgrids are excluded from this analysis.

63 BNEF (2021), *Power grid long-term outlook*.

64 BNEF (2021), *Copper and aluminium compete to build the future power grid*.

65 US DoE (2022), *Electric grid supply chain review*; T&D World (2022), *Transformative times: Update on the US transformer supply chain*; E&E News (2022), *How a transformer shortage threatens the grid*.

66 E&E News (2022), *How a transformer shortage threatens the grid*.

67 US DoE (2022), *Electric grid supply chain review*; BEIS/National HVDC Centre (2021), *HVDC supply chain overview*; Alassi et al. (2019), *HVDC Transmission: Technology review, market trends and future outlook*.

68 For example, SF_6 has a global warming potential (GWP) around 23,000 times higher than carbon dioxide. US Environmental Protection Agency (2022), *Sulfur Hexafluoride (SF6) Basics*.

69 See e.g., Schneider Electric (2020), *Schneider Electric wins industrial energy efficiency award at Hannover Messe for SF6-free medium voltage switchgear*; Siemens Energy (2023), *The path to zero: F-gas-free power transmission*.

70 OEC (Accessed February 2023), *Electric conductors, nes <80 volts, with connectors*; OEC (Accessed February 2023), *Electrical transformers*.

Heat Pumps

Heat pump supply chains are characterised by a common manufacturing base with the air conditioning industry, and a highly regional market where most heat pumps are produced locally (though by global companies). Indeed, many heat pump units are sold as "reversible heat pumps", capable of delivering both heating and air-conditioning needs.

Overall, heat pump supply chains are assessed as lower risk than other clean energy technologies.

1. **There are no inherent barriers from a materials perspective or to scaling new manufacturing capacity – though the latter will have to expand rapidly to meet growing demand. Any bottlenecks that could emerge around component manufacturing are likely to be short-lived.**

Overall, a diversified and competitive market across Tier 1 and Tier 2 manufacturers is well positioned to respond to market demand signals. Given the synergies with the air conditioning industry, there are larger manufacturers (e.g., Daikin, Mitsubishi, Midea) who can produce at scale, and repurposing of production lines can increase heat pump manufacturing in the short-term. It is important to note, however, that the market for compressors (a critical input to all heat pump/AC units) is limited to fewer, more specialised producers.[71] In the short-term, there could be some temporary bottlenecks around heat pump component manufacturing, including due to requirements for specialist kit suppliers.

There is some challenge around evolving regulations on permitted refrigerants (especially F-gases), although companies are already developing the next generation of refrigerants to meet requirements. There is an increasing regulatory drive against the use of fluorinated gases (F-gases) as refrigerants in heat pumps due to their very high global warming potential. Alternative gases such as carbon dioxide or propane are an option, with heat pump manufacturers already adapting, although there are some technical and cost challenges – and regulatory certainty is required for them to be able to plan ahead sufficiently for these.[72]

2. **The major environmental concern regarding heat pumps is their current use of fluorinated gases for refrigeration, which are a class of gases with very high global warming potential.**

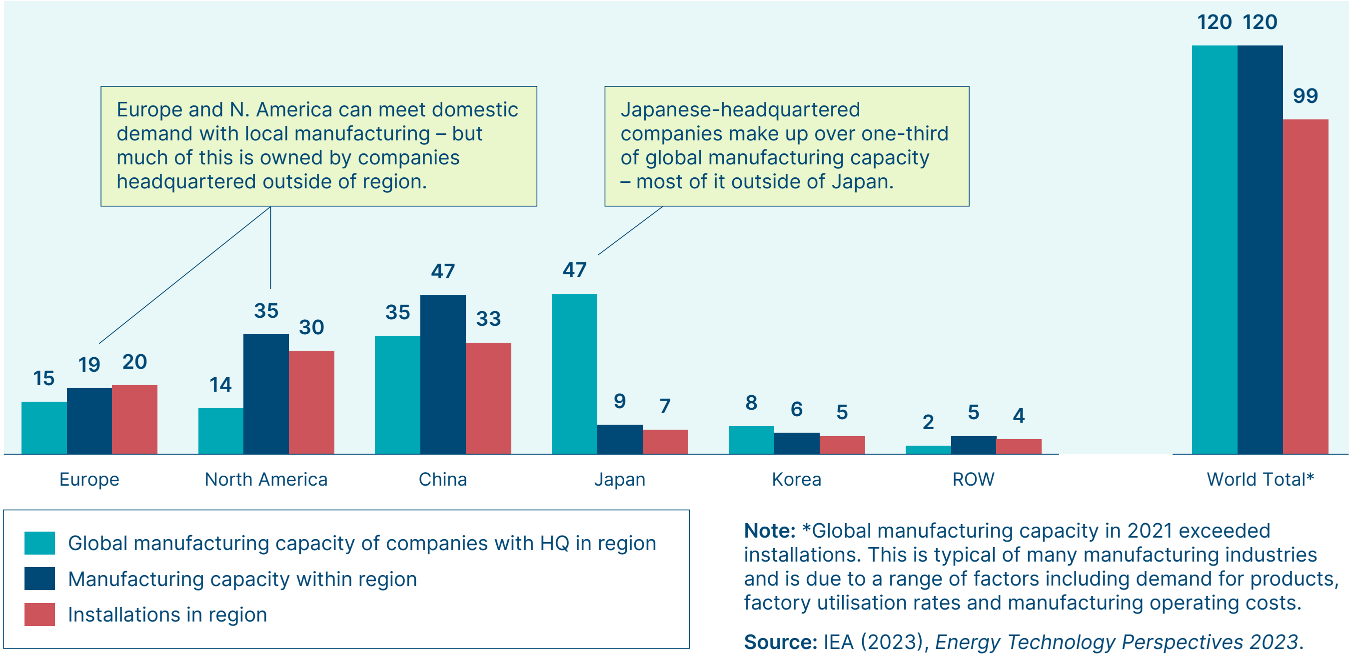
Leakage of refrigerants can contribute up to 40% of life-cycle emissions associated with heat pumps,[73] which has prompted a strong regulatory push to rule out use of high-GWP F-gases.

3. **There are no concerns over market concentration for heat pumps, given the diversified manufacturing base across countries relative to current demand, as highlighted in Exhibit 2.10.**

Heat pumps are not widely traded – regional manufacturing capacity is sufficient to meet supply across the world

Exhibit 2.10

Heat pump manufacturing capacity by company HQs and plant location, and installations, by region, 2021
Thermal GW



Note: *Global manufacturing capacity in 2021 exceeded installations. This is typical of many manufacturing industries and is due to a range of factors including demand for products, factory utilisation rates and manufacturing operating costs.

Source: IEA (2023), *Energy Technology Perspectives 2023*.

[71] For example, Danfoss, Bitzer or Emerson Copeland. BEIS (2020), *Heat Pump Manufacturing Supply Chain Research Project*.

[72] IEA (2022), *The future of heat pumps*.

[73] Ibid.

While out of scope for this report, a key challenge around building heat pumps at scale are the skills and labour required to carry out high volumes of installations, especially at residential level [Box B].

Box B **Developing the skilled workforce to enable heat pump deployment**

The rapid deployment of heat pumps, as well as accompanying efficiency measures (such as insulation, which enables heat pump adoption), will require major growth in a skilled technical workforce, in particular given the dispersed nature of the residential market. Employment in the heat pump industry spans several dimensions including installation (about half the total global heat pump workforce) and operations and maintenance. Given the need to scale from a small base, rapid growth in the number of installers is required [Exhibit 2.11]. Meeting REPowerEU targets, for example, would require the number of installers in the EU to grow from around 40,000 in 2019 to 110,000 in 2030.[1] The UK Climate Change Committee cites estimates that to decarbonise residential heating in the UK, around 200,000 new full-time jobs will be needed by 2030, with the vast majority in heat pump installation.[2]

Lead times for training skilled workers in these occupations (either via new entrants or reskilling, e.g., from boiler installers) can take multiple years, as they require obtaining specific certifications, in particular due to the need to handle refrigerants. However, if re-training of plumbing and heating engineers is an option, this can in some cases be very fast – on the order of days, rather than years.[3]

Other specialisation points include being able to conduct property assessments, calculation of heat losses to design the installation, and updating parts of the existing heating system and electrical wiring.[4]

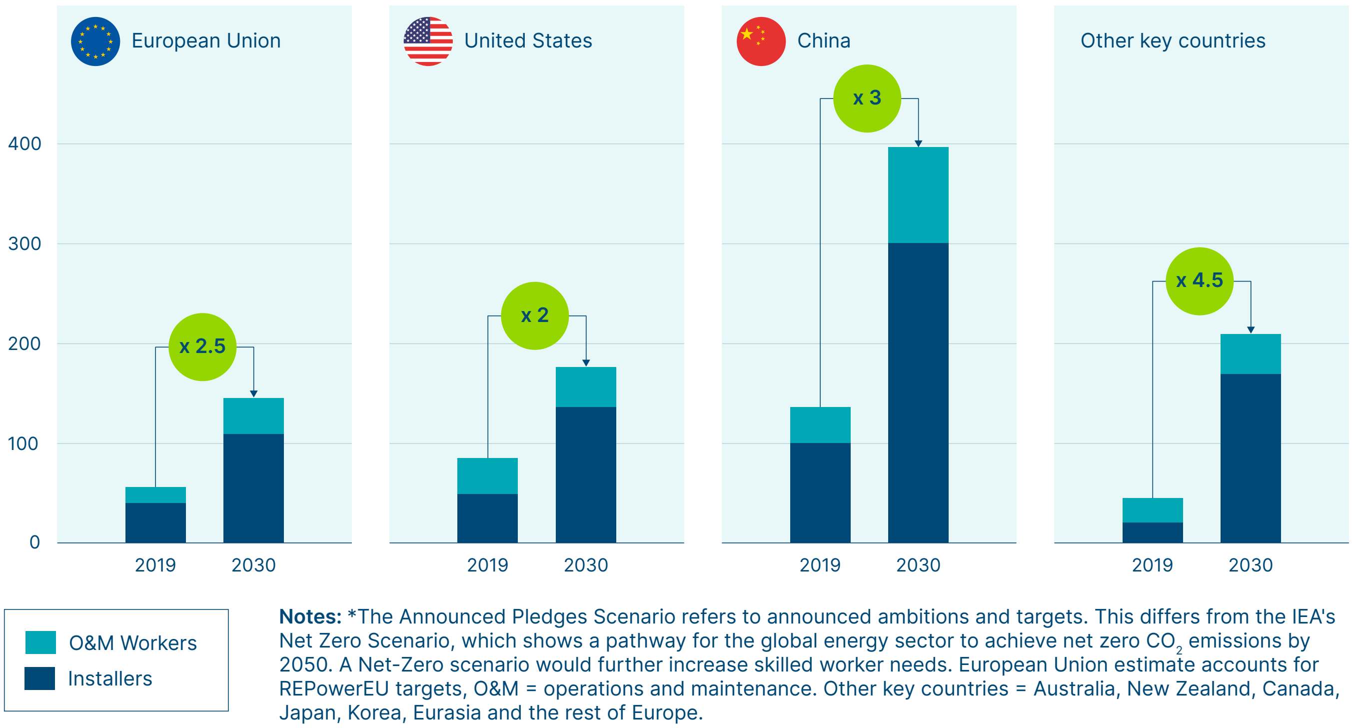
The EU is currently already facing a shortage of workers in occupations related to heat pump installations, such as plumbers, pipefitters, air-conditioning and refrigeration mechanisms, and electricians.[5] Unless clear signals are set about the net-zero trajectory and heat pump deployment – and therefore future work opportunities – workers may be dissuaded from pursuing lengthy and onerous certification schemes.

[1] IEA (2022), *The Future of Heat Pumps*;
[2] UK Climate Change Committee, *Independent Assessment: The UK's Heat and Buildings Strategy*;
[3] Ecuity/West of England Combined Authority (2021), *Retrofit skills market analysis*;
[4] IEA (2022), *The Future of Heat Pumps*;
[5] IEA analysis based on ELA (2021).

Even under IEA's Announced Pledges Scenario*, heat pump installers will need to grow by 3.5 times across key geographies

Exhibit 2.11

Employment in heat pumps by region/country in APS, 2019 and 2030
Thousand employees



Notes: *The Announced Pledges Scenario refers to announced ambitions and targets. This differs from the IEA's Net Zero Scenario, which shows a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. A Net-Zero scenario would further increase skilled worker needs. European Union estimate accounts for REPowerEU targets, O&M = operations and maintenance. Other key countries = Australia, New Zealand, Canada, Japan, Korea, Eurasia and the rest of Europe.

Source: IEA (2022), *Future of Heat Pumps*.

Electrolysers

Electrolyser supply chains are characterised by differing requirements for the two major technologies: Alkaline and PEM (Proton Exchange Membrane) electrolysers. Alkaline electrolyser stacks require nickel and zirconium as key materials, while PEM electrolyser stacks require platinum group metals (PGMs, especially iridium, palladium, platinum and ruthenium) and titanium.

Compared with other clean energy technologies, electrolysers are at a much earlier stage of development, which means that supply chains will need to grow even more rapidly from their current base [Exhibit 2.12]. Risk considerations across the three dimensions are:

1. **Technology choice between PEM and Alkaline will determine demand pathways for materials and components, but no major barriers are expected on either side as innovation can reduce material needs. While the electrolyser market is at very early stages, announced manufacturing capacity has been growing rapidly.**

There are some potential supply challenges for rapidly increasing demand for **nickel** (Alkaline) and **platinum group metals** (PEM).

- On nickel, however, demand from electrolysers is much lower than from batteries, and less high purity nickel is required, easing potential supply concerns.
- For PGMs, although demand might rise rapidly, total volumes will be much lower than current demand from ICE catalytic convertors.[74] Furthermore, the market share out to 2030 is likely to be dominated by **Alkaline** electrolysers, making up ~80% of current market [Exhibit 2.12], easing the pace of demand growth – and in parallel, rapid **innovation is taking place to reduce PGM intensity** of PEM electrolysers.[75]

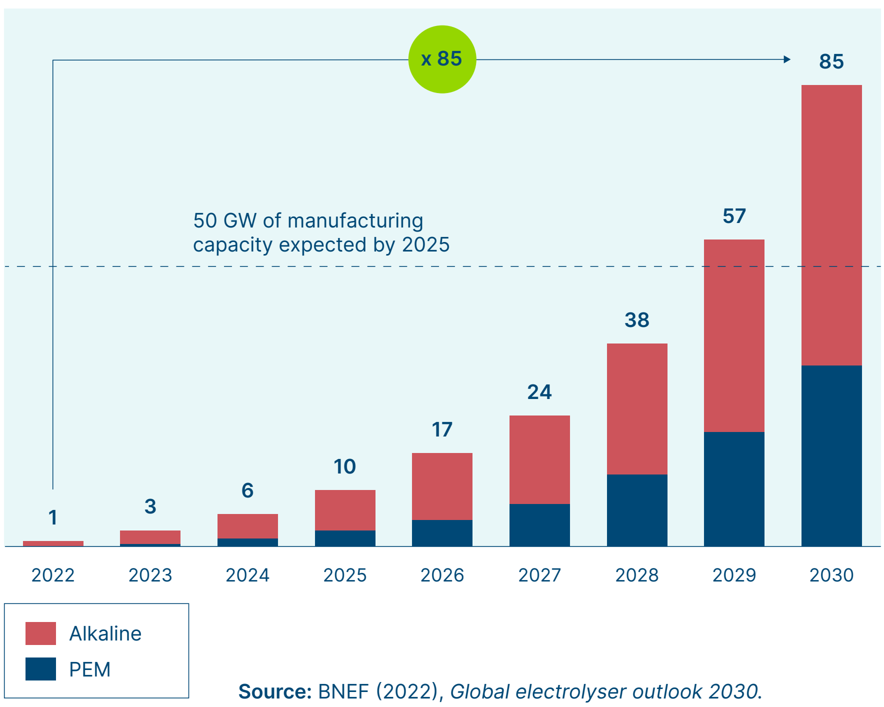
For total manufacturing capacity, **the extremely rapid pace of potential demand and supply growth for green hydrogen make it difficult to judge how the balance between supply and demand will evolve**:

- Until 2022, well below one million tonnes (Mt) of hydrogen per annum was produced via electrolysis (out of about 95 Mt per annum total production) and electrolyser production has, until recently, been a small-scale business characterised by unautomated processes and high costs.[76] By 2050, ETC estimates suggest that total global hydrogen demand could

Electrolyser market is small but growing rapidly – manufacturing capacity isn't a concern but PEM vs. Alkaline trade-offs will be key the key market dynamic going forwards

Exhibit 2.12

Annual electrolyser installations
GW



Alkaline electrolysers require:

Nickel for the electrode catalysts and bipolar plates coatings.

Zirconium for the membrane/ diaphragm.

PEM electrolysers require:

Platinum Group Metals (Pd, Pt, Ir, Ru) for the electrode catalysts and bipolar plates coatings.

Titanium for the porous transportation layers and bipolar plates.

Source: BNEF (2022), *Global electrolyser outlook 2030.*

74 E.g., current auto catalyst demand is for platinum is approximately 100 tonnes per yr, and deploying approximately 100 GW of electrolysers in 2030 with a loading of approximately 0.3 kg per MW of platinum would give annual demand of at most 30 tonnes per year.

75 See e.g., Kiemel et al. (2021), *Critical materials for water electrolysers at the example of the energy transition in Germany*.

76 IEA (2022), *Global hydrogen review*.

reach 500–800 Mt per annum, of which a large majority (e.g., approximately 450–700 Mt) will likely be produced via electrolysis, implying a need for about 3,500–8,000 GW of electrolyser capacity.[77]

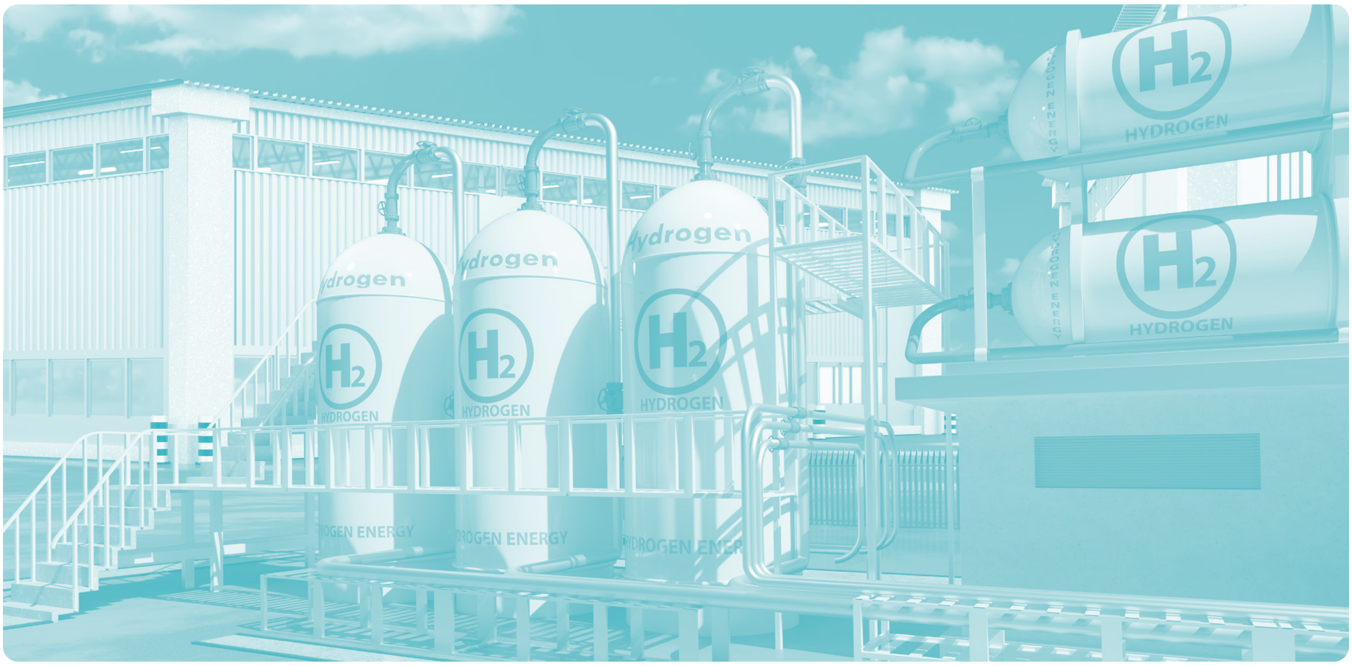
- Compared with this eventual need, estimates for the growth of electrolyser installations, reaching 85 GW per annum by 2030 and cumulative installations of 240 GW by the end of this decade are still modest [Exhibit 2.12]. However, this reflects the expectation that green hydrogen demand is likely to develop somewhat more slowly in the 2020s, before growing dramatically in the 2030s.[78] Announced plans for a cumulative 50 GW of global electrolyser manufacturing capacity by 2025, with continued growth certain thereafter, would therefore seem sufficient to meet demand during this decade.[79]
- However, within this global picture, there are significant regional differences. Electrolyser manufacturing capacity is growing rapidly in China, and electrolyser prices inside China have fallen to around $400 per kW or still lower.[80] In Europe, prices continue to be far above this level, and potential early users of green hydrogen report that price quotes for green hydrogen or electrolyser supply in the mid-2020s are higher than expected. Some forecasts suggest that European electrolyser prices will still be in the range of $400–500 per kW by 2030.[81] Several factors that may be restricting effective capacity include reduced capacity for cell manufacturing in some plants, as well a lack of track record of some electrolyser manufacturers.[82]

2. **There are some environmental and social concerns for electrolyser supply chains around PGMs.**

Very low ore grades for PGMs lead to **high water and carbon intensity** of production for PGM mining. However, volumes used in electrolysers are likely to be lower than current demand from the auto industry.

3. **Use of PGMs leads to some risks around concentration of supply, but this is contained.**

Supply of PGMs is heavily concentrated, with South Africa accounting for over 70% of platinum supply and 40% of palladium, and Russia making up another 40% of palladium.[83]



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[77] The range illustrated assumes an efficiency of 45 kWh per kg, implying a need for ~21,250–31,500 TWh to produce 450–700 Mt, and average capacity utilisation between 4,000–5,500 hours per annum. Capacity utilisation may be high where grid electricity is used, but will be much lower where electrolysers run on dedicated renewable electricity supply, or where grid electricity is only used when time specific tariffs are low.

[78] The ETC estimates that low-carbon hydrogen demand could be 40–60 Mt in 2030, but then grow very rapidly to 500–800 Mt by 2050 – from less than 1 Mt currently. See ETC (2021), *Making the hydrogen economy possible*.

[79] BNEF (2022), *Global electrolyser outlook 2030*.

[80] BNEF (2022), *Electrolysis system capex by 2050 – Updated forecast*.

[81] Ibid.; US Department of Energy (2023), *Pathways to Commercial Liftoff: Clean Hydrogen*.

[82] BNEF (2023), *1H 2023 Hydrogen Market Outlook*.

[83] USGS (2023), *Mineral commodity summaries*.

The previous section mapped clean energy supply chains and assessed the potential areas of risk across key technologies. Overall, while there are no fundamental barriers at the global level to ensure the supply of key inputs can meet growing demand, there are likely to be some areas of potential bottlenecks, which link to three cross-cutting risks:

1. **Across some supply chain areas, more frequent price volatility is expected due to market tightness.** In particular, this is the case for technologies which present more complex manufacturing value chains (e.g., wind, grids, battery cathodes), and for specific raw materials (e.g., copper, lithium) where longer mining lead times and fewer substitution options mean that the market is likely to be tight for longer.
2. **There are currently some wider environmental and social concerns around mining and manufacturing that need to be appropriately addressed, which could pose supply challenges for companies.** These include concerns around labour and human rights, environmental impacts such as water access and biodiversity, and considerations around carbon intensity and lifecycle GHG emissions.
3. **Supply chains for solar PV and battery manufacturing are highly concentrated geographically at several stages, which could lead to frictions for supply.** Future growth expectations for clean energy markets mean the prospect of supply growth around the world is not a "zero-sum game", providing opportunities across regions and industries. However, action to near-shore production will involve some trade-offs between costs and other priorities (e.g., local jobs or manufacturing, content requirements).

In this chapter, we address in detail each of the three areas above to illustrate areas of concerns. We also discuss these areas of risk in the specific context of the EU in our accompanying *EU Policy Toolkit*.

1. Market tightness risks

The issue of market tightness and supply being able to keep pace with demand growth is more severe at some supply chain stages than others. The upstream part of supply chains – mining and materials – presents the most significant concerns due to more inelastic supply responses, as well as limited substitution options in some cases. Broadly, the manufacturing stage is less of a concern thanks to much shorter lead times for factories. While out of scope in this report, technology-based assessments also highlight that further downstream, towards installation, there could be greater risk for bottlenecks around sufficient skilled labour to install technologies at pace in particular geographies (e.g., for heat pumps).

Manufacturing

Analysis of required demand, possible supply and lead times for the development of factory capacity and transport capability suggests that the supply of manufactured inputs is unlikely to face insurmountable barriers at a global scale. But the precise picture differs significantly by specific product:

- In the case of **solar** PV, ETC analysis[84] suggests that the world will need to be installing at least 600 GW per annum by 2030 to be on a path to net-zero, while existing or announced capacity could be capable of producing almost 1,000 GW each year.[85] This, together with improved panel efficiency, is likely to drive strong cost and price reduction, enabling a faster rate of installation than our minimum estimated requirement.
- For **batteries**, rapid development is driven by the structure of the industry; global scale EV manufacturers have made stretching commitments to launch battery EVs, and made firm off-take commitments to battery companies who are then able to finance fairly rapid plant construction, aided in some cases by government subsidies. Currently announced plans indeed could imply as much as 10,900 GWh per annum capacity by 2030 – far outstripping expected demand even for a net-zero aligned scenario. But many of these announced plans will not get implemented since some battery companies will fail to gain EV manufacturer nominations in a highly competitive market.

84 ETC (2021), *Making clean electrification possible*.

85 For example, existing, announced and under-construction module manufacturing capacity is approximately 994 GW. BNEF (2023), *Interactive data tool – Solar PV equipment manufacturers*.

- For onshore and offshore **wind** turbines, current capacity is well short of the 180 GW and 90 GW per annum likely to be required by 2030, but the timescales required for manufacturing plant construction would allow for adequately rapid development provided there were clear signals that future would be forthcoming.
- Similarly, the lead times for constructing **electrolyser** and **heat pump** factories could make possible 100 GW of electrolyser output and 320 GW of heat pump output globally by 2030.

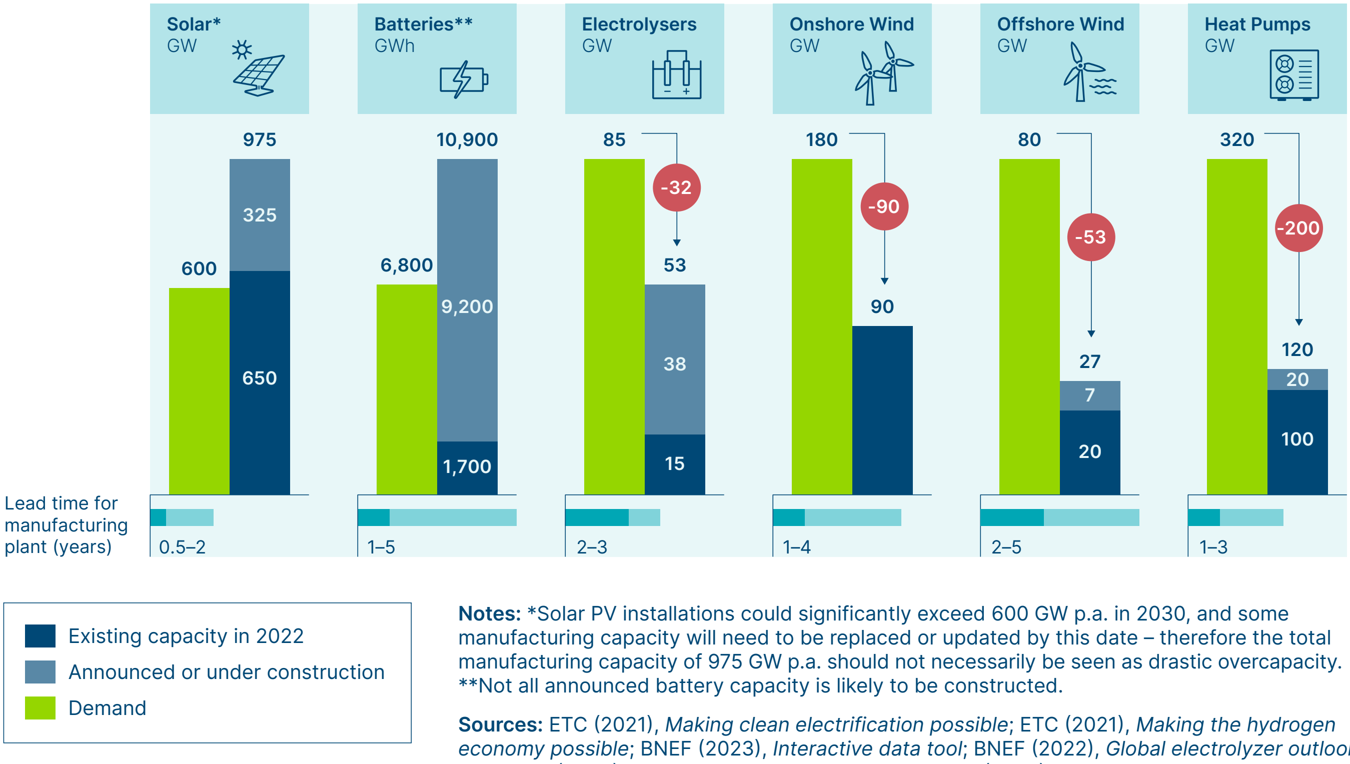
One cross-cutting risk for clean energy technologies arises from their intensive use of **semiconductors**, often for power and electronics management.[86] Ongoing shortages related to capacity build-up and production development lead times[87] could affect the energy transition, with risks particularly concentrated in the automotive sector where the transition to EVs will drive much higher requirements for semiconductor chips.[88] Furthermore, wider trade risks are also prevalent, as highlighted by ongoing restrictions on trade in semiconductor equipment to China.[89] Europe appears particularly exposed on this front, given it accounts for only 10% of global production capacity and is strongly reliant on imports, especially from China and Taiwan.[90]

Finally, a crucial point to consider is the complexity of particular technologies, or of components and equipment required in their manufacture. Delays in obtaining particular pieces of equipment, such as kilns for battery cathode materials, or clean room environments for solar PV or grid transformers, can lead to disruptions for particularly complex stages of manufacturing. Linked to this is the speed of ramp-up to full capacity for manufacturing: factories located in geographies, or run by companies, with significant experience in a particular industry will be able to achieve a faster ramp-up to higher utilisation factors.

Solar and battery manufacturing capacity is likely to be sufficient to meet growing demand; wind, electrolyser and heat pump capacity will have to expand significantly

Exhibit 3.1

Share of existing, announced and remaining gap to 2030 in manufacturing capacity for clean energy technologies
GW / GWh



Notes: *Solar PV installations could significantly exceed 600 GW p.a. in 2030, and some manufacturing capacity will need to be replaced or updated by this date – therefore the total manufacturing capacity of 975 GW p.a. should not necessarily be seen as drastic overcapacity. **Not all announced battery capacity is likely to be constructed.

Sources: ETC (2021), *Making clean electrification possible*; ETC (2021), *Making the hydrogen economy possible*; BNEF (2023), *Interactive data tool*; BNEF (2022), *Global electrolyzer outlook 2030*; IEA (2023), *Energy technology perspectives*; IEA (2022), *The future of heat pumps*.

86 Ballentine et al. (2008), *The role of semiconductors in clean energy.*

87 IEEE Spectrum (2023), *How and when the chip shortage will end, in 4 key charts.*

88 Electric vehicles can require anywhere from two to eleven times as many semiconductors, relative to ICE vehicles. BNEF estimate that ~9 million vehicles (both EV and ICE) were not built in 2021 due to semiconductor chip shortages. BNEF (2021), *Understanding the automotive semiconductor shortage*; BCG (2022), *Tracking the next phase of the automotive semiconductor shortage.*

89 See e.g., NY Times (2022), *With new crackdown, Biden wages global campaign on Chinese technology*; Silicon (2022), *TSMC warns it will close operations if China invades Taiwan.*

90 Deloitte (2022), *A new dawn for European chips.*

Materials

In general, more significant risks around market balances are likely to occur at the upstream stage, around materials and resources.

Firstly, it is important to stress that there are sufficient material resources to meet the demands of the energy transition. Global land-based resources[91] are well in excess of the cumulative demand for primary (mined) materials from the energy transition and other sectors between 2020–50 [Exhibit 3.2].[92] There is no lack of resources of energy transition materials, either of major industrial materials or specialist materials.

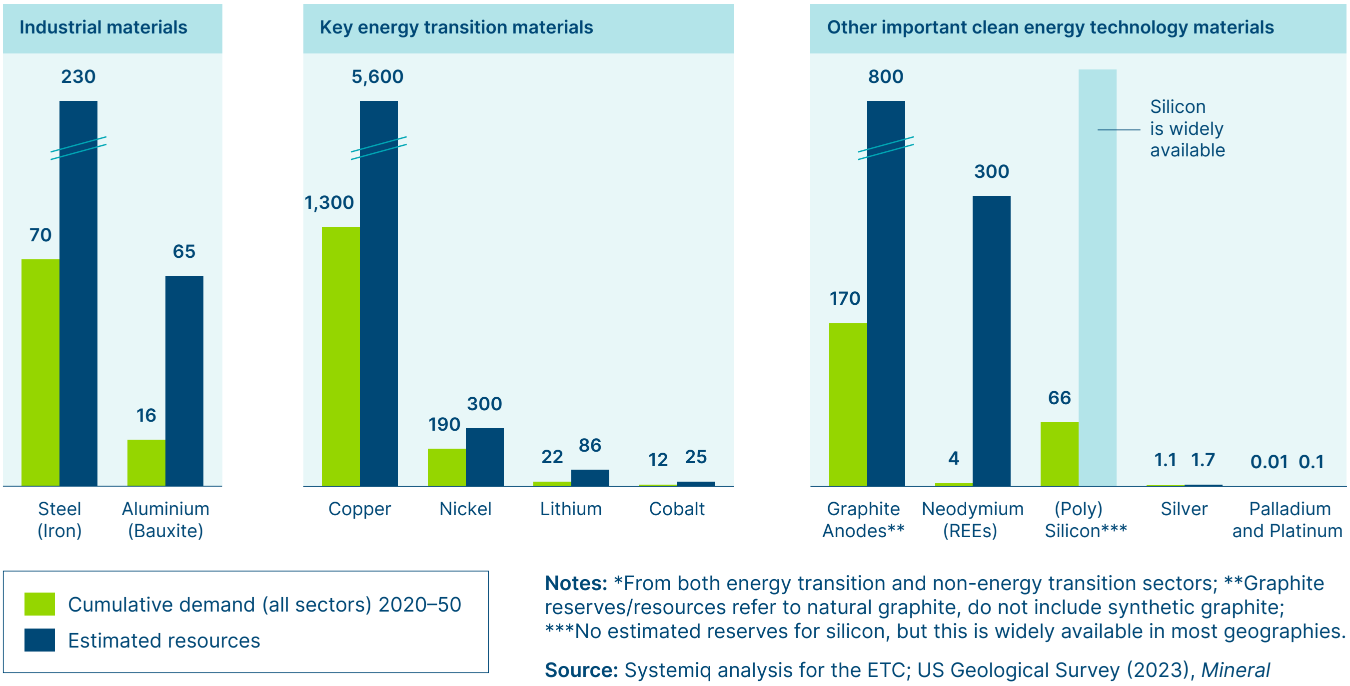
However, the main challenge is around scaling supply of key energy transition materials fast enough to meet demand. This is a bigger issue for some materials than others, and here we highlight five key materials needed across clean technologies [Exhibit 3.3]. **The largest concerns are for copper and lithium, where strong growth to 2030 could lead to insufficient supply pipelines – spurring high prices and potential shortages**.

Copper: Given its excellent conductive properties, copper is the "material of electrification", used in all energy transition technologies. Demand is expected to rise rapidly, driven predominantly by the expansion of power grids, and by 2030, up to half of copper demand could come from products and projects related to the energy transition.[93] This rapid growth could lead to an undersupplied copper market as supply struggles to expand at the same pace in coming years. Three key challenges around supply are potentially long lead times for new copper projects, declining ore grades, and falling production from existing mines.[94] There is some potential for high prices to incentivise greater thrifting, substitution, and increased secondary supply, but the scale of potential primary demand reductions is likely to be much lower than rapidly rising overall demand.[95]

There are enough resources to meet total materials demand between 2020–50, including demand from both the energy transition and other sectors

Exhibit 3.2

Cumulative demand 2020–50*, and estimated resources
Billion metric tonnes (Industrial materials); Million metric tonnes (Key energy transition materials, Other materials)



Notes: *From both energy transition and non-energy transition sectors; **Graphite reserves/resources refer to natural graphite, do not include synthetic graphite; ***No estimated reserves for silicon, but this is widely available in most geographies.

Source: Systemiq analysis for the ETC; US Geological Survey (2023), *Mineral commodity summaries.*

[91] "Resources" define the total amount of a mineral/commodity that is geologically available on land in sufficient concentrations that extraction is potentially feasible. "Reserves" are a working inventory of economically-extractable minerals/commodities that are currently recoverable.

[92] The ETC will be discussing this topic in more detail in an upcoming report on *Material and Resource Needs for the Energy Transition*.

[93] Systemiq analysis for the ETC; S&P Global (2022), *The future of copper*; IEA (2021), *The role of critical minerals in clean energy transitions*.

[94] IEA (2021), *The role of critical minerals in clean energy transitions*; S&P Global (2022), *The future of copper*; Goldman Sachs (2021), *Copper is the new oil*.

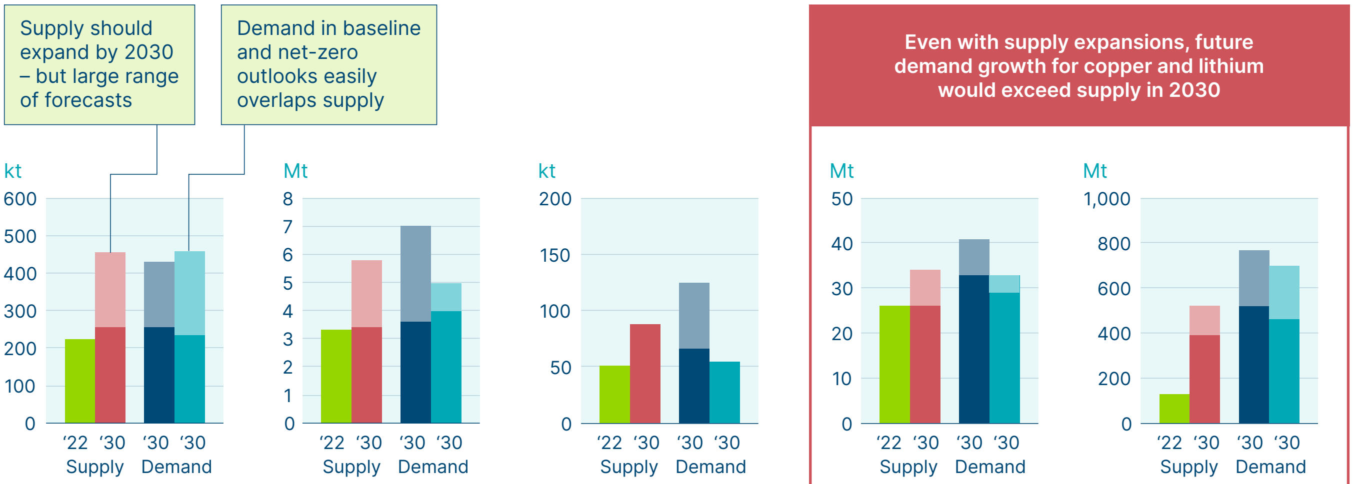
[95] For example, BNEF estimate that copper substitution in grids could amounts to ~0.4 Mt per annum, and Goldman Sachs estimate total substitution potential reaching ~0.7 Mt per annum by 2025. BNEF (2021), *Copper and aluminum compete to build the future power grid*; Goldman Sachs (2021), *Copper is the new oil*.

2030 supply forecasts for copper and lithium show tighter market balance

Exhibit 3.3

Demand and supply forecasts for key energy transition materials in 2030

Nickel, Copper = Million metric tonnes; Cobalt, Lithium, Neodymium = Thousand metric tonnes;



Cobalt

Demand forecasts falling sharply after shift to low-cobalt NMC.

Some uncertainty over stability of DRC supply.

Nickel

Can shift to LFP batteries to reduce demand.

Rapid supply expansion in Indonesia.

Neodymium

Rising but uncertain demand growth from wind + BEVs.

Supply can respond to high prices quickly.

Copper

Used in all clean energy technologies, demand difficult to substitute.

Supply expansion tricky due to ore grades, low investment.

Lithium

No viable substitution across battery chemistries at the moment.

Supply expanding but not quickly enough – gaps likely through to 2030.

- 2022 – Supply
- 2030 – Supply
- 2030 – Net-Zero Demand
- 2030 – Baseline Demand
- Ranges

Source: Systemiq analysis for the ETC; IEA (2023), *Energy technology perspectives* and IEA (2022), *World Energy Investments*; BNEF (2023), *Transition Metals Outlook*; ICF/RMI (2023), *Net zero roadmap to 2050 for copper & nickel mining value chains*; S&P Global (2022), *The future of copper*; S&P Global Market Intelligence (2022), *Lithium project pipeline insufficient to meet looming major deficit*; Benchmark Mineral Intelligence (2023), *Albemarle's turbo-charged demand data showcases lithium's growing supply problem*; Albemarle (2023), *Strategic update*; McKinsey & Co. (2023), *Bridging the copper supply gap;* McKinsey & Co. (2022), *Lithium mining: How new production technologies could fuel the global EV revolution.*

Lithium: Lithium is used across all current lithium-ion batteries, where the rapid rise of EVs is expected to drive strong growth in demand to 2030. Lithium is hard to substitute away from, with alternative sodium-based battery chemistries unlikely to play a major role before 2030.[96] Given this, there is significant pressure on supply to undergo very rapid expansion from a relatively small base, especially from key producing locations in Australia (for hard rock mining) and South America (for brine-based extraction). Even though supply projections have increased in recent years,[97] most major supply outlooks see a supply deficit in 2030, across both "business-as-usual" and net-zero aligned pathways [Exhibit 3.3].[98] Ongoing development of new extraction techniques, notably Direct Lithium Extraction (a way to remove lithium from brines by bonding it to an extraction material), may unlock further supply expansions and help ease concerns.[99] Supply of refined lithium (carbonate or hydroxide) is also expected to grow rapidly and is less of a risk, with refining capacity growing faster than mined supply.[100]

For nickel, cobalt, and neodymium, a series of factors means market balances are under less pressure:

Nickel: Demand for nickel has risen rapidly in recent years, driven predominantly by its use in EV batteries. Nickel is also used in hydrogen electrolysers and in steel alloys used across other clean energy and other sectors. An ongoing shift away from cobalt-rich NMC batteries has led to increasing nickel demand – but this is likely to be countered by the rapid rise of nickel-free LFP batteries. The growth in market share of LFP batteries (approximately 35% of passenger EV market in 2021) has the potential to strongly reduce growth in nickel demand over the coming decade.[101] On the supply side, very strong growth in production in Indonesia in the past few years has exceeded expectations, aided by accelerated permitting and administrative procedures – and moderated concerns around potential supply shortages in coming years.[102] There could be shortages of high-purity class 1 nickel (both nickel sulphate and powders/briquettes) over the short-to-mid term, due to rapid demand growth.[103] However, there is also potential for lower-than-expected stainless steel production to unlock greater quantities of class 1 nickel for batteries.[104]

Cobalt: Although still used in a wide variety of battery chemistries, rapid innovation has greatly reduced projections of future demand growth for cobalt. The ongoing shift to low-cobalt NMC and cobalt-free LFP batteries have helped cut demand projections for 2030 by 50%.[105] Thus, although some growth in supply will be needed to 2030, this would only be slightly faster than growth from the past decade.[106] Much of this growth would come from the Democratic Republic of the Congo (DRC), the world's largest producer, but expanded supply could also come from Indonesia and Australia. Supply of cobalt sulphate is also expected to be more than sufficient to meet demand from batteries.[107]

Neodymium: Neodymium is used in high-strength permanent magnets, which are crucial to convert rotation into electricity (and *vice-versa*) in both wind turbines and electric vehicles. Demand is expected to grow quickly to 2030, although there is some uncertainty around both the type of electric motors used in EVs (some can be free of rare earth elements), and certain wind turbine models have much lower rare earth element requirements.[108] Supply of neodymium is not constrained, with production expected to expand quite quickly in China (the largest current supplier), as well as in Myanmar, Australia, and the USA.

These views are summarised in Exhibit 3.3, which highlights the higher risk potential for lithium and copper.

Finally, the issue of ramp-up and capacity utilisation is also a crucial one for mining and refining output. This can affect existing projects, for example via unexpected equipment failures or maintenance closures leading to down-time,[109] or steeper "learning-by-doing" requirements in regions with less experience in mining or refining leading to slower ramp-up to full output once projects are commissioned.

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96 BNEF (2022), *Technology Radar: Sodium-ion batteries*.

97 E.g., BNEF's *2H 2020 Battery Metals Outlook* projected supply of approximately 340 kt of lithium in 2030; this has since risen to approximately 510 kt of lithium in the most recent *2H 2022 Battery Metals Outlook*.

98 See e.g., IEA (2023), *Energy technology perspectives*; McKinsey & Co. (2022), *Lithium mining: How new production technologies could fuel the global EV revolution*; BNEF (2023), *Transition metals outlook*.

99 McKinsey & Co. (2022), *Lithium mining: How new production technologies could fuel the global EV revolution*; Vera et al. (2023), *Environmental impacts of direct lithium extraction from brines*.

100 BNEF (2022), *2H Battery metals outlook*.

101 BNEF (2022), *Long-term electric vehicle outlook*.

102 IEA (2023), *Energy technology perspectives*; S&P Global (2022), *Nickel industry margins surged in 2021 amid stronger nickel prices*; S&P Global (2022), *Commodities 2022: Analysts have mixed views for nickel market*.

103 BNEF (2022), *2H Battery metals outlook*.

104 Ibid.

105 See S.115 in Nat Bullard (2023), *Decarbonization: The long view, trends and transience, net zero*; BNEF (2022), *Long-term electric vehicle outlook*.

106 Production of cobalt grew approximately 60% between 2010–20, and would need to grow by approximately 100% between 2020–30. IEA (2023), *Energy technology perspectives*; McKinsey & Co. (2022), *The raw-materials challenge*.

107 BNEF (2022), *2H Battery metals outlook*.

108 See e.g., IEA (2021), *The role of critical minerals in clean energy transitions*; Electrek (2023), *Tesla is going (back) to EV motors with no rare earth elements*.

109 See e.g., S&P Global (2022), *The future of copper*.

2. Environmental and social considerations

Across both mining and manufacturing, there are areas that present concerns around environmental and social issues in certain supply chains. Addressing these risks is crucial in order to:

- Mitigate and reduce the environmental and social impacts associated with the manufacturing and deployment of clean energy technologies.
- Ensure buy-in for the energy transition on the part of local communities and wider society.
- Avoid disruptions to production, e.g., via opposition to new projects, site closures, or lack of access to finance, all potentially due to poor environmental and social standards.

As mentioned in the previous chapter, the most significant issues relate to the concentration of the polysilicon supply chain in Xinjiang, and battery supply chains given their current high environmental and carbon footprint.

Carbon footprint of production

Although the operating emissions associated with clean energy technologies are far lower than their fossil-fuel based alternatives (e.g., wind and solar vs. gas and coal for electricity production,[110] or battery-electric vehicles vs. combustion-engine vehicles[111]), there is still an opportunity to lower the embodied carbon emissions from the supply chains of clean energy technologies.

It is important to keep in mind that a large fraction of embodied emissions from manufacturing arise from electricity consumption. As grids decarbonise across the world, manufacturing will in turn have lower associated emissions. In many cases, new manufacturing sites are already being paired with renewable power-purchase agreements, ensuring that lower emissions are being locked in throughout a project's lifetime.

For most materials mine-site emissions make up a small share of emissions associated with material production,[112] with refining typically being an emission-intensive step. The refining and processing of a range of energy transition materials requires high temperatures and therefore large amounts of energy, often provided by power grids which are currently dominated by coal generation, e.g., in China and Indonesia. This is especially a concern for three materials:

- **Nickel**, where future production of nickel will likely be dominated by laterite ores, whose production process entails two-to-six times the emissions intensity of current sulphide-based supply.[113]
- **Lithium**, where the now-dominant extraction methods to produce lithium carbonate and hydroxide from hard rock are three-to-five times more emissions intensive than brine-based production of lithium carbonate.[114]
- **Polysilicon**, where production is heavily concentrated in Xinjiang, with manufacturing plants often co-located with coal-fired power plants [Exhibit 3.4], leading to very high associated emissions – although rapid renewables deployment in the region should decrease this in coming years.[115]

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110 UNECE (2021), *Lifecycle assessment of electricity generation options*; Pehl et al. (2017), *Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling*.

111 Ricardo Energy (2020), *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*; IEA (2021), *The role of critical minerals in clean energy transitions*.

112 Less than 50% of the carbon footprint of copper, and 15% of the carbon footprint of nickel, are due to mine-site emissions. Copper Alliance (2023), *Copper – the pathway to net zero*; IFC (2023), *Net zero roadmap to 2050 for copper and nickel mining value chains*.

113 Emissions intensity of Class 1 nickel from sulphide ores is approximately 10 tCO_2e per tonne of nickel, vs. approximately 19 for laterite extraction using high-pressure acid leaching, and approximately 60 for laterite extraction via intermediate steps of matte and nickel pig iron. IEA (2021), *The role of critical minerals in clean energy transitions*.

114 IEA (2021), *The role of critical minerals in clean energy transitions*.

115 IEA (2022), *Special report on solar PV global supply chains*; Hallam et al. (2022), *A polysilicon learning curve and the material requirements for broad electrification with photovoltaics by 2050*.

Although the steel and aluminium sectors also have large associated emissions and are often used across clean energy technologies, the energy transition accounts for a lower share of the total demand for those sectors, and clear strategies for sectoral decarbonisation are being developed.[116]

Several clean energy technologies also have high carbon footprints associated with downstream manufacturing, with the two technologies of highest concern being solar panels and batteries. The manufacturing of ingots, wafers and cells for solar modules, and of cathodes, anodes and battery assembly, is very electricity-intensive. Combined with the currently high carbon intensity of the power grid in China, where most production is currently concentrated (see below), this leads to high embodied emissions for production of solar panels [Exhibit 3.4], and also of batteries.[117]

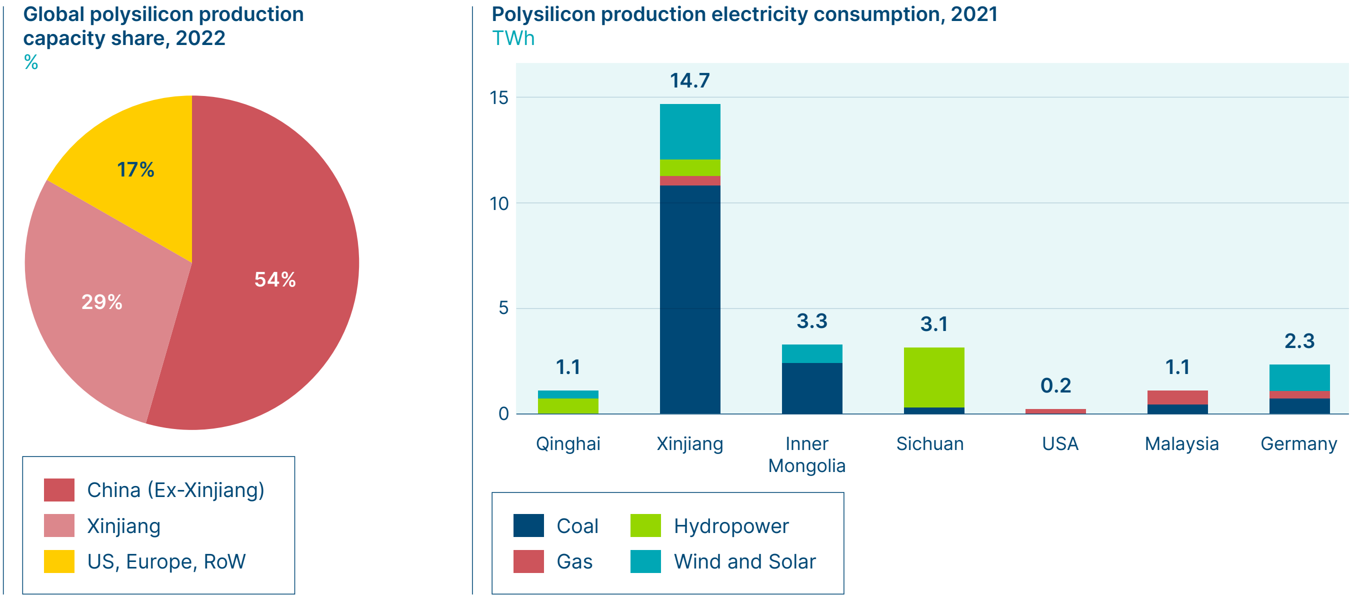
However, there is a clear opportunity for decarbonising supply chains via either:

- **Decarbonisation within countries where existing mining, refining or manufacturing capacity is concentrated**. Chinese-based supply for instance could be decarbonised via a shift to dedicated low carbon electricity supply, and will eventually decarbonise even where grid electricity is used, as China's massive renewables investments reduce its carbon intensity. Similarly, Ricardo Energy estimate that future battery production could have approximately 75% lower emissions thanks to improved production efficiency and decarbonised power.[118]
- **A shift to near-shored/more diversified supply locations**. As Exhibit 3.5 illustrates, shifting solar panel or lithium refining to countries with lower grid carbon intensity could help significantly decarbonise production.[119]

Either shift could be encouraged by regulations which require reduced lifecycle carbon emissions for key products (e.g., batteries and solar panels) or by carbon pricing combined with carbon border adjustments.

Polysilicon production in China currently relies on large amounts of coal power, especially in Xinjiang

Exhibit 3.4



Source: The Breakthrough Institute (2022), *Sins of a solar empire*; Murphy and Elimä/Sheffield Hallam University (2021), *In broad daylight*; IEA (2022), *Special report on solar PV global supply chains*; BNEF (2023), *Interactive data tool – Equipment manufacturers.*

[116] See e.g., Mission Possible Partnership (2022), *Making net-zero steel/aluminium possible*.

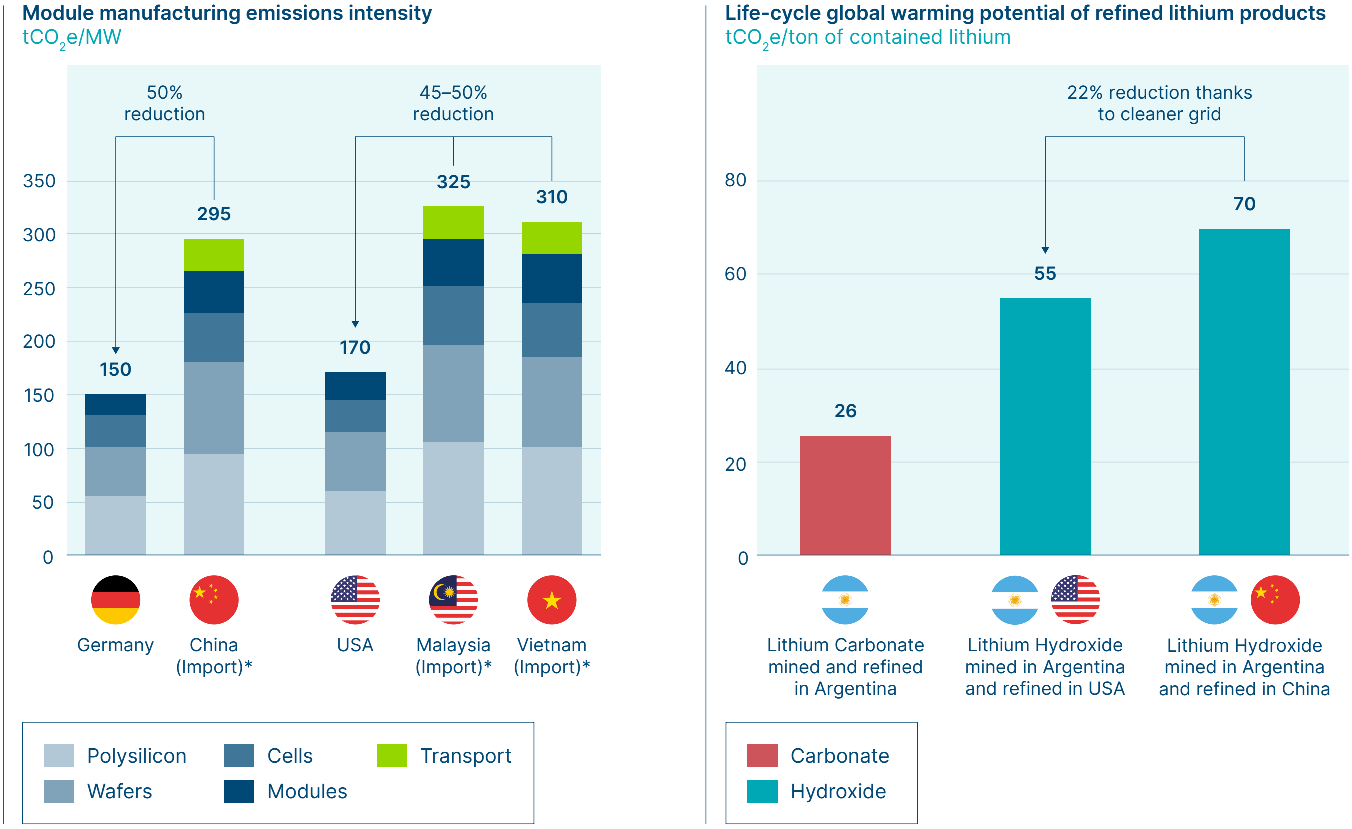
[117] See e.g., IEA (2022), *Special report on solar PV global supply chains*; Faraday Institution (2021), *The UK: A low carbon location to manufacture, drive and recycle electric vehicles*.

[118] See Figure 5.60 in Ricardo Energy (2020), *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*.

[119] Similarly, analysis by Minviro for lithium producer Livent shows that shifting of lithium hydroxide refining from China to the USA could reduce associated emissions by 20%. Minviro/Livent (2022), *2021 Sustainability Report*.

Production of solar PV or refined battery materials could be decarbonised by using low-carbon electricity in China, or by shifting production to countries with less carbon-intensive grids

Exhibit 3.5



Note: *Assuming final product (solar PV module) is transported from producing country to Germany/USA.

Source: Minviro/Livent (2022), *2021 Sustainability Report*; Ricardo Energy (2020), *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*; IEA (2022), *Special report on solar PV global supply chains*.

Impacts on nature and biodiversity

The impacts of clean energy technology production go beyond emissions: mining and refining of key energy transition materials is associated with impacts on water consumption, local air pollution, land-use change, and biodiversity. The ETC will cover these concerns in detail in an upcoming report on *Resource and Material Requirements for the Energy Transition*, but here we highlight a few of the areas of potential risk:

- **Water consumption** from mining, although very small at a global level compared with other uses and in particular agriculture, will likely increase over coming decades, driven by the high water intensity of lithium, nickel and copper extraction – exacerbating water scarcity in key regions (e.g., northern Chile, parts of Australia).[120]
- **Air and water pollution**, arising from dust and particulate generation during mining, the emission of sulphur dioxide and nitrogen oxides during smelting and refining processes, and the key issue of acid mine drainage from mine tailings or slag heaps. On this front, the worst offender is often copper (excluding gold, which has little relevance to the energy transition).[121] A key aspect is the appropriate management of waste and tailings,[122] which if not done to high standards can lead to local environmental impacts, and in the worst cases to local tailings dam collapses, with devastating local effects.[123]

[120] Meissner (2021), *The impact of metal mining on global water stress and regional carrying capacities – A GIS-based water impact assessment*; IFC (2023), *Net zero roadmap to 2050 for copper and nickel mining value chains*.

[121] International Resource Panel (2019), *Global resources outlook*; Izydorczyk et al. (2021), *Potential environmental pollution from copper metallurgy and methods of management*.

[122] See e.g., ICMM (2022), *Tailings reduction roadmap*.

[123] For example, the Mariana mining disaster. See e.g., France24 (2016), *The Mariana mining disaster*.

- Impacts on **local land-use change, nature and biodiversity**. Although direct mining land use is very low (mining uses approximately 0.1% of global habitable land),[124] the indirect impacts from mining on deforestation and biodiversity loss can be significant.[125] A key issue here are "secondary" or induced impacts beyond the mine site, where wider local development can lead to accelerated deforestation or other impacts.

The local environmental impacts associated with running and operating clean energy technologies are beyond the scope of this work but are also likely to be low, with for example low global land use requirements for solar and wind farms, and low associated biodiversity impacts.[126]

Human rights and social concerns

Two areas of clean energy technology supply chains stand out for their impact on human rights: production of polysilicon in Xinjiang, and the supply of cobalt from the Democratic Republic of Congo (DRC).

Concerns have been raised regarding human rights issues in Xinjiang, covering both the **production of polysilicon** and the coal mining and electricity generation used to power polysilicon production.[127] Given the large market share of Xinjiang polysilicon production and the common use of blending of polysilicon from multiple suppliers into ingots, many downstream solar manufacturers may be using polysilicon from Xinjiang.

The supply of **conflict minerals from the DRC** have become a headline issue since the mid-2000s, with a long history linked to the ongoing conflict and armed uprisings in the eastern parts of the country.[128] A range of reports have highlighted concerns ranging from poor working conditions, human rights abuses, low standards for health and safety, and the use of child labour.[129] Given the strong inter-linkages between armed conflict and local artisanal and small-scale mining operations, as well as allegations of corruption, these concerns have struggled to be addressed by interventions from governments, including regulation on conflict minerals, or industry.[130] Efforts to formalise aspects of the artisanal and small-scale mining sector have had some successes,[131] but the societal impacts of local conflict and its interaction with resource extraction remain severe.

There are also other specific instances of human rights concerns, often linked to poorly regulated or illegal mining. For example, unpermitted mining of rare earth elements in Myanmar has been linked to local militia groups and child labour,[132] and the rapid expansion of nickel mining in Indonesia has been linked to extensive corruption. These examples, alongside those above, show the importance of enforcing regulation at national and international level, and of expanding the use of traceability in order to track impacts across supply chains (discussed further in Chapter 4).

More broadly, it is clear that the cost of many of the environmental and social impacts of material extraction and clean energy supply chains would fall almost exclusively on local communities impacted by mining, alongside other considerations around corruption, working conditions, consent and more. There is a risk that the global benefits of decarbonisation are unfairly traded off against highly-concentrated local costs associated with scaling supply chains without a proper regard for sustainable and responsible sourcing.

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[124] Existing mine sites cover approximately 100,000 km^2. Maus et al. (2022), *An update on global mining land use*.

[125] Sonter et al. (2017), *Mining drives extensive deforestation in the Brazilian Amazon*; Giljum et al. (2022), *A pantropical assessment of deforestation caused by industrial mining*.

[126] See e.g., ETC (2021), *Making clean electrification possible*; ETC (2023), *Streamlining planning and permitting to accelerate wind and solar deployment*; Holland et al. (2019), *The influence of the global electric power system on terrestrial biodiversity*.

[127] UN OHCHR (2022), *Assessment of human rights concerns in the Xinjiang Uyghur Autonomous Region, People's Republic of China*; The Breakthrough Institute (2022), *Sins of a solar empire*; Murphy and Elimä / Sheffield Hallam University (2021), *In broad daylight*.

[128] See e.g., Amnesty International / AfreWatch (2016), *This is what we die for: Human rights abuses in the DRC power the global trade in cobalt*; The Economist (2022), *The world should not ignore the horrors of eastern Congo*.

[129] Business & Human Rights Resource Centre (2021), *Transition Minerals Tracker: 2021 Analysis*; Mancini et al. (2018), *Social impact assessment in the mining sector: Review and comparison of indicators frameworks*.

[130] US Government Accountability Office (2022), *Overall peace and security in Eastern DRC has not improved since 2014*.

[131] World Economic Forum (2020), *Making mining safe and fair: Artisanal cobalt extraction in the DRC*.

[132] Global Witness (2022), *Myanmar's poisoned mountains*; Tempo (2023), *Illegal nickel laundering*.

3. High concentration of supply chains

The concentration of existing supply chains in particular geographies or companies is not inherently a negative. However, high levels of concentration do present a potential risk in the case of exogenous shocks (as seen with the Covid-19 pandemic), or sudden changes in policy and international relations (as seen with historical bans or quotas on the export of Indonesia nickel or rare earth elements from China) – both of which can impact supply over very short timescales. Thus, concentration of supply chains should be viewed by policymakers and business leaders through the lens of risk management above all else.

Concentration is an issue across three distinct supply chain steps:

1. Mining:

a) Geographic concentration. Current mined supply of key energy transition minerals is highly concentrated, most notably in the case of cobalt mining in the DRC, lithium supply from Chile and Australia, and the mining of rare earth elements in China [Exhibit 3.6]. Even for more diversified copper, the four largest producing countries control over 50% of global production. Reserves and resources of minerals are more geographically distributed, and supply is expected to come online from new geographies in coming years.[133] However, long lead times of 5–20 years imply that a major re-distribution of mined production is unlikely in the period to 2030.

b) Company concentration. Mining tends to be quite diversified across companies, although smaller markets for certain metals can lead to higher concentration. Most notably, mining of cobalt is dominated by Glencore and CMOC Group (previously China Molybdenum Company Ltd.), with the two operating three of the largest cobalt-producing mines (Katanga, Mutanda, and Tenke Fungurume) and together are expected to produce around 90 kt of cobalt in 2023 – around 40% of the market.[134]

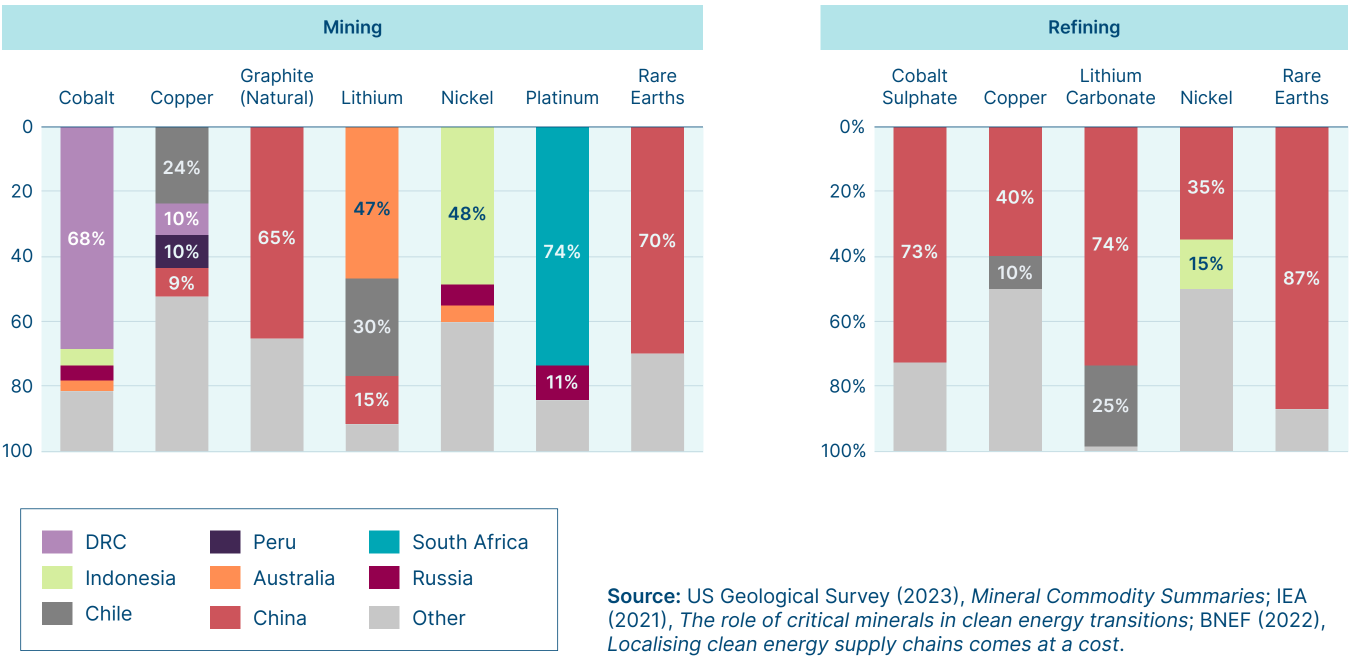
2. Refining:

Current refined supply of key input materials is more heavily concentrated than mined minerals, with China dominating supply across five key energy transition materials [Exhibit 3.6].

Mining and refining of key raw materials is highly concentrated, exposing global markets to supply disruption risks

Exhibit 3.6

Share of global mining and refining production by country, 2022
%



Source: US Geological Survey (2023), *Mineral Commodity Summaries*; IEA (2021), *The role of critical minerals in clean energy transitions*; BNEF (2022), *Localising clean energy supply chains comes at a cost*.

133 USGS (2023), *Mineral commodity summaries*; IEA (2023), *Energy technology perspectives*.

134 BNEF (2023), *Glencore set to lose crown as top cobalt miner to China's CMOC*.

3. Manufacturing:

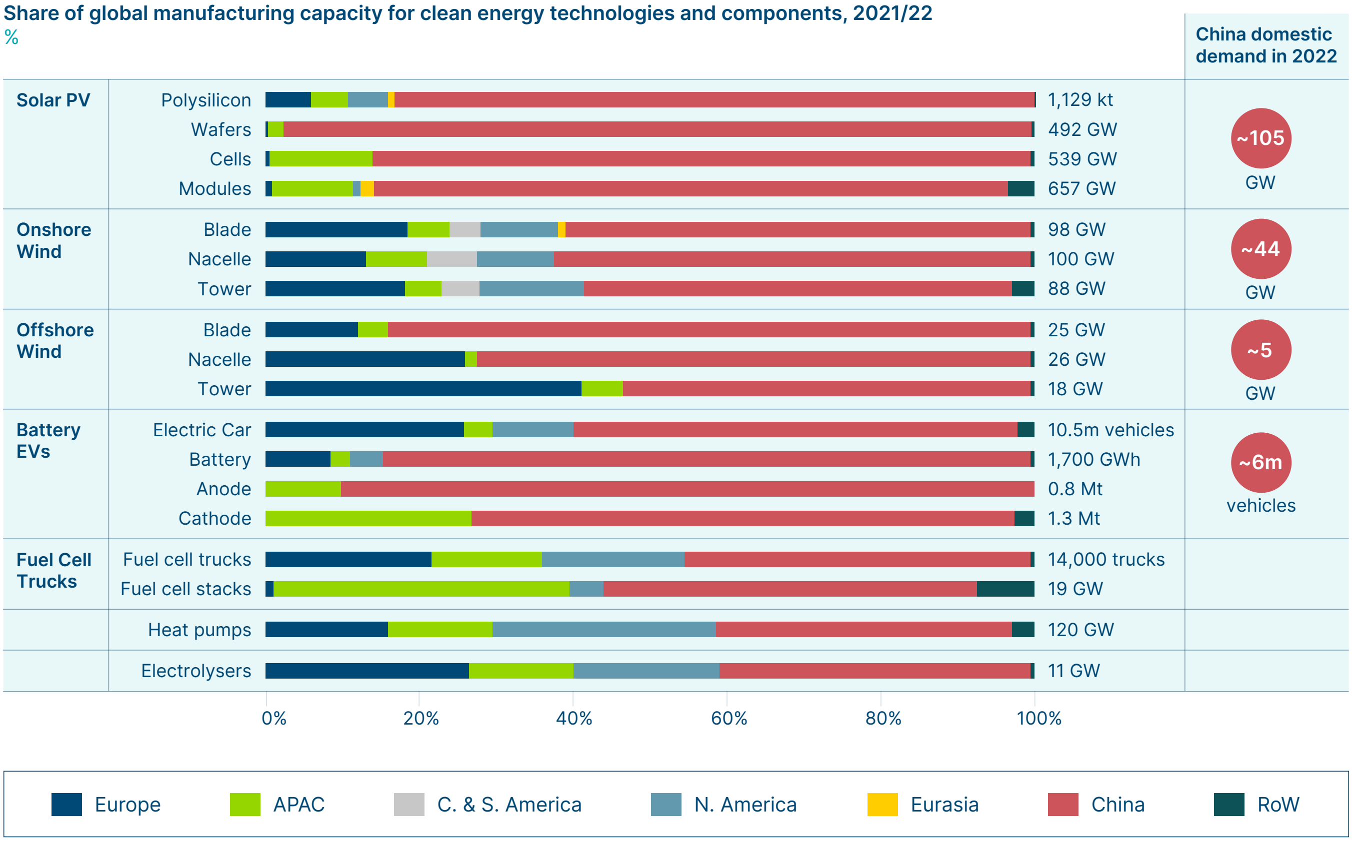
a) As outlined above, the highest level of **geographic concentration** in downstream clean energy technology supply chains is in the case of solar PV and batteries. However, Exhibit 3.7 shows that concentration is an issue across other clean energy technologies as well. A large proportion of manufacturing capacity in China is dedicated to domestic demand from the impressive pace of deployment of clean energy technologies. However, the very high (over 75% in many cases) share of production located in China could pose risks for specific companies or countries if sudden shocks appear – as happened with diminished manufacturing capacity following the Covid-19 pandemic and associated lockdowns.

b) Furthermore, there is also a more limited risk around **company concentration** of key manufacturing steps. This is much less of a risk in simpler, assembly-type manufacturing stages (e.g., battery or solar module assembly), where barriers to entry are low. However, company concentration be a risk for smaller markets with highly complex or customised equipment and higher barriers to entry, such as HVDC cabling, polysilicon production, or manufacturing of offshore wind turbine installation vessels.

Looking ahead, the rapid growth across all clean energy technologies presents a clear opportunity for a wide range of companies and countries over coming decades. For example, the increase in battery manufacturing capacity over the coming decade could see a near forty-fold increase in capacity in Europe – a staggering opportunity for companies and countries to take part in a growing market [Exhibit 3.8]. Thus, the issue of location of supply chains should not be seen as zero-sum: diversification can represent an opportunity both to reduce risks and spread to benefits of the energy transition more broadly.

Today, China has major share in downstream clean energy technology supply chains

Exhibit 3.7

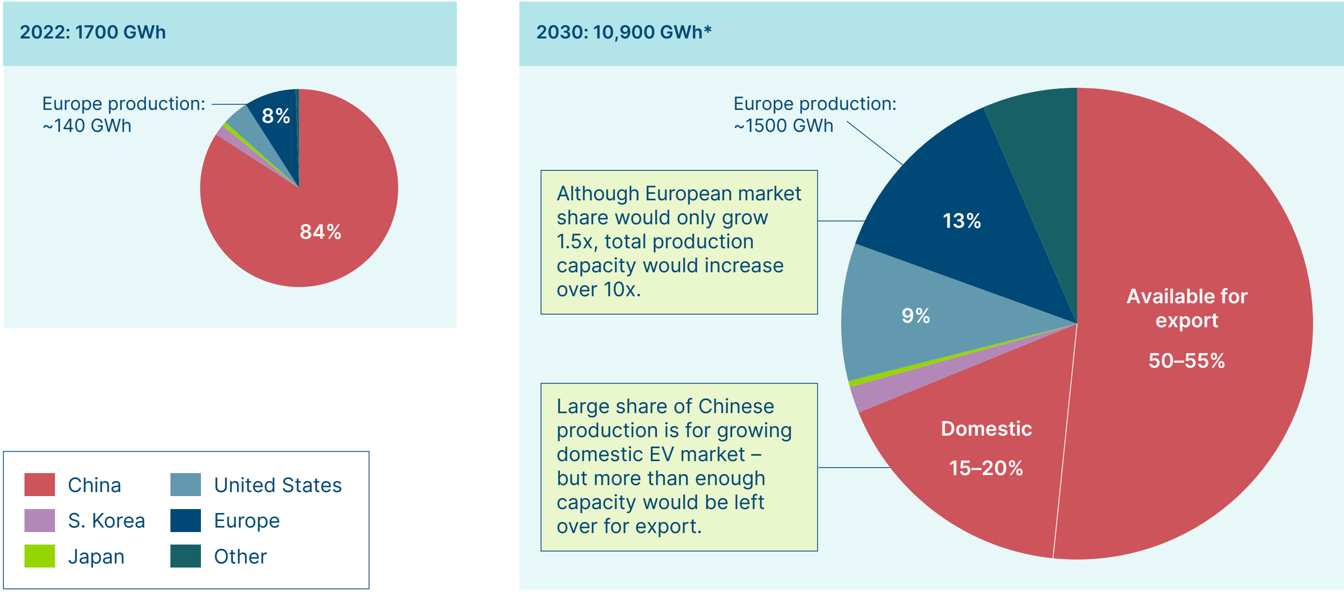


Source: IEA (2023), *Energy technology perspectives*; BNEF (2023), *Interactive data tool – Equipment manufacturers*; BNEF (2022), *Localizing clean energy supply chains comes at a cost.*

Clean energy manufacturing competition does not need to be zero-sum: rapidly-expanding market presents opportunity for all major players

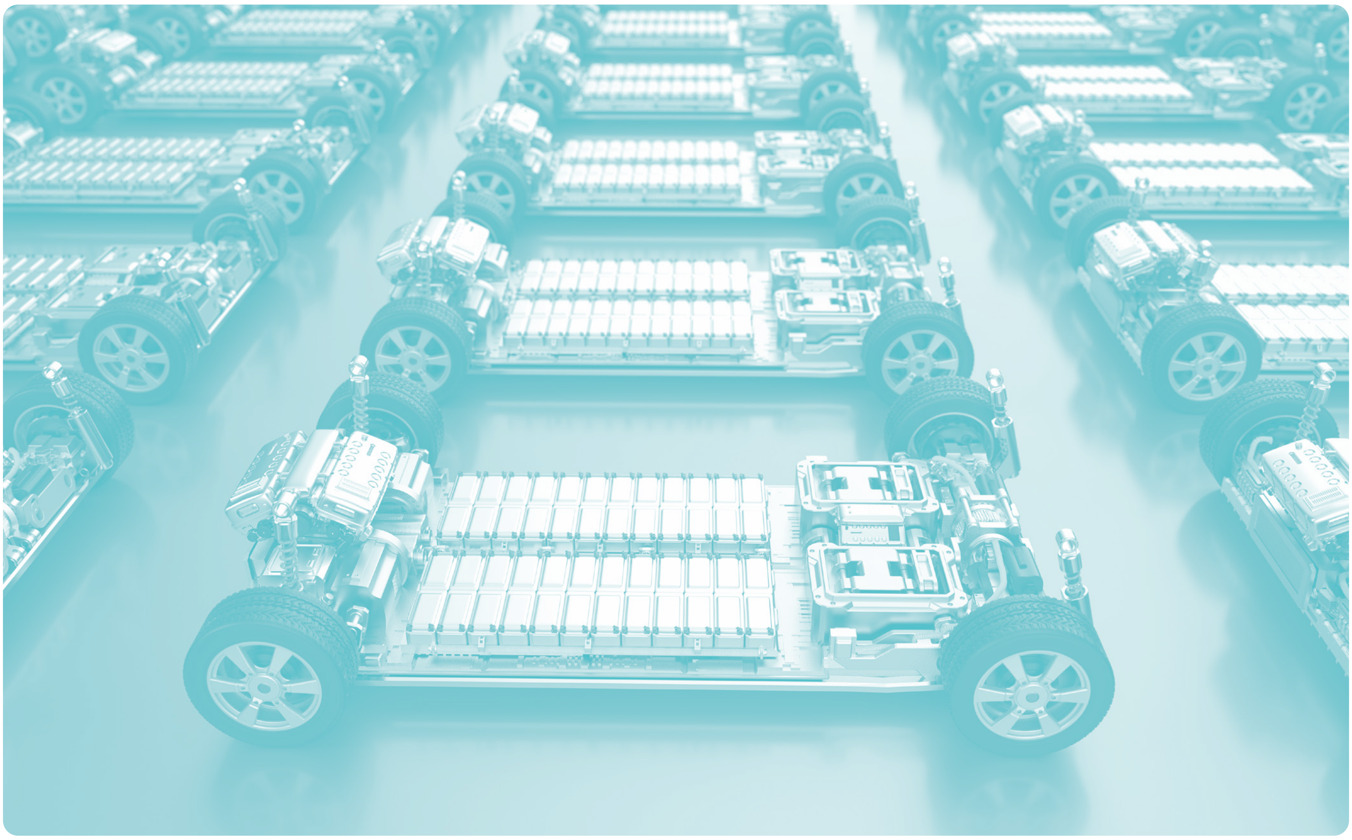
Exhibit 3.8

Country market share of battery production, 2022 vs. 2030
%



Note: *Announced capacity – it is unlikely that all announced projects would reach final investment decision.

Source: Systemiq analysis for the ETC; Benchmark Mineral Intelligence (2022), *Lithium-ion battery gigafactory assessment – August*; BNEF (2023), *Interactive data tool – Battery cell manufacturers*; McKinsey & Co. (2023), *Battery 2030: Resilient, sustainable, and circular*.



Key actions and recommendations

4

This Insights Briefing has focused on identifying where global supply chain constraints and environmental impacts might be most significant. This section describes public policies and industry actions which can reduce the risk that these constraints and impacts might limit the pace of the required energy transition.

Overall, the assessment in this report concludes that there are some areas of potential bottlenecks in clean energy supply chains, driven by market tightness, environmental and social concerns, as well as high concentration. At a global scale, these risks do not pose a fundamental barrier to scaling clean energy technologies. In some instances, however, managing these challenges may involve some trade-offs between the speed of the transition and reducing environmental and social impacts, or localisation production.

First and foremost, ensuring clarity of vision over the shape and pace of the energy transition will be critical to reallocate resources and financing to unlock bottlenecks and deploy clean energy technologies. The more that the broad shape and timeline of the future transition is clear, the greater the extent to which supply chain challenges will be solved by market competition and private investment.

There is an important distinction between countries setting a clear net-zero vision, which is critical, and any supporting industrial policy, which a country may choose to adopt based on other objectives:

- **A clear strategic vision for the overall energy transition** is required to ensure smooth deployment of global clean energy technology supply chains, via clear targets for key sectors (e.g., power sector decarbonisation targets over time, renewable energy and nuclear deployment targets specifying GW installed by future dates, dates for ICE phase-out and bans etc, targets for heat pump installation and dates for phasing out of residential gas boilers).
- **Industrial, manufacturing and trade policy** may additionally be used to achieve separate domestic production objectives, which will depend on the particular political-economic priorities of specific governments.

In addition, specific public policies and industry driven actions should seek to address the three major risk areas which could lead to bottlenecks [Exhibit 4.1]:

1. **Ensuring as best possible that supply and demand for key inputs develop in a consistent fashion.**
2. **Reducing the adverse environmental impact and improving the social impact of supply chain developments – driven by increasing tracking and traceability throughout supply chains.**
3. **Ensuring diversified, resilient, and secure supply.**

In particular, actions to achieve less concentrated and more secure supply chains could entail some more significant trade-offs – for instance, between short-term cost and degree of localisation. This is especially the case in the EU and North America, where in many cases manufacturing and mining is (re-)starting from a low base.

This section therefore provides a brief summary of the actions required on dimensions 1 and 2, which will also be described in more detail in the forthcoming ETC report on *Materials and Resources Needs for the Energy Transition*. It will then discuss the trade-offs entailed in the pursuit of increased energy security, and policy approaches which can help achieve an optimal result.

High-level recommendations for governments and industry

Exhibit 4.1

Fundamental driver: a strategic vision for the energy transition established by governments, including net-zero targets, supporting sectoral targets (e.g., GW capacity deployment, ICE phase out ban dates), policies that send clear signals on the pace and scale of clean energy deployment, and clear volume needs (e.g., Mt of copper likely to be required).

Addressing supply-demand imbalances

1

- *Demand:* Accelerate improvements in **materials and technology efficiency** through targeted incentives and research and development, as well as support for circular economy business models.
- *Demand:* Create economic incentives for **scaling recycling** and the secondary supply of critical materials.
- *Supply:* Accelerate permitting, expand and de-risk investments, and engage with local communities to **expand supply from the mine site to manufacturing**.
- International **engagement and data sharing** to understand demand and supply forecasts and potential constraints and increase transparency, e.g., via IEA outlooks and round-tables with governments and industry.

Developing sustainable and responsible supply chains

2

- **Strong regulations on environmental and social impacts** of clean energy technologies, starting with **carbon intensity**. Aim to decarbonise and decrease impacts at the mine site and throughout manufacturing value chains, by driving clean energy procurement, increased process efficiency and best-practice environmental standards.
- **Use purchasing power to drive projects** with high environmental and social standards.
- **Define and adopt high-quality voluntary** environment and social standards.
- **Improve and require supply chain traceability** through industry-wide engagement and trusted third-party auditors.

Ensuring diversified, resilient and secure supply

3

- **Adopt strategies to diversify supply** for mining, refining and manufacturing:
  - This can include friend-shoring, signing joint ventures and off-taker agreements, and agreeing strategic partnerships with key companies and countries.
  - **Focus action on location of production**, not ownership – to allow strong competition across markets.
- **Where near-shoring is assessed as strategically beneficial**, develop a suite of actions to **maximise benefits of near-shoring** of value chains, including alignment of near-shored industries with domestic growth areas.

1. Addressing supply-demand imbalances

Actions to alleviate supply-demand imbalances can either reduce the scale of the required demand growth, facilitate growth in supply, or improve understanding of future likely supply/demand balances given current trends. They could be particularly important in relation to lithium and copper, but are relevant across all the inputs we considered in Chapters 2 and 3. Industry, and in particular policy actions, can support four objectives:

Reducing demand via improvements in technology and material efficiency

Industry: Industry should continue driving technological progress to improve the efficiency of technologies and of material use, responding to expected imbalances in future supply and demand (e.g., the example of substitution away from cobalt and nickel in battery technology to new chemistries discussed in Chapter 2). There should also be a concerted push from industry to develop circular business models (including around second life, refurbishment, and modal shift) which can reduce overall material intensity, including by supporting innovation.[135]

Governments: Public policy can give further impetus by deliberately supporting technological developments which address likely future supply constraints (for example, the development and deployment of sodium-ion batteries or other technologies to moderate future lithium demand, or technological innovations to reduce copper requirements in transmission and distribution). Policy tools could include targeted incentives, R&D support,

[135] Systemiq (2021), *Everything-as-a-Service*.

and prizes for "breakthrough" improvements in performance. For instance, the Australian National Renewable Energy Agency recently set a target to improve solar cell efficiencies to over 30%, and reduce the cost of solar modules to below $0.3 per W, by 2030.[136] Furthermore, public policy should support the development of circular business models which reduce material and technology intensity for clean energy, including via economic and market instruments (e.g., adapting tax frameworks that favour repairs and refurbishments), as well as targeted funding mechanisms and regulation (e.g., regulation which requires producers to cover end-of-life costs via extended producer responsibility).[137]

Reducing primary materials demand via maximum recycling

Increased recycling has huge potential to reduce long-term demand for primary material – although it will take time for large volumes of materials to reach end-of-life. The long timescales associated with stock-turnover of clean energy technologies mean that strong action to put in place infrastructure, logistics and regulation for recycling should start now.

Industry: Industry should take action to develop greater recycling, in particular driven by market forces in cases where recycled mineral supply can be lower cost than primary supply – learning from industries where recycling is currently widespread, such as platinum group metals from auto catalysts and industry.[138] Furthermore, industry should work to increase innovation around more advanced recycling technology (e.g., shredders) and processes (such as direct recycling for EV batteries).[139]

Governments: Public policy should strongly encourage and require maximum recycling, driving the scale development which will reduce recycling cost. For example, proposals in the European Battery Regulation set targets for collection of batteries at end of life (reaching 73% in 2030), recovery rates for specific materials (e.g., recovering 80% of lithium by 2031), as well as targets for recycled content for batteries (e.g., 6% lithium by 2035, 12% by 2030), to ensure there is high-quality closed-loop recycling.[140]

Facilitating primary mineral supply and manufacturing capacity development

Industry: Prompted by price signals, companies should seek to grow new supply and maximise existing supply sources and operations, supported by technology, including digital technologies. For example, for copper, new reagents could be used to extract further copper supply from the leaching process; and artificial intelligence and machine learning could be deployed to assist in identifying new deposits.[141] For new supply projects, industry should also engage with local communities to ensure strong trust-building and active consent in projects.

Governments: A crucial priority for public policy will be to accelerate permitting processes for both mining and manufacturing developments, supported by the engagement with local communities to ensure maximum possible support. Proposals in the recent European NZIA, for example, include the streamlining of administrative requirements and facilitating permitting, with manufacturing projects for clean energy technologies given priority status.[142] Governments should also seek to de-risk investments in new mining and manufacturing projects, including increasing the scope for MDBs to partner with private capital on mining projects in lower-income countries.

Enhancing supply/demand transparency via improved information

The energy transition, like all previous waves of technological change, is bound to lead to surges of demand and supply which result in large price swings up and down: perfect coordination will never be achieved. But maximum transparency of available supply- and demand-related data and high quality analysis of future potential trends can at least moderate the volatility.

Industry: Collaboration through roundtables and expert panels, in partnership with governments, could drive greater transparency, such as the UK Critical Minerals Expert Committee.

Governments: Recent publications from the International Energy Agency and World Bank,[143] and a recent agreement between Canadian and UK governments to collaborate on critical minerals, are good initial steps.

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136 ARENAWire (2023), *Solar research funding to drive costs lower*.

137 Systemiq (2021), *Everything-as-a-Service*.

138 Recycled platinum and palladium make up around 50% of annual supply, see Hageluken and Goldmann (2022), *Recycling and circular economy – towards a closed loop for metals in emerging clean technologies*.

139 Science (2021), *A dead battery dilemma*.

140 EU Commission (2022), *Green Deal: EU agrees new law on more sustainable and circular batteries to support EU's energy transition and competitive industry*.

141 The Economist (2023), *Copper is the missing ingredient of the energy transition*; Reuters (2022), *Billionaire-backed KoBold Metals to invest in Zambia copper mine*.

142 EU Commission (2023), *Net zero industry act*; Carbon Brief (2023), *Q&A: How the EU wants to race to net-zero with 'Green Deal Industrial Plan'*.

143 See e.g., IEA (2021), *The role of critical minerals in clean energy transitions*; IEA (2022), *Special report on solar PV global supply chains*; IEA (2022), *Global supply chains of EV batteries*; IEA (2023), *Energy technology perspectives*; World Bank (2020), *Minerals for climate action*.

2. Developing environmentally and socially sustainable supply chains

Governments and industry must take action to minimise the carbon emissions from mining, refining and manufacturing activities, to reduce adverse local environmental impacts and to address social issues. These actions should combine:

Strong regulation of life-cycle carbon emissions

This will require establishing standards for Scope 1, 2 and 3 emissions measurement and disclosure – and should be focused on solar panels, batteries and EVs. This will enable carbon intensity of products to be assessed and compared, whatever the location of supply.

Governments: There are several regulatory models:

- Public regulation or procurement requirements can create incentives for low carbon production. For instance, the French government has introduced a "Simplified Carbon Assessment" to enable embodied carbon emissions to become a significant factor in tender applications for new solar PV projects.[144]
- Public regulation can mandate a low carbon intensity for all supply, whether domestically sourced or imported. By making clear that this will be the end point of regulatory development, governments can create strong incentives for the decarbonisation of supply chains across the world.

Industry: Industry could put forward voluntary requirements (e.g., imposed by EV manufacturers on battery suppliers). In response to this – as well as policy levers, suppliers will need to take actions to reduce and eventually eliminate carbon emissions in both their own operation and their supply chains, in particular via the use of dedicated zero-carbon electricity supply or power purchase agreements in countries where grid electricity is still carbon intensive.

Strong regulation around wider environmental and social impacts

Governments: Governments should set binding due diligence legislation. For example, existing regulations such as the US Uyghur Forced Labor Prevention Act, or the EU directive on corporate sustainability due diligence, are good first steps on this front. However, action is needed to ensure broader adoption across more clean energy technologies and to ensure strong enforcement.

Using purchasing power to ensure high local environmental and social standards

Industry and governments: Major companies, government purchasers or major investors can include requirements for high sustainability throughout supply chains, potentially associated with particular voluntary standards or audits.

Defining and adopting high-quality voluntary environmental and social standards

Industry: Adoption of voluntary standards such as the Copper Mark, IRMA, or Towards Sustainable Mining can help companies accelerate action on sustainable supply chains – as can strong corporate governance that prioritises emissions reductions and responsible supply. For example, Nexans – a major grid manufacturer – has joined the Copper Mark to promote sustainable copper production practises and increase its use of due diligence in its supply chain.[145]

Improving and requiring supply chain traceability

Industry: Industry-wide engagement and trusted third-party auditors should push for supply chain traceability. Promoting large-scale trials of supply chain auditing can help companies understand impacts across supply chains: companies such as Circulor, the ongoing development of the Battery Passport by the Global Battery Alliance, and the Battery Pass Consortium, are taking promising steps towards implementation of full traceability.

There is an opportunity for the coming generation of mining, refining and manufacturing to reap commercial rewards for high environmental and social standards in geographies where regulation incentivises this, as an area of competitive advantage.

[144] Ultra Low-Carbon Solar Alliance (2021), *Reducing the carbon footprint of solar: the French model.*

[145] Nexans (2021), *Nexans joins the Copper Mark to promote responsible copper production.*

3. Ensuring diversified, resilient and secure supply

Faced with the concentration in supply chains which Chapter 2 and 3 described, many countries – and in particular the US and the EU – are now seeking to develop more diverse, resilient and secure sources of supply. Whilst there are naturally greater constraints to relocating mining operations due to natural resource endowments, the remainder of value chains from refining and processing through to manufacturing can more easily be relocated. In addition, many individual companies are seeking to develop supply chains which are less vulnerable to any future economic or geopolitical disruptions.

The supply chain strategies pursued include the objective (in particular in the US) of "near-shoring" or "friend-shoring" key supply chain elements – with a significant share of mining, refining or manufacturing capacity located within the country, in nearby countries or in countries which are considered geopolitical allies. This reflects both a desire to reduce vulnerability to any future political risks and to foster domestic technological development and economic and employment growth.

Exhibit 4.2 describes some of the policies already in place or now being put in place in China, the US, the EU and India.

The impetus to develop more diversified and secure supply chains is an inevitable response to the degree of concentration which Chapters 2 and 3 illustrated; and in principle, less concentrated supply chains could be designed in ways which accelerate the pace of the energy transition and reduce the risk of disruption.

Exhibit 4.3 identifies a series of actions that can be taken to diversify mining, refining and manufacturing, without a specific focus on domestic relocation of production. Existing examples include:

- Manufacturers such as Tesla or GM making direct investments, vertical integration or signing strategic partnerships for mineral supply.[146]
- Battery manufacturers opening new factories across different geographies, to meet local demand and particular regulatory requirements (e.g., local content rules).[147]
- Governments signing international partnerships to secure supply, such as the Minerals Security Partnership, led by the US government, which includes an explicit focus on high environmental and social standards.[148]

In terms of maximising the benefits of more extensive action to relocate production domestically, this will require:

- Recognising the potential trade-offs involved in building more localised supply chains. There could be trade-offs between achieving political priorities across jobs, manufacturing, trade and energy security, versus increased costs (e.g., capex for a battery plant, or higher energy prices).
- Focusing localisation strategies on the most appropriate sectors and implementing them in an optimal fashion. There may be feasibility challenges to building new projects, covering: more stringent environmental and social standards, quotas on local content, slower permitting, difficulty accessing finance and a general lower investment risk appetite.

[146] See e.g., C&EN (2023), *GM to invest $650 million in Nevada lithium mine*; Financial Times (2020), *Tesla to buy cobalt from Glencore for new car plants*.

[147] For example, LG Energy Solution has announced projects in Poland and the US. Pulse News (2022), *LG Energy doubles battery capacity in Poland*; Energy Storage News (2023), *LG Energy Solution building US factory with 16 GWh dedicated to battery storage*.

[148] US State Department (2023), *Minerals Security Partnership (MSP) Principles for Responsible Critical Minerals Supply Chains*.

Policy measures to respond to new dynamics are already being set out

Exhibit 4.2

China	• **Long-standing state support** for deployment and manufacturing of low-carbon technologies, especially solar and batteries • E.g., development of government **Five Year Plans**, large financial support from **China Development Bank**, early-stage Brightness Program for rural electrification using solar PV to **grow domestic demand, local government support** to establish industrial parks etc.
USA	• **US Inflation Reduction Act** passed in August 2022, includes tax credits for low-carbon electricity generation and domestic manufacturing • **Wider policy package** on clean energy technologies and industrial competitiveness, e.g., Infrastructure, Investments and Jobs Act, CHIPS & Science Act
EU	• Commission work on **EU Green Deal**, including **Critical Raw Materials Act, Net Zero Industry Act** • Emissions Trading Scheme and proposals for Carbon Border Adjustment Mechanism to cover high-emissions manufacturing and industry
India	• **Production Linked Incentive** schemes to boost domestic manufacturing, including on **electric vehicles** (~$3.2 bn) and **solar PV module** manufacturing (~$2.4 bn) • **Import tariffs on solar modules** manufactured in China

Source: IEA (2023), *Policies database*; BNEF (2022), *Localizing clean energy supply chains comes at a cost*; Harvard/Fairbank Center for Chinese Studies (2022), *How China is winning the race for clean energy technologies*; Gregory Newet (2023), *How solar energy became cheap*; Kaya Advisory/Inevitable Policy Response (2022), *The US discovers its climate policy: A holistic assessment and implications*; EU Commission (2023), *Green deal industrial plan*; EU Commission (2021), *Carbon border adjustment mechanism*; S&P Global (2022), *India's solar power prospects compromised by steep import duty, commodity hikes*; Indian Ministry of Heavy Industries (2022); PV Magazine (2022), *Indian government approves second phase of solar manufacturing incentive scheme*.

Ensuring diversified, resilient and secure supply – diversified supply and increased energy security

Exhibit 4.3

Adopt strategies to manage supply dependence for mining, refining and manufacturing:

	Key Actors: Industry	Key Actors: Policymakers
Securing supply from different mine sites/manufacturers, **to diversify supply chain** – striking a balance between full diversification and single points of failure.	✓	
Manufacturers starting **joint ventures**, carrying out **vertical integration**, signing **off-taker agreements** to secure future supply.	✓	
Agreeing **strategic international partnerships and 'friend-shoring'**, to ensure a diversified but aligned source of supply where relevant.		✓
Ensuring production, content and diversification targets are focused on **location of production**, not ownership – to allow strong competition across markets and supply chains.		✓

Priority Areas: Ensure that any one country or company does not provide >80% of supply for a particular material/product; ensure diversified and free flow of trade for clean energy supply chains. Priority areas are mining of cobalt and rare earths; refining of all energy transition materials; manufacturing supply chain of solar and batteries.

Trade-offs in supply chain localisation

Policy choices around near-shoring will be in part driven by geopolitical considerations. But it is important to understand the potential trade-offs to guide an optimal policy approach.

Re-locating production could in many cases impose an initial increase in the cost of key technologies as production shifts from locations which currently benefit from large economies of scale and acquired experience. For example, BNEF estimates that the capital costs of building out solar PV manufacturing capacity from polysilicon through to modules are currently almost four times higher in the EU and the US than in China.[149]

This effect can be thought of as "restricting" a clean energy technology to a particular region or market, pulling it backwards and up along its cost curve, or "learning curve" [Box C].

Localisation strategies should therefore be designed to ensure that the overall global effect does not severely impact costs of the transition. They also need to reflect realistic assessment of trade-offs involved across three dimensions.

- **Local value add**, with local production generating a domestic GDP contribution and tax revenues. However, this would need to be weighed against any subsidies required to successfully relocate production away from least-cost locations.
- **Employment**, with potential to increase domestic jobs in manufacturing. However, as manufacturing is increasingly automated, the total employment impact may be limited; in many countries indeed, domestic employment creation in residential building retrofit and installation is likely to be more significant than in manufacturing (for example as noted in Box B for residential heat pump installation).
- **Geopolitical considerations**, with localisation reducing import dependency which might create vulnerabilities in periods of geopolitical stress. Furthermore, setting out strong measures to relocalise production (e.g., the US IRA) could be used as a tool to shape global economic trade and investment decisions in line with a country's policy preferences. However, while some diversification will be possible, countries and companies cannot eliminate all dependencies without incurring significant cost increases.

Box C Defining learning curves

Many technologies go through a process of cost decline over time, as increases in capacity see scale effects reduce the costs of manufacture. The rate at which this progress takes place is captured via a "learning rate", defined as the reduction in cost for each doubling of technology capacity deployment. For example, learning rates for solar, batteries and wind over the past decade have been 28%, 17%, and 13% respectively.[1,2,3]

"Learning curves" are a graphical representation of the learning rate. For a more detailed discussion and examples across clean energy technologies, see Malhotra and Schmidt[3], and Way et al.[4]

In terms of "near-shoring", as mentioned, this could restrict a clean energy technology to a particular region or market, pulling it backwards and up along its learning curve. Following this initial increase in costs, the pace of future cost declines would depend on a mix of policy choices and market dynamics [Exhibit 4.4]. There are two potential scenarios:

1. **A slowdown in deployment and permanently higher costs, due to a mix of:**

- **Higher ongoing costs** (labour, energy, financing).
- **More restrictive regulations** which constrain rapid scale-up of mining, refining or manufacturing.
- **Finite size of market** at regional/national scale, setting a limit to economy of scale driven cost reductions.
- **Overly-stringent requirements for localisation all component supplies**, even where additional costs are high and risks from import reliance limited.

2. **An accelerated shift back down along learning curve resulting from:**

- Companies **sharing learning** between factories in different regions, accelerating productivity improvements regardless of factory location.
- Global sharing of **faster innovation**, incentivised by particular policies or industrial strategies paired with near-shoring.
- More **robust, less volatile supply** chains that are not as disrupted by external shocks.
- An overall **faster than expected growth** in clean energy deployment as all countries pursue aggressive decarbonisation and as companies in all countries pursue technological leadership.

[1] BNEF (2022), *4Q Global PV market outlook*;
[2] BNEF (2022), *Lithium-ion battery price survey*;
[3] Malhotra and Schmidt (2020), *Accelerating low-carbon innovation*;
[4] Way et al. (2022), *Empirically grounded technology forecasts and the energy transition*.

[149] BNEF (2022), *Building solar factories to rival China won't be cheap*.

Near-shoring would lead to higher costs, moving back and up the learning curve; but a mix of policy and market dynamics could bring rapid cost declines after a few years

Exhibit 4.4

Solar Example: Initially, near-shoring dynamics can be seen as moving back and up a clean energy technology 'learning curve', and a range of factors will influence how costs come down in future years
Solar learning curve: US$/W (Y-axis); MW (X-axis)

1 → 2

Initially, higher capital and other input costs may lead to higher prices/LCOEs.

Near-shoring 'restricts' a clean energy technology to a particular region, pulling it backwards along the deployment curve.

2 → 3A

A slowdown in deployment and permanently higher costs from:

- Higher ongoing costs (labour, energy, finance)
- Slower regulation, increased bureaucracy
- Smaller market size at regional/ national scale
- Protectionist policies/trade barriers

2 → 3B

An accelerated shift back down along learning curve could be due to:

- Global sharing of faster innovation
- Companies sharing learning between factories in different regions
- More robust, less volatile supply chains
- A faster-than-expected growth in clean energy deployments

◆ Historical prices
······ 28% Learning curve

Source: BNEF (2022), *4Q Global PV market outlook*; Helveston et al. (2021), *Quantifying the cost savings of global solar photovoltaic supply chains*; Way et al. (2022), *Empirically grounded technology forecasts and the energy transition.*

Focusing localisation strategies and effective implementation

Supply chain localisation strategies are likely to be most effective if they carefully consider key sectors and implementation [Exhibit 4.5], including that they:

- **Reflect the different market dynamics and supply chain complexity of different sectors.** Solar PV, battery and electrolyser production will be concentrated in very large-scale factories driving large economy of scale and learning curve effects; simple production subsidies can be effective in influencing location decisions, but it is important to ensure that these do not come at expense of global technology transfer. Wind turbine supply and installation (particularly offshore) entail a more complex supply chain but one which is inherently local; the challenge is therefore less to induce a shift in production location, than to ensure that the supply chain develops fast enough to support deployment targets.
- **Are aligned with a country's distinctive energy transition pathway and natural comparative advantage.** For example, given the UK's focus on offshore wind, developing a strong domestic supply chain should be a key priority. Similarly, the very widespread use of two- and three-wheelers in Southeast Asian countries creates a big opportunity to build large-scale local manufacturing capacity in electric two- and three-wheelers and related batteries.
- **Focus on the location of production and related supply chains rather than the ownership of companies**, thus maximising the potential for global transfer of technology and know-how while achieving the economic and security benefits of increased local production and reduced import reliance.

Ensuring diversified, resilient and secure supply – trade-offs of near-shoring

Exhibit 4.5

Where near-shoring is strategically beneficial, develop a suite of actions to maximise benefits of near-shoring of value chains

Action	Key Actors: Industry	Key Actors: Policymakers
Developing a **strategic vision of material and clean energy technology requirements by governments** to plan required supply chain built-out ahead of time, e.g., by setting out government strategy on critical raw materials or convening expert forums for discussion with industry. This could include understanding links with other sectors (e.g., defence), and import/export volumes.	✓	✓
Understand clearly the **considerations of near-shoring trade-offs for a particular geography or company**, including assessments of local industrial strategy, policy regime, energy and labour costs etc. Near-shoring should **focus on areas where there is strong growth/potential** in a particular country, e.g., electric two-wheelers in Indonesia, offshore wind in UK. For technologies earlier along deployment paths, **clear policy targets should provide certainty for large-scale growth in domestic demand**, ahead of a scale-up in domestic supply chains (e.g., ICE bans).	✓	✓
Only using gradual build-ups in domestic production/content requirements, to allow domestic supply chains to scale at a reasonable pace.		✓
Providing **incentives for construction** of domestic production capacity, tied to **accelerated permitting** alongside **explicit requirements for higher environmental and social standards than in existing production**. This should go with **community engagement**, to achieve local consent for new projects.		✓

Priority Areas: Ensure that near-shoring is aligned with areas of growth/strength for a country; government incentives for near-shoring should not distort market and competition.

Conclusion

5

Supply chain volatility has emerged as an important trend in the clean energy landscape, with the Covid-19 pandemic and global economic recovery, as well as Russia's invasion of Ukraine, feeding into higher prices. Securing resilient supply chains will be critical to ensuring a smooth progression of the energy transition. **This analysis has shown that while, at the global level, there are no inherent barriers to the scale-up of supply chains, clear actions from policymakers and industry must help to navigate challenges.** Three major cross-cutting challenges emerge:

- There could be tight markets for some key input materials, notably for some raw materials (lithium, copper) as well as shorter-lived volatility or delays for some more complex components.
- There are specific environmental and social risks especially relevant to solar PV and batteries.
- There is a high degree of concentration of production across many steps of clean energy technology supply chains.

In some instances, managing these challenges may involve some trade-offs between the speed of the transition and reducing environmental and social impacts, or localisation of production.

A critical priority for governments is to set out a clear strategic vision for the energy transition, supported by sectoral targets. Overall, the more clarity over the shape and timeline of the future transition, the more likely that supply chain challenges can be solved by market competition and private investment. Furthermore, governments can play an important role to shape incentives and introduce regulation that reduces market balance challenges, and must also set out regulation to ensure that supply chains for the growing clean energy sector minimise social and environmental risks.

Overall, the role of industry in driving innovation to reduce the scale of the challenge will be key – one that has already been demonstrated, such as in the evolution of battery technology away from materials perceived to have higher supply challenges (e.g., cobalt). Industry must also lead responsibly on social and environmental risks to ensure that the transition continues to have buy-in across society.

As the current political discussion centres on opportunities around relocation of clean energy supply chains, this Insights Briefing has outlined clear steps to ensure that any effort around relocation is carefully considered. The pace and scale of clean energy deployment means that all countries should be able to benefit from growing markets and grasp new opportunities around industrial competitiveness and energy security. However, in some cases, relocation of production is likely to entail short-term cost increases for the energy transition – which will require careful balancing against political priorities. Ensuring a balanced approach that can support a low-cost, fast-paced global energy transition, as well as meeting domestic political priorities, is vital.

The accompanying *EU Policy Toolkit* to this Insights Briefing takes a closer look at the key issues and required responses from a European perspective. The energy and geopolitical crisis resulting from Russia's invasion of Ukraine has accelerated Europe's imperative to turn away from fossil fuels, and therefore the need to ensure that clean energy deployment is not held back by supply chain issues. Furthermore, Europe is currently in a position of import dependency across many parts of clean supply chains, in particular with higher exposure towards the upstream sector (importing raw materials)[150] – a risk that is being addressed through policy proposals as part of the Green Deal Industrial Plan.

[150] EU Joint Research Council (2023), *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study*; Eurometaux (2022), *Metals for clean energy: Pathways to solving Europe's raw materials challenge*.

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