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नवीकरणीय ऊर्जा मंत्रालय
MINISTRY OF
NEW AND
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सत्यमेव जयते

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Developing Resilient Renewable Energy Supply Chains for Global Clean Energy Transition

Report

CEEW
THE COUNCIL

Acknowledgement

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Disclaimer

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GOVERNMENT OF INDIA
MINISTRY OF NEW AND RENEWABLE ENERGY

Dated: 28th March, 2023

Foreword

The rapid adoption of renewable energy at affordable prices and a massive scale and fast enough to collectively reach net-zero goals is a challenge that confronts the world today. On the brighter side, today, policymakers, regulators, grid operators and the private sector have varied technology options to choose from and the potential of renewable energy is proven to be enormous. Concurrently, steadily improving technology designs and performance are continuously driving down prices, and the cost of generating renewable electricity.

Countries are making efforts to raise their clean energy goals to tackle climate change and achieve Sustainable Development Goals. A series of global economic challenges and disruptions since the beginning of this decade have raised some critical questions and unraveled risks that can slow down the global clean energy transition. The geopolitical developments and the Covid pandemic adversely impacted the availability and prices of energy fuels, renewable energy technology components, and mineral resources. Countries realized that reliance on only a few technology suppliers, and component manufacturers lead to energy security and affordability concerns, and put the energy transition goals to risk.

The critical question that needs to be examined is, what type of transformations are required in the renewable energy supply chain that would enable rapid deployment of renewables at affordable prices? International forums must highlight the experience and concerns of government officials, regulators, grid operators, electric utilities, renewable energy developers, investors, industry, consumers, the finance sector, and other key players on the above question. The world can continue to experience the enormous benefits from renewables including zero fuel costs, electricity prices free from volatility and external influence, reduced reliance on fossil fuel imports, and significantly reduced pollution and water use by working towards enhancing diversification and resilience of supply chains.

This report on *'Developing Resilient Renewable Energy Supply Chains to Strengthen and Facilitate the Global Clean Energy Transition'* under India's G20 presidency would be a useful contribution to ongoing deliberations. Based on the analysis of supply chain challenges and opportunities in solar PV, wind, lithium-ion batteries and green hydrogen and deliberation and consultation with stakeholders,

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and domestic and international experts, the report identifies the following four strategic priorities for G20 countries to pursue and makes specific and actionable recommendations -

1. **Ensure comprehensive tracking** of global RE manufacturing capacity and trade flows to inform expansion and diversification strategies and foster competition in trade.

2. **Create new avenues of supply and enhanced investments across supply chains** to meet the increasing demand for clean technologies**.**
3. **Enable co-development of technologies** and innovations by sharing best practices on procurement and formalizing collaborations between technology-development labs across the world

4. **Facilitate the development of globally accepted standards and certification systems for new and** emerging RE technologies such as green hydrogen.

I compliment the Council on Energy, Environment and Water (CEEW) for their unique/in depth analysis of the manufacturing and trading landscape in key RE sectors, carefully listening to stakeholders and experts and condensing complex dynamics into useful findings and recommendations. We hope and expect that the report will help inform a robust consideration of collective changes that will put the world on the path to rapid scaling-up of renewable energy with resulting benefits to the economy, environment and most importantly, our people.

Bhupinder S. Bhalla

The transition to renewables will yield multiple socio-economic benefits: saving millions of lives lost to fossil-fuel pollutants, reducing energy dependency for the 80 per cent of people living in fossil fuel–importing countries, and driving local job creation and boosting livelihoods, particularly for women and the youth.

Image: iStock

Preface

Dr Arunabha Ghosh
CEO, CEEW

Whether the world needs an energy transition is no longer in question. Rather, the question is how to achieve it, and how soon. The answer to both of those questions will depend on how we develop the supply chains of renewable energy (RE) technologies that will feed the energy transition. By 2050, 90 per cent of electricity generation would need to come from renewable energy sources to meet net zero by 2050. To enable these RE sources to penetrate hard-to-abate sectors, such as mobility and industry, technologies such as batteries and green hydrogen would need to be produced at far larger scales than is the case currently. RE supply chains will need to develop at an unprecedented pace if we are to avoid a climate catastrophe. And yet these supply chains will also need to be resilient against fluctuating geopolitics and variations in global trade patterns.

The COVID-19 pandemic brought into focus the risks posed by the increasing complexity and concentration of global supply chains. Renewable energy supply chains are no exception. Today's RE supply chains were built piecemeal to feed a fledgling industry. The vulnerabilities of this scatter-shot approach are becoming even more apparent as RE technologies like solar and wind become more mainstream. Given the rapid rate of deployment needed for the energy transition, and the significant technological and investment challenges that this would entail, the global community needs to cooperate and collaborate to ensure the resilience of tomorrow's supply chains.

This report suggests that effective multilateralism must be the way forward to reconfigure RE supply chains, and the G20 is the ideal platform for such an approach. The world's largest economies have been primarily responsible for deploying renewable energy and building supply chains too. They bear a significant responsibility to ensure that these supply chains support the global community as a whole. Importantly, the response to supply chain vulnerabilities should be to look outward, rather than inward. Energy security is not the same as energy independence. An interdependent global supply chain will be better able to support the energy transition than individual countries responding to risks by shutting their borders, thereby stifling innovation, spooking investments, and making the energy transition more expensive (and slower) in the long run.

Given the border-agnostic nature of the climate crisis, G20 countries should ensure that smaller economies are equal partners in facilitating the global energy transition. This is particularly true for the Global South, which is often a consumer, rather than a producer, of RE technologies. Addressing the climate crisis should go hand-in-hand with achieving other sustainable development goals by creating local jobs and supporting livelihoods across the world and give the regions that will deploy the most clean energy infrastructure an added stake in clean technology development and manufacturing. Future RE supply chains can be a key economic engine for the 21st century given the right investments and policy levers are implemented by the global community. I hope that this report will initiate the much-needed conversation on building through collaboration a resilient RE supply chain.

The rapid adoption of RE will not only help decarbonise electricity systems but also help realise the desired impacts of the SDGs.

Image: iStock

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Acronyms and abbreviations

AEM	anion exchange membrane
ALK	alkaline electrolyser
APAC	Asia-Pacific Regions
ASME	American Society of Mechanical Engineers
BIS	Bureau of Indian Standards
BMS	battery management system
CAGR	compound annual growth rate
CdTe	cadmium telluride
CGA	Compressed Gas Association
CI(G)S	copper indium gallium selenide
COVID-19	coronavirus disease
DLE	direct lithium extraction
DNi	direct nickel process
EIGA	European Industrial Gases Association
EMDE	Emerging And Developing Economies
EoL	end of life
EU	European Union
EV	electric vehicles
EVA	ethylene vinyl acetate
G20	Group of Twenty
GHG	greenhouse gases
Gt	gigatonnes
GW	gigawatts
GWh	gigawatt-hours
H2	hydrogen
HHI	Herfindahl–Hirschman Index
HJT	heterojunction technology
HS	harmonised system
IBC	interdigitated back contact
IP	intellectual property
ISO	International Organization for Standardization
kW	kilowatt
kWh	kilowatt-hours
LATAM	Latin America
LFP	lithium ferro-phosphate
LIB	lithium-ion battery
MTPA	million tonnes per annum
MW	megawatt
NCA	nickel cobalt aluminium oxide
NMC	nickel manganese cobalt oxide
NPTEL	National Programme on Technology Enhanced Learning

O&M	operation and maintenance
OEM	original equipment manufacturers
PEM	proton exchange membrane
PERC	passivation emitter rear contact cell
PV	photo-voltaic
R&D	research and development
RE	renewable energy
REE	rare earth elements
REO	rare earth oxides
RIR	recycle input rate
SAF	sustainable aviation fuel
SDG	sustainable development goals
SiO2	silicon dioxide
SOEC	solid oxide electrolyser cell
STEM	science, technology, engineering, and mathematics
TMS	thermal management system
TOPCon	tunnel oxide passivated contact
TWh	terawatt-hour
UK	United Kingdom
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
US	United States
US DOE	United State Department of Energy
USA	United States of America
USGS	United State Geological Survey
WTO	World Trade Organisation

A speedy and risk-proof transition to RE will only be possible if countries can secure access to uninterrupted and affordable supply chains of key technologies.

Image: iStock

Executive summary

The current global economic development aspirations coincide with intensifying climate risks, growing geo-political adversities, and shrinking carbon space. For several countries, progress on the sustainable development goals (SDGs) is slow, energy demand is rising, and their fiscal bandwidth is stressed as they strike a balance between cleaning up their energy mix and maintaining the affordability of energy supplies for large proportions of their populations (UN 2022, Carbon Tracker and CEEW 2021, Ghosh, A., Ganesan, K. 2015). For the world to achieve a net-zero future, solar and wind power capacities must grow 20 and 11 times between 2020 and 2050, respectively (IRENA 2022, IEA 2021a). With the rise in the share of variable renewable energy (RE) in the electricity systems, storage solutions must see a massive growth. And, for the hard-to-abate sectors, green hydrogen ecosystem must be scaled up rapidly.

The rapid adoption of RE will not only help decarbonise the electricity systems but also help realise the desired impacts of the SDGs. However, a speedy and risk-proof transition to RE will only be possible if countries can secure access to uninterrupted and affordable supply chains of key technologies.

This report presents the current structure of global supply chains for solar photovoltaic (solar PV), onshore and offshore wind, lithium-ion batteries (LIBs), and green hydrogen. It briefly discusses the manufacturing landscape for critical components in these supply chains, including requirements of key minerals, skills, logistics, infrastructure, and associated innovations. Finally, and most importantly, the report captures the evolution of exports and imports of key components and equipment in the aforementioned sectors over the last decade – 2012 to 2021. This analysis further assesses the concentration and dependency of and on key components and products. The key findings include:

- **Manufacturing capacities of RE technologies and their sub-components are highly concentrated in a few geographies**. The location and quantum of manufacturing capacities are important metrics to determine the global supply-chain resilience. The analysis shows that the manufacturing capabilities across the RE technologies are highly concentrated in a handful of countries. However, the expansion of manufacturing capacities in certain countries has catered to meeting domestic deployment demand for the technology. Therefore, it also important to study two additional aspects of supply chains over time. One, the import dependencies of key components and equipment between countries and regions. Two, the countries that dominate the global supplies of key technologies and components.

> Many countries, particularly those with lower incomes, have a highly concentrated import mix across solar, wind, and lithium-ion batteries.

- **There has been a steady growth in global trade, albeit with a high concentration of exporters.** Despite a significant decrease in prices, the traded values of solar modules, LIBs, and wind generators have increased steadily over the last decade. For example, over the last decade, 70 per cent of the global exports in solar PV have come from only 4 countries. Similarly, in wind, only 4 countries accounted for more than 80 per cent of the total exports in the last 10 years.
- **Many countries, particularly those with lower incomes, have a highly concentrated import mix across solar, wind, and lithium-ion batteries; the concentration has only increased with time.** The concentration of RE-manufacturing facilities has had a drastic effect on the import mix of individual countries. In most cases, the concentration of imports of individual countries was greater than the already high concentration globally. Further, the level of import concentration varies by the income levels of the countries participating in global trade. In 2021, almost 90 per cent of lower-middle income countries and 65 per cent of high-income countries had concentrated imports in solar PV. For wind, more than 90 per cent of the countries have shown a high import concentration over the last decade. In the case of LIBs, 100 per cent of the lower-middle-income countries consistently had concentrated imports over the last 10 years. In the same duration, the number of high-income countries with concentrated battery imports increased from ~30 per cent to over 60 per cent. These trends point to concentrated supply chains, making them vulnerable to risks.
- **Green hydrogen is in its nascent stages of development and needs a collaborative effort to scale up efficiently**. Globally only 8 GW/yr of electrolyser manufacturing capacity had been deployed (IEA 2022c). To achieve the global net-zero target by 2050, 850 GW of electrolyser needs to be deployed by 2030 (IEA 2022f). To meet these deployment target we may need atleast 100 GW of annual manufacturing capacity whereas country-level commitments only amount to 62 GW per annum by 2030 (IEA 2022c). Similarly, investments worth USD 700 billion are needed (Hydrogen Council 2022), whereas global

commitments stand at approximately USD 100 billion within limited geographies. Apart from the capacity and deployment challenges, electrolyser and fuel cells, which are at the heart of the green hydrogen ecosystem, use critical minerals and rare earth elements with the same access issues that plague other RE solutions. Finally, a disconnect between standards, regulations, and certification systems could significantly slow down the scaling-up of the green hydrogen ecosystem. Addressing all these challenges will require a collaborative effort to develop resilient supply chains and provide global access to this new energy vector.

Based on the analysis and insights, the report identifies four strategic priorities for the Group of Twenty (G20) to ensure resilient RE supply chains. These are:

Ensure comprehensive tracking of global RE manufacturing capacity and trade flows to inform expansion and diversification strategies and foster competition in trade. This must include tracking of

- Trade-flow data with greater accuracy
- Manufacturing capacity across the sectoral value chains
- New and innovative projects, applications and technology demonstrations

Create new avenues of supply and enhanced investments across supply chains to meet the increasing demand for clean technologies**.** These avenues must lead to:

- Dedicated financing for manufacturing through multilateral development banks
- Development of handbooks and courses to train individuals and institutions on creating local value chains
- Development and prioritisation of infrastructure for the production and movement of raw materials and finished products
- Development of global standards on infusing circularity in RE supply chains

> A disconnect between standards, regulations, and certification systems could significantly slow down the scaling-up of the green hydrogen ecosystem.

Enable co-development of technologies and innovations. This could happen through:

- Sharing best practices on public procurement models which help scale up advanced technologies
- Formalising collaborations between technology-development labs across the world

Facilitate development of globally accepted standards and certification systems for new and emerging RE technologies such as green hydrogen. This must include:

- Establishment of interoperability in operational and safety standards
- Development of harmonised and universally acceptable certification systems for healthy global trade

1. Background

The Intergovernmental Panel on Climate Change (IPCC) estimated that starting 2020, the total carbon budget remaining, for a 50 per cent chance of temperature rise to remain below 1.5 degrees celsius, as 500 gigatonnes (GT) CO2 (IPCC 2022). At the current annual average emissions rate of ~50 GT observed during 2010-19 (IPCC 2022), this budget will be exhausted before 2030. Global emissions must be reduced by 45 per cent by 2030 and decline drastically thereafter (UNEP 2022). Globally, 88 parties, including the major emitters, have adopted net-zero targets, covering approximately 79 per cent of global GHG emissions.(UNEP 2022).

Emerging economies will witness a rising energy demand; 88 per cent of the growth in electricity demand between 2019 and 2040 is expected to come from these economies (CEEW 2021). However, this will coincide with a shrinking carbon space and an urgency to decarbonise the global economy. Thus, the growth in emerging and developing economies (EMDEs) must be fuelled by clean energy sources. The transition to renewables will yield multiple socio-economic benefits: saving millions of lives lost to fossil-fuel pollutants, reducing energy dependency for the 80 per cent of people living in fossil fuel–importing countries, driving local job creation and boosting livelihoods, particularly for women and the youth (CEEW 2021), thus furthering the SDGs.

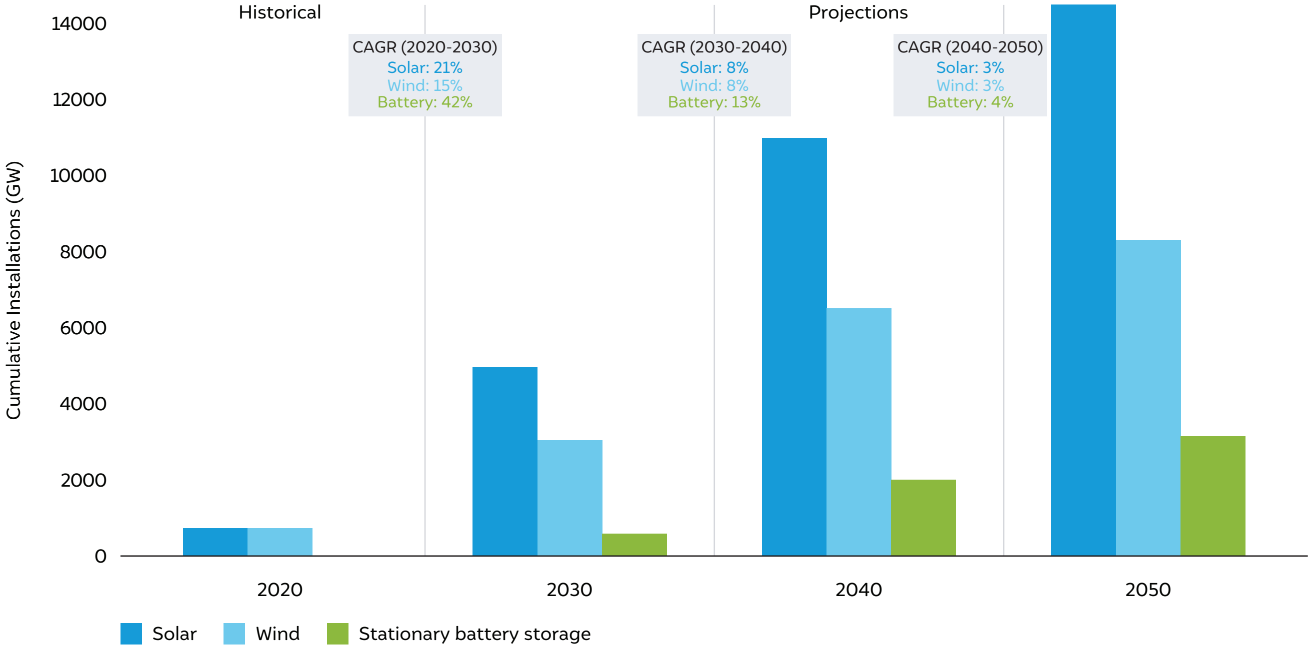
1.1 Importance of integrated supply chains for a global energy transition

As per the International Energy Agency's (IEA's) report on "Renewable Electricity", to reach net-zero emissions by 2050 globally, the share of renewables in the electricity sector must increase from 28.7 per cent in 2021 to 90 per cent in 2050 (IEA 2022a). Solar and wind technologies will be the major contributors to meeting these milestones, from a combined capacity of 1,449 GW in 2020 to over 22,723 GW in 2050 (Figure 1). As the share of intermittent renewable energy increases, the deployment of energy storage technologies would also need to increase. It is projected that battery technology will be the preferential energy storage technology for the next few decades and that battery installation in 2030 and 2050 will be 2311 GW and 3860 GW respectively (IEA 2022b). Batteries will also see significant use in the mobility sector (shown in Figure 2), with 5600 GWh and 10400 GWh of demand expected by 2030 and 2050 respectively (CEEW,IEA,UC-DAVIS,WRI 2023). Currently, lithium-ion batteries dominate the market. It is expected that while the demand for lithium-ion batteries will continue to grow, alternative technologies with simpler and shorter supply chains may also gain preference.

Similarly, green hydrogen will be an important fuel to decarbonise hard-to-abate sectors. It is estimated that electrolyser capacity must reach 850 GW by 2030 and 3,500 GW by 2050 to achieve the global net-zero target by 2050 (IEA 2021b). Nearly 100 GW of electrolyser manufacturing capacity is needed to deploy 850 GW of electrolyser capacity globally by 2030. Figure 3 shows that, until the year 2021, the manufacturing capacity was only about 8 GW/annum. However, several countries are ramping up manufacturing capacity, and it is expected to reach 62 GW by 2030 (IEA 2022b). This is approximately 61 per cent of the total capacity required and will only manifest by 2030. Hence, there is a significant additional capacity required in the short term to achieve the 2030 production targets. To reach global net-zero green hydrogen production capacity must reach 75 MTPA and 330 MTPA by 2030 and 2050 respectively, up from only 0.8 MTPA currently (Hydrogen Council 2022). The production capacities of electrolyser as well as green hydrogen indicate the scale of expansion required in supply chains. Hence, the entire supply chain needs to be established soon. This is both an opportunity and a challenge. A cooperative approach will help scale green hydrogen rapidly and ensure that countries meet their 2030 agenda goals and subsequent net-zero targets.

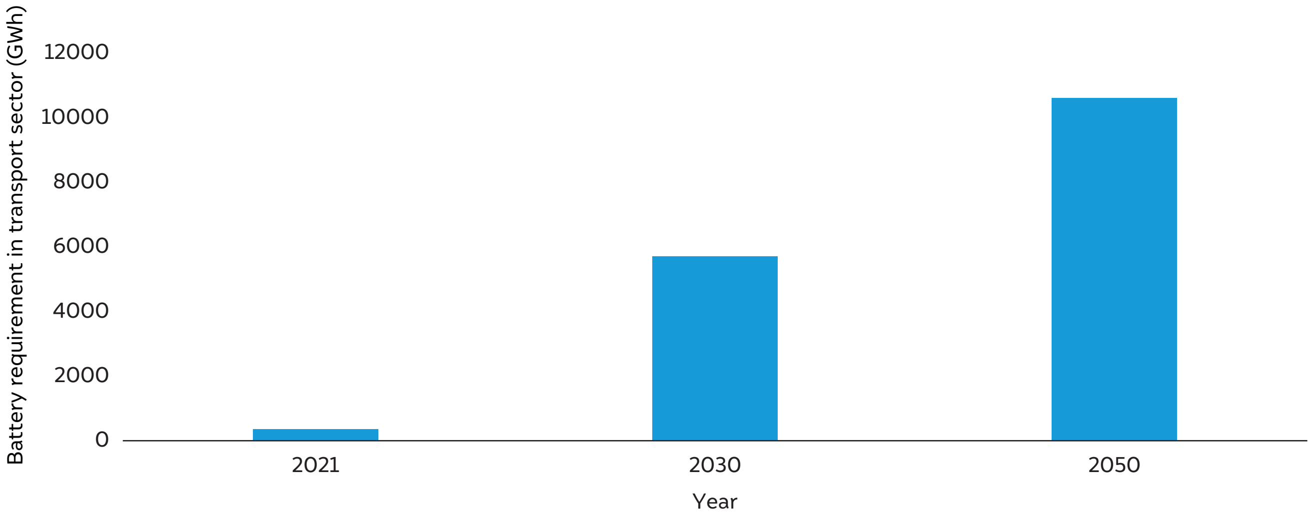
For renewables, the supply chain includes the production and delivery of raw materials for components, energy generation and its transmission and distribution to the end user, operation and maintenance (O&M), and end-of-life factors such as recycling and waste management, covering diverse individuals, companies, and countries (Jelti et al. 2021). This implies that a diverse set of actors with varying objectives and interests must work in collaboration to achieve uninterrupted, secure, and affordable RE supply chains.

Figure 1 Solar, wind, and stationary storage capacities must grow 20, 11 and 172 times between 2020 and 2050, respectively as per IEA's net-zero scenario



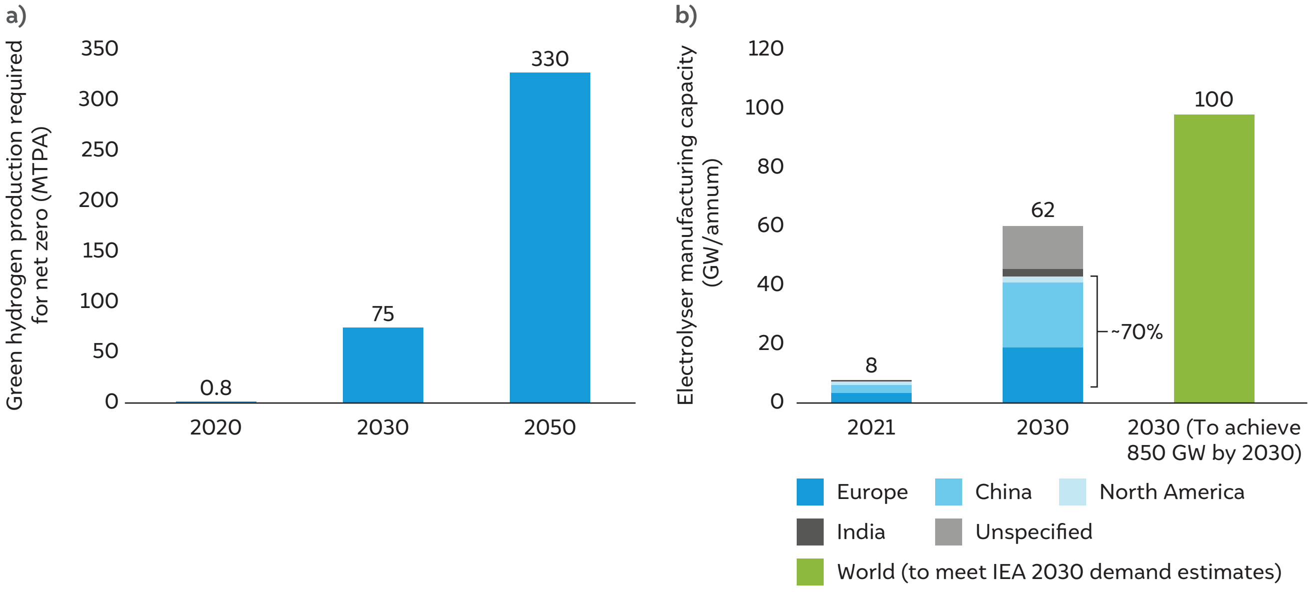
Source: IEA 2021a

Figure 2 The electrification of the mobility sector in coming years will lead to increasing demand for batteries



Source: (CEEW, IEA, UC-DAVIS, WRI 2023)

Figure 3 Achieving global net-zero ambitions will require a significant increase in global green hydrogen production and a matching growth in electrolyser manufacturing capacity



Source: (Hydrogen Council 2022, IEA 2022b)

1.2 Importance of supply chain management for meeting sustainable development goals

Supply chain networks are primarily influenced by government policy and stakeholders (i.e., the customers, suppliers, and third parties) (Seuring & Müller 2008). Changes in policy and shifting incentives of the stakeholders can alter these networks. Collaborations across supply chains are vital to achieving several SDGs and have positive economic and environmental implications (Chauhan et al. 2022; Yang and Gong 2021).

Thus, there is a need to ensure that the adoption of RE technology bolsters countries' efforts towards meeting the SDGs. The rapid adoption of RE and collaborations across value chains can advance the progress of the following SDGs: SDG 7 (affordable and clean energy), SDG 13 (climate action), SDG 8 (decent work and economic growth), SDG 11 (sustainable cities and communities), and SDG 12 (responsible production and consumption).

However, the increased pressure of the current development paradigm on the environment and economies is evident: planetary boundaries are changing, fiscal resources are under pressure, and the available carbon space is declining fast. The COVID-19 pandemic and the recent geopolitical developments have further exacerbated these pressures. As a result, uninterrupted and affordable RE supply chains are at threat, putting the SDGs at risk.

1.3 Supply-chain resilience is critical with the continuously rising quantum of trade in RE technologies

Regions worldwide have varying natural resources, energy fuels, and non-fuel minerals endowments. While this is closely linked with their economic productivity, well-being, prosperity, and growth prospects, trade activity has heralded the economic interconnectedness of countries. It enabled production processes and raw materials to be located where it was cost-effective and the products to be transported to the end consumers as needed (Javorcik 2020). In the case of RE, most of the world is import dependent.

While the global trade of RE technologies has risen, only a handful of countries supply RE components and equipment to the world. The growth in RE deployment across developed and developing countries is at risk if it relies only on a limited number of exporters. Availability of RE supply chain components will be at risk should the manufacturing locations be affected due to geopolitical developments, price volatility of materials, and climate risks. New manufacturing capacities must therefore be developed in a relatively more distributed fashion to facilitate trade and reduce the impact of supply disruptions.

1.4 About the report

This report aims to support the readers in understanding the present structure of global supply chains for solar PV, onshore and offshore wind, LIBs, and green hydrogen. The report briefly discusses the manufacturing landscape for critical components in these supply chains, including requirements of key minerals, skills, logistics, infrastructure and associated innovations. Finally, and most importantly, the report captures the evolution of trade flows for crucial commodities and equipment in the mentioned sectors over the last decade (2012–2021) and highlights the concentration and dependencies across developing and developed countries. Our research and analyses lead to 11 targeted recommendations for the G20 to establish resilient RE supply chains for a clean and prosperous future for all.

2. Supply chain insights

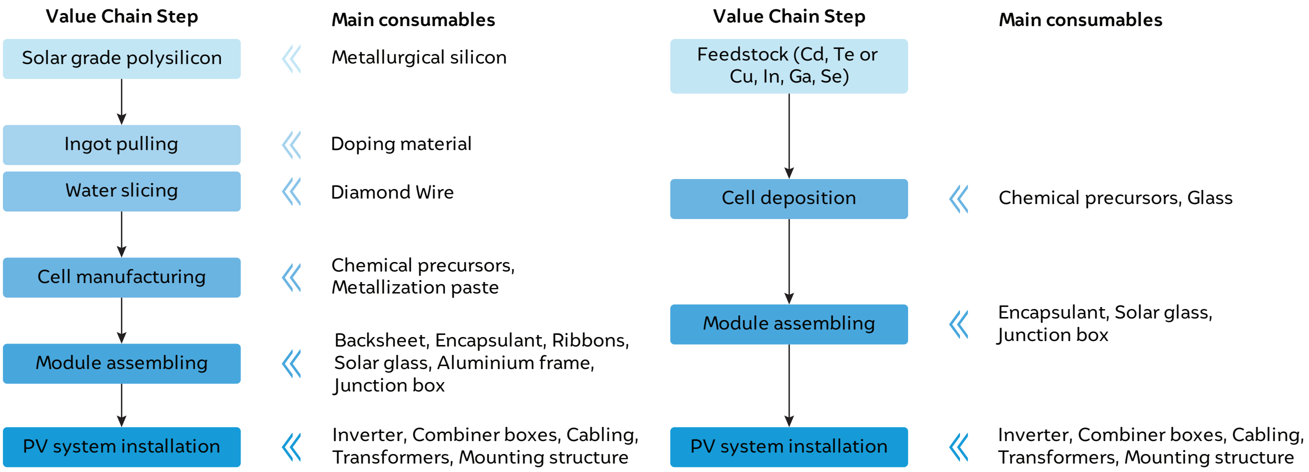
2.1 Solar-photovoltaics

Currently, there are two main production routes for solar PV: wafer-based crystalline silicon (c-Si) and thin film (Figure 4), with the former responsible for over 95 per cent of production in 2021. The primary raw material for the crystalline-silicon value chain is metallurgical-grade polysilicon, which is produced from quartz. Producing solar-PV modules using thin-film technologies (e.g., copper indium gallium selenide – CI(G)S, cadmium telluride – CdTe, or the upcoming perovskites) is simpler than c-Si modules because of the fewer steps required.

Figure 4 Two primary production methods for solar PV include wafer-based crystalline silicon (c-Si) and thin film technology

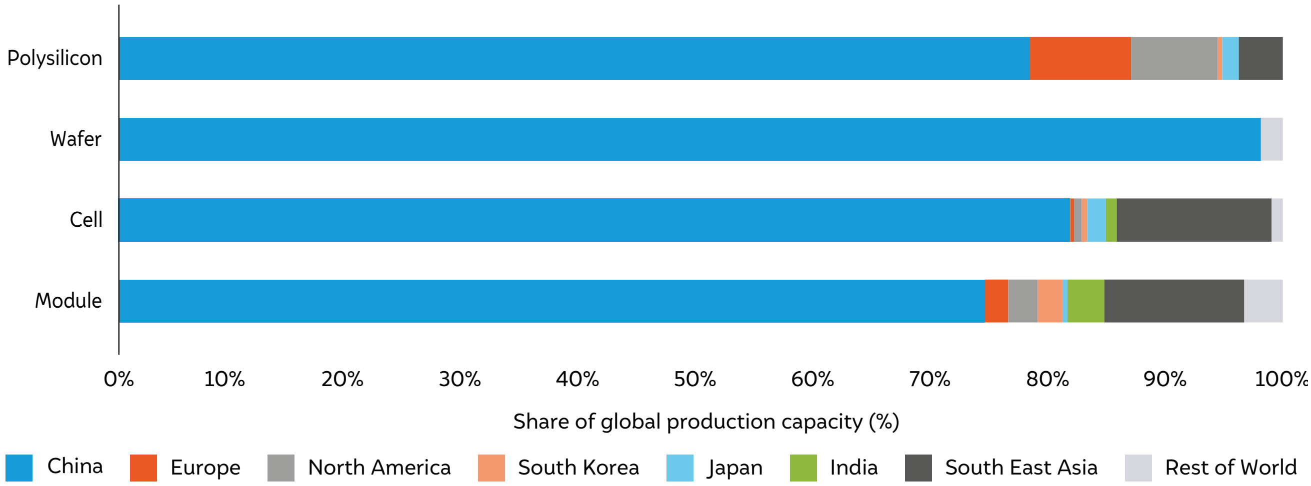
Schematic view of the main steps of the c-Si PV-module value chain

Thin-film value chain



Sources: ISA (2023)

Figure 5 In 2021, every step of the solar PV value chain was concentrated in a few countries



Source: ISA (2023)

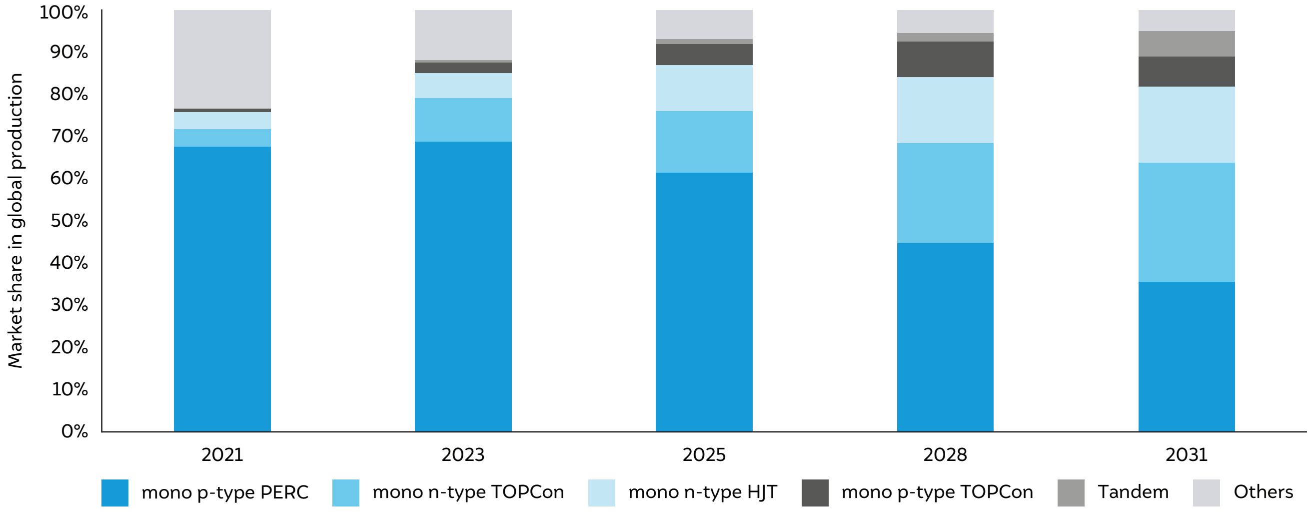
Global solar-module manufacturing capacity

The global manufacturing capacity of solar modules and other raw materials has risen significantly in the last decade. However, this growth is concentrated. Figure 5 shows the total manufacturing capacity across major regions for the crystalline-silicon modules in 2021. It should be noted that many countries have taken initiatives to scale up domestic solar manufacturing, and shares of other regions may increase in the coming decade. Global polysilicon, wafer, cell and module manufacturing capacities were 294 GW, 414 GW, 441 GW and 482 GW, respectively.

Polysilicon and wafer production is a technically complex process and requires reliable and continuous electricity. Additionally, these manufacturing units are large and require large amounts of capital for set-up and operation. Hence, the cost of capital becomes an essential factor for competitiveness, leading to a significant concentration in the industry.

The next step is solar-cell manufacturing. Different types of solar cells exist with varying efficiencies. In 2021, mono p-type PERC took over 80 per cent of the market share. However, emerging technologies, such as heterojunction technology (HJT), TOPCon, and interdigitated back contact (IBC), are expected to become more cost competitive by the end of the current decade. Such emerging cell types yield higher efficiencies but at greater cost and complexity. However, it is expected that, by 2030, the share of mono p-type PERC will reduce, and new technologies, like TOPCon and HJT, will have more than 50 per cent share (CEEW 2022), as shown in Figure 6.

Figure 6 Over the coming years, new technologies like TOPCon and HJT are expected to make up more than 50 per cent of global solar PV production



Source: CEEW (2022)

The final stage in solar-PV manufacturing is module assembly, which is the least capital-intensive stage and requires less technical expertise than the earlier stages. Several multi-cell strings are encapsulated, i.e., assembled with a sheet of glass, two foils of cell encapsulant (typically Ethylene-vinyl acetate – EVA resin), and a back sheet (typically aluminium or another sheet of glass) to make a module that can be consequently framed and then equipped with a junction box. The remaining material value – and the bulk of the raw-material weight – is incorporated at this step. For CdTe thin-film modules, most of the raw material cost comes from this stage (primarily glass and aluminium back sheets). Over time, thinner glass has resulted in lesser weight and cost of glass per module, but this is partly reversed by an increase in glass–glass modules, which are particularly important for bifacial designs. Aluminium has over 99 per cent of the market share for frames, though frameless modules are a growing option and could represent ~15 per cent of the market within a decade. Although cheaper to produce, frameless modules can impose additional costs downstream (for example, in special packaging) (ISA, 2023).

Material requirement

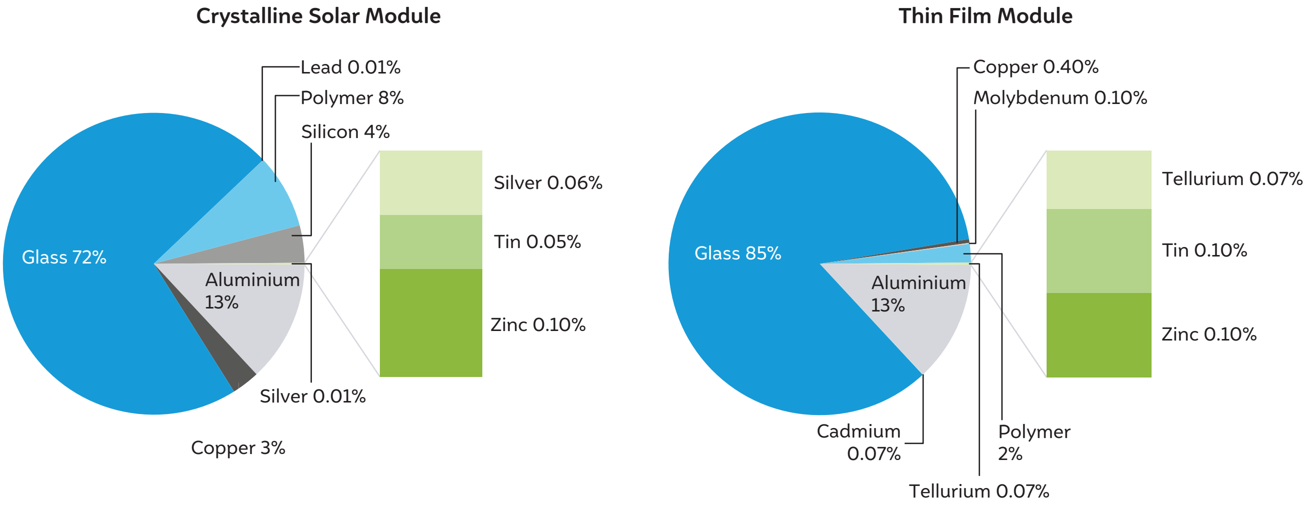
Solar modules require many kinds of raw materials and minerals. Aluminium, glass, copper, polymer, and silicon are some of the key materials and minerals with the highest weight share (Figure 7). As the demand for solar modules grows, the demand for many minerals is expected to increase significantly. The exploration and mining of some of these minerals can take up to a decade. Investments in the value chain must thus be made accordingly.

Infrastructure and skill requirement

Quartz mining and module assembling are the simplest processes in terms of requirements. Module manufacturing relies on the assembly of elements that have been manufactured in more-complex processes upstream in the value chain. They require low labour costs, low-to-medium skills, reliable and developed infrastructure, and, in the case of quartz mining, raw-material availability. Assembling lines are also significantly less capital-intensive and can thus be started with a lower initial investment.

While cell manufacturing requires slightly more capital than module manufacturing, its infrastructure requirement is similar to solar modules. The success of cell manufacturing requires a skilled workforce and the presence of research and development (R&D) centres if innovative technologies, like n-type monocrystalline, are being targeted by the facility. Access to patents and intellectual property rights (IPRs) is also crucial for this step.

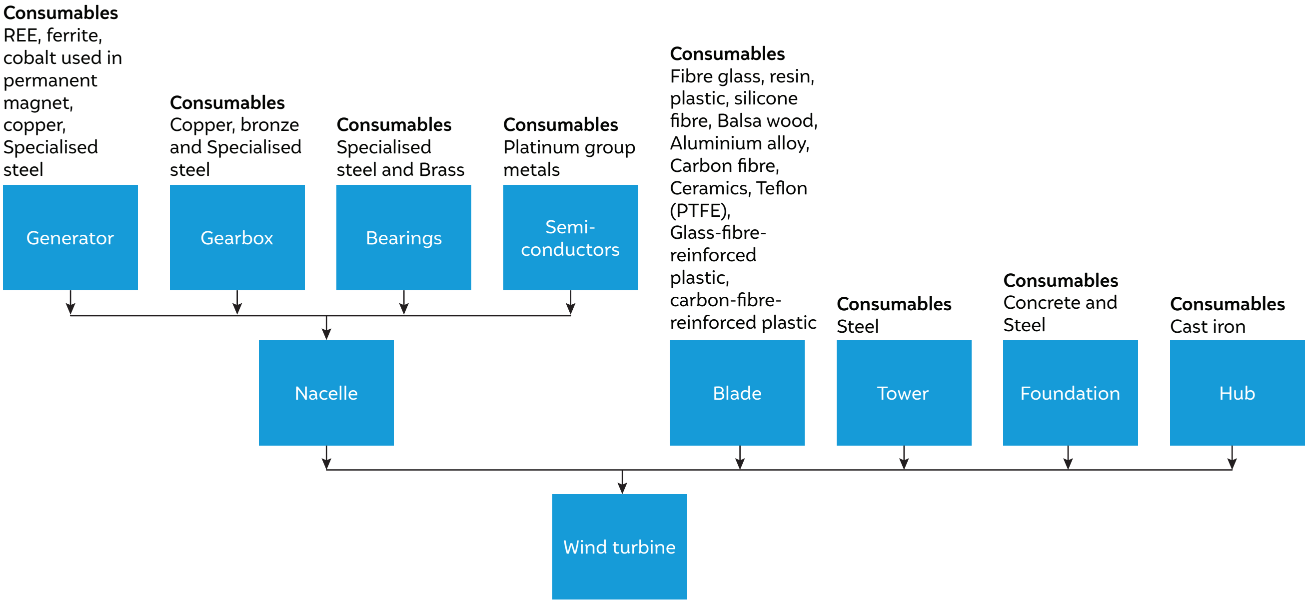
Figure 7 Solar modules need several raw materials and minerals, including aluminium, glass, copper, polymer, and silicon, with the highest share (by weight)


Crystalline Solar Module

Thin Film Module

Source: IEA (2022)

Figure 8 Manufacturing a wind turbine involves assembly of several components, some of which are highly specialised in nature



Source: Author's compilation based on literature review (Ayee et al. 2009; GWEC 2022)

Manufacturing steps, such as metallurgical-grade silicon, solar-grade silicon, and ingot and wafer manufacturing, are very complex; they are the most capital-intensive and require highly skilled workers. Access to 24-hour (reliable and cheap) electricity is also essential. Additionally, an industrial ecosystem in the region plays a vital role in the success of these sections of the value chain.

2.2 Wind

The wind supply chain consists of various assembly lines, shown in Figure 8. The global supply chain involves participation by (i) original equipment manufacturers (OEMs) that set up assembly lines or turbine-manufacturing facilities to supply finished products (wind turbines) for installation at project sites, (ii) suppliers of individual components and sub-components, and (iii) manufacturers of equipment and machinery used for producing key components and installation of turbines on project sites. The logistics of installation, construction, operation, and maintenance are also crucial steps in the wind supply chain. Manufacturers have to strike the right balance between the in-house production of components and outsourcing to third parties to deliver on their turbine designs (GWEC 2022).

Global manufacturing capacities

In 2020, the total nacelle manufacturing capacity was 120 GW(GWEC 2022). Major countries or regions include China (58 per cent), Europe (18.5 per cent), the USA (10 per cent) and India (8.5 per cent). Seven of the top 10 manufacturing companies in 2020 were in the Asia-Pacific region (6 in China) (BNEF 2021). Based on functionality[1] and cost-share, the tower, rotor blade, generator, and gearbox are the key components in a wind turbine (CSTEP and WISE 2015; IRENA 2012).

Component manufacturing

In 2020, China and the EU had the highest share of the manufacturing capacity of generators, blades, and gearboxes. Demand for generators and blades was equally met through in-house production by OEMs and third-party vendors specialising in producing these components. For gearboxes, 87 per cent of the demand was met through third-party vendors (GWEC 2022) (Figure 9).

Between 2016 and 2021, developed countries saw a reduction in the manufacturing capacity of onshore wind turbine blades (a crucial component). These reductions have increased their reliance on imports David, Andrew. 2021b). As blade manufacturing is labour-intensive, countries with low labour costs – majorly developing economies – provide competitive grounds for meeting global demand (David, Andrew. 2021a).

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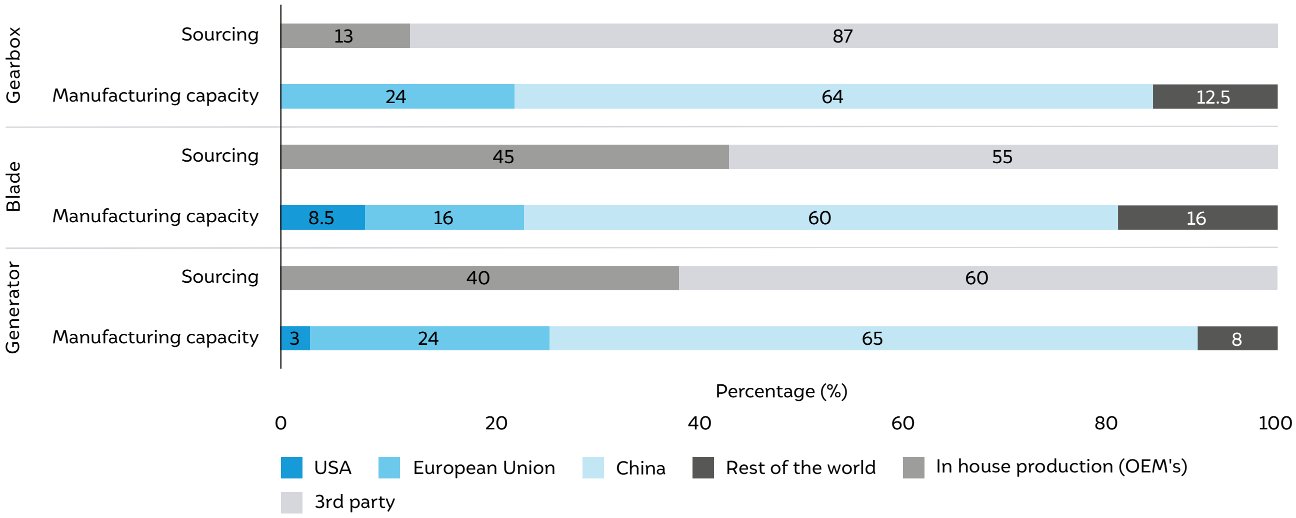
[1] Functionality refers to a component's importance in the operation of the wind farm.

Figure 9 In 2020, China and the EU had the highest manufacturing capacity of generators, blades, and gearboxes



Source: Authors' analysis based on data received from GWEC.

Figure 9 shows that the manufacturing capacities of components and sub-components are concentrated. This implies a higher risk of interruptions in the availability of these components, if the manufacturing locations get affected due to geopolitical developments, price volatility of materials, and climate risks. New manufacturing capacities must therefore be developed in a relatively more distributed fashion to ease trade and reduce the impact of supply disruptions.

Infrastructure and skill requirement

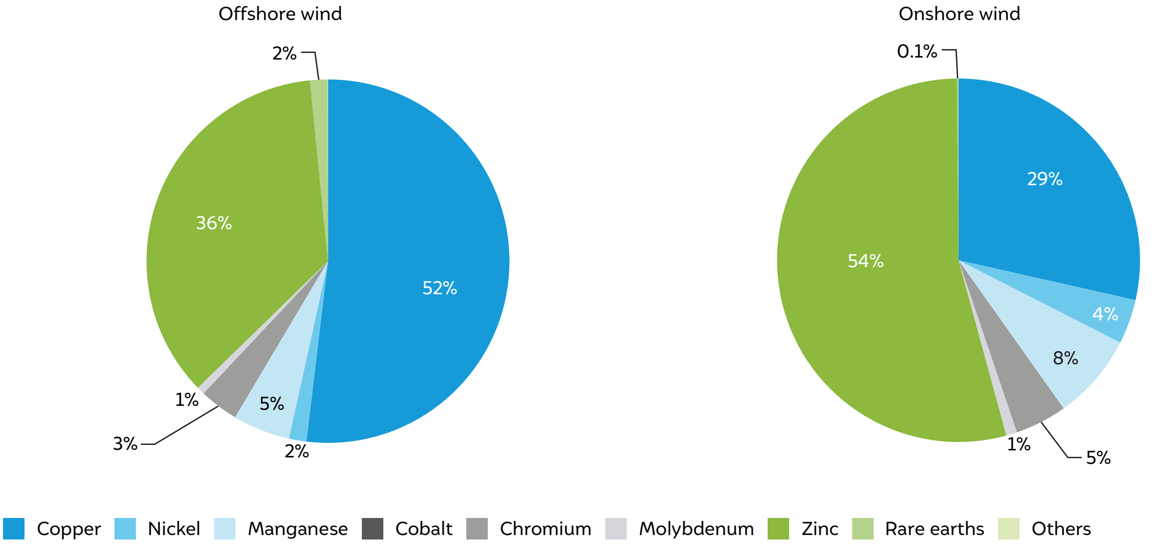
Technology in the wind sector is fast-evolving (Lucena 2021). For example, the capacity of onshore wind turbines is expected to increase from an average of 2.6 MW in 2018 to 4-5 MW for projects to be commissioned by 2025 (IRENA 2019). For offshore, it is expected that projects in 2025 will be based on turbine ratings of 12 MW and above, which are expected to increase further to 15 to 20 MW over the next decade (IRENA 2019). Thus, offshore wind has unique challenges due to the size and weight of the turbines and associated components. Installation of turbines at sites is also dependent on specialised and heavy machinery, such as lifting cranes, the manufacturing of which is also concentrated (Knauber, Sarah 2022). Countries with a high potential for offshore wind must build port infrastructure and deploy a large number of vessels for laying cables and installing, operating, and maintaining wind turbines (NREL 2022).

Innovations could also make supply chains more cost-effective and resilient. For instance, new technologies could make rotor blades lighter (reducing transportation and manufacturing costs), use locally available raw materials, or enable hybrid and cost-effective tower designs that can be assembled on-site (which would reduce transportation costs) (CSTEP and WISE 2015, DOE 2023).

Continuous changes in technology and turbine sizes imply additional investments in upgrading manufacturing facilities for key components and assembly lines. While these upgrades are desirable for the growth of the wind sector, they also need significant financing capabilities and workforces with civil and electrical engineering skills.

In terms of the skills and expertise of the workforce, the requirement of science, technology, engineering and mathematics (STEM) professionals is higher in the wind sector, more so in onshore projects when compared to other mature RE technologies such as solar PV (GWEC 2022). STEM courses typically require additional years of formal education and capabilities to finance the same. This implies that high lead-times and additional efforts are needed to generate a workforce suitable for the wind industry. The majority of the wind sector's workforce comes from China and Europe (IEA 2022e), which are the major hubs of manufacturing facilities. While training systems for the onshore wind sector are established, the growth of offshore wind will require newer and more diverse skill sets, such as training to adhere to safety guidelines relevant to professionals working at heights and sea survival (IEA 2022e). There is a significant skill overlap between the offshore oil and gas industry and the offshore wind industry (GWEC 2022); thus, the offshore oil and gas sector could help in meeting the skill needs for an accelerated deployment of offshore wind.

Figure 10 Copper and zinc form bulk of the mineral requirement in onshore and offshore wind turbines



Source: IEA 2021d

Due to the factors highlighted above, and highly competitive power-procurement markets, diversification of wind manufacturing and supply chains is a challenging task. Thus, demand-side policies and offtake assurances may be needed to involve local suppliers of components and sub-components. Additionally, scaling up offshore wind deployments can be challenging unless domestic (or regional) supply chains are established, and manufacturing and procurement facilities are developed on ports.

Material requirement

Construction of wind farms necessitates several materials (like concrete and steel) and key minerals (such as copper, zinc, and manganese). Concrete and steel comprise 90 per cent of the material requirement for onshore wind farms, whereas steel accounts for 90 per cent of the material required for offshore wind farms (GWEC 2022).

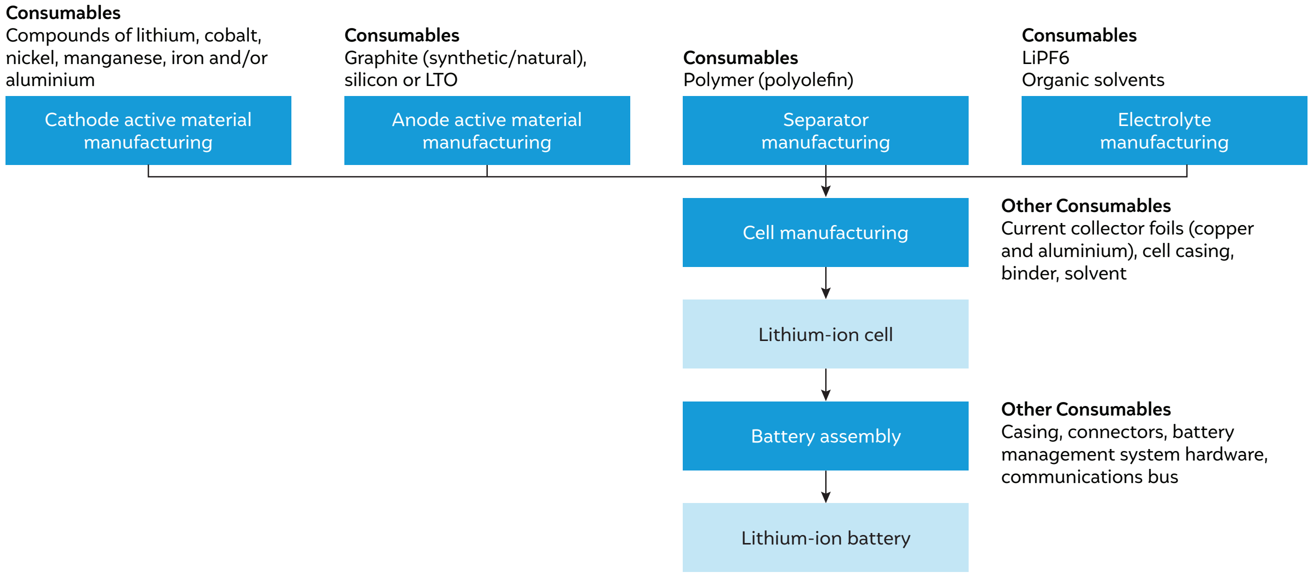
As shown in figure 10, within the overall requirement of key minerals - copper and zinc account for 83 per cent and 88 per cent of the mineral requirement in onshore and offshore wind turbines, respectively (IEA 2021c).

2.3 Lithium-ion battery

The electrification of the mobility sector will increase the demand for batteries. Similarly, for uses in grid, batteries are expected to have the largest market share. While many battery technologies have been developed and are in process of development, lithium-ion batteries (LIB) will have the largest market share for both grid and mobility sectors (IEA 2021c). The primary LIB supply chain has multiple steps, starting with the mining and refining of raw materials to the manufacturing of battery cells, the assembly of the batteries, and finally, the deployment of the batteries in various applications. The expected demand for batteries has increased the flow of investments across the battery value chain.

The capacity addition to the battery supply chain has been more prominent in specific geographies. This geographic concentration throughout the supply chain has been due to on-ground advantages in terms of supply (e.g., availability of mineral resources), demand (e.g., proximity to EV-manufacturing hubs), and other enablers (e.g., preferential manufacturing policies and access to finance) (Bridge and Faigen 2022). Many supply-chain steps are also technology-intensive, and a small number of companies dominate the global supply chain. Figure 11 highlights the complexity of the LIB supply chain, as well as the variety of inputs that go into making a battery. LIBs consist of multiple cells, a casing, and a battery-management system (BMS). While most of the battery supply chain is common to all LIBs, a distinction exists based on the chemistry used in the battery cathode. The two most common cathode chemistries – nickel manganese cobalt oxide (NMC) and lithium ferro-phosphate (LFP) – are both made using lithium, but NMC cathodes also require nickel, manganese, and cobalt, while LFP can be made using more abundant minerals such as iron and phosphate.

Figure 11 LIB supply chain in detail with major inputs



Source: Authors' analysis

Battery and component manufacturing

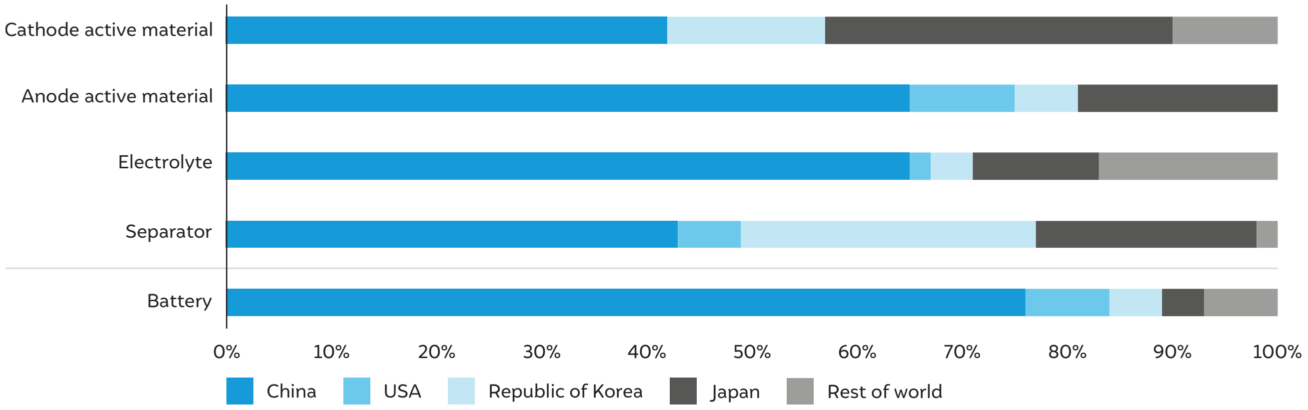
Battery manufacturing is generally a combination of two separate manufacturing processes: cell manufacturing and battery assembly. In some cases, both processes occur in the same integrated plant. Often, cells are manufactured at a single mega-factory and then distributed to various battery assemblers and OEMs.

The key processes involved in battery manufacturing are electrode production, cell production, cell finishing, and battery assembly. The first stage of manufacturing an LIB cell is the production of the electrodes. Electrode production is followed by cell production, which takes place in a dry room to minimise moisture intrusion in the cell. At this stage, the electrodes, electrolytes, and other cell components are all assembled into a single finished product: the LIB cell. After cell production, the cell-finishing stage begins, where the cells are charged and discharged for the first time in a controlled manner.

Battery assembly involves the production of battery modules and the final battery pack. Battery cells are assembled within a housing along with a BMS and thermal management system (TMS). Cell manufacturing is a highly technology-intensive process, and the trend has been towards higher-capacity manufacturing plants. The capital cost of battery manufacturing has also come down significantly in recent years (IEA 2020a). Similarly, the battery component–manufacturing ecosystem is quite concentrated globally.

Three countries dominate battery cell–component manufacturing: China, Japan, and Republic of Korea (DOE 2021). For three of the components highlighted – cathode material, anode material, and separators – more than 90 per cent of manufacturing capacity is concentrated in only these three countries. As of 2020 (shown in Figure 12), battery manufacturing is concentrated in China and is expected to stay concentrated there over the coming years.

Figure 12 Market concentration of battery component manufacturing in 2020 was significant



Source: DOE (2021)

Infrastructure and skill requirement

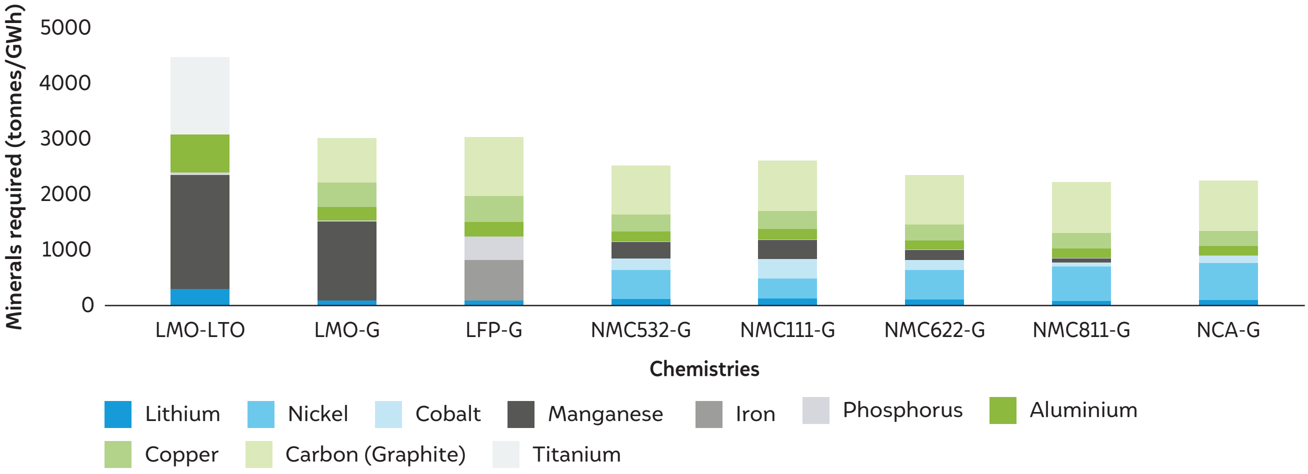
Beyond production capacities and access to raw materials, battery supply chains are reliant on several additional factors. Access to energy, availability of skilled workers, and sufficient and safe shipping infrastructure are all necessary for the battery supply chain to function.

- **Manufacturing energy usage**: Battery cell manufacturing is an energy-intensive process. Current battery-manufacturing plants are estimated to use 50–65 kWh of energy per kWh of battery produced (Kurland 2020). This energy is delivered either in the form of electricity or heat. The energy usage is of relevance given the scale of newly constructed battery plants, which require access to many terawatt-hours of energy annually during operation.
- **Skilled labour force:** Skilled workers are another important consideration for the battery supply chain. It is estimated that around 80 jobs are created per GWh of battery-manufacturing capacity (EIT and Fraunhofer 2021). Another 300 jobs could be created in the upstream supply chain (EIT and Fraunhofer 2021). The most sought-after labour force includes electrochemists, inorganic-materials scientists, and process engineers. Technical workers with sufficient vocational training are also in high demand in the battery sector.
- **Shipping**: Shipping and transportation of batteries present a safety hazard. The risk is mitigated by protecting the cell and pack terminals by covering them in insulating, non-conductive material. Additionally, providing adequate cushioning while packaging prevents accidental damage to the batteries. Labelling and markings also ensure that the prescribed handling protocol is followed. UN codes, such as UN3090, UN3091, UN3480, and UN3481, govern the transportation of different types of batteries (TT Club and UK P&I Club 2022).
- **New technologies:** The development of advanced cell chemistry (ACC) battery chemistries could have significant effects on battery supply chains. Certain chemistries, such as sodium-ion, could use similar manufacturing processes, but would entail the creation of new upstream and midstream supply chains to cater to demand. In the case new technologies like redox flow or metal-air batteries are scaled up in a significant way, a completely new supply chain will need to be developed to meet future demand.

Material requirement

The production of battery components – in particular, the cell components – entails the use of a large quantum of minerals such as lithium, cobalt, nickel, manganese, copper and titanium. Many of the minerals used to produce batteries are scarce or not mined in large quantities. The amount and type of mineral being used depend on the chemistry of the battery being used. Figure 13 showcases the different minerals used in the production of cell components and the quantity required (in tonnes) per GWh of battery storage capacity.

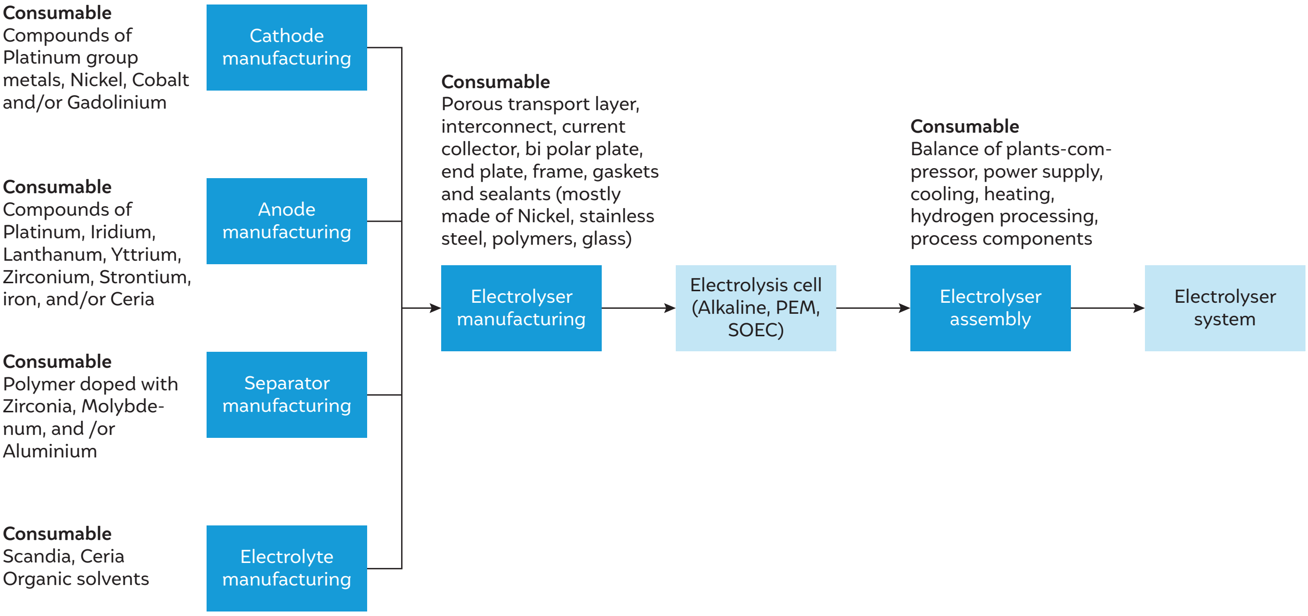
Figure 13 Mineral demand from different lithium-ion-battery chemistries (tonnes/GWh)



Source: Authors' analysis using BatPac 5.0 and GREET model, Argonne National Laboratory (2020)

Note: LMO-LTO – lithium manganese oxide – lithium titanate oxide, LMO-G – lithium manganese oxide, LFP-G – lithium ferro-phosphate, NMC – Nickel manganese oxide, NCA – nickel cobalt aluminium oxide

Figure 14 Manufacturing process of electrolyser cell and system requires several important consumables and processing steps



Source: Authors' representation

2.4 Green hydrogen

The green-hydrogen supply chain mainly consists of the following physical parts: electrolyser technology and manufacturing, RE technology, manufacturing and operational characteristics, and infrastructure to move the green hydrogen. The intangible parts of the supply chain include finance, standards, certification, and skills. Figure 14 highlights the hydrogen supply chain, as well as the variety of inputs that go into making an electrolyser.

For green-hydrogen production, the operational characteristics of RE are important. Green hydrogen is defined differently across geographies depending on how the intermittency of RE (solar or wind) is managed. Hence, a lack of consistency in this definition results in supply chains with market-access barriers. Infrastructure to move green hydrogen includes pipelines and dispensation stations for refuelling transport vehicles.

Planned capacity additions

Some of the major countries shown in the annexure 1 with their hydrogen targets envisage the production of around 50 MTPA green hydrogen that corresponds to an electrolyser capacity of 550 GW deployments by 2030. IEA has projected an electrolyser capacity requirement of 850 GW by 2030 and 3500 GW by 2050 to achieve the net-zero targets by 2050 (IEA 2021b). The development of an ecosystem globally will require an estimated USD 700 billion by 2030 and between USD 7–8 trillion by 2050 (Hydrogen Council 2021). These estimates include costs for hydrogen production, infrastructure development, and end-user investments. Currently, there is only 550 MW of electrolyser capacity deployed globally (Hydrogen Council 2022). Therefore, almost all the investment is yet to be made. Several countries have specific financial commitments to deploy hydrogen-based solutions. Most countries have focused on green hydrogen, however, some countries, such as Canada, the EU, Japan, Republic of Korea, and the UK, will also deploy 'low-carbon' hydrogen solutions.

Annexure 2 shows that countries have committed approximately USD 100 billion to the research and development, production, transport infrastructure, and end use of green hydrogen; this includes carbon capture and storage solutions for countries considering low-carbon hydrogen production. While significant, this global financial commitment to hydrogen-based solutions falls short by over USD 600 billion to meet the global 2030 needs. Finance is the prerequisite for deploying capacity and developing supply chains. Hence, building resilient supply chains will require easier access to low-cost capital, especially for developing countries.

Potential challenges in future supply chains

The green-hydrogen supply chain is in a nascent stage of development. Countries are making efforts to determine the specific pathway(s) for producing the hydrogen as well as the appropriate application in their economies; the supply chains are also being shaped accordingly.

Annexure 3 provides sectoral focus of individual countries in utilising green hydrogen and derivatives (Alex Badgett, Joe Brauch, et. al. 2022). Most of the countries given in Annexure 3 are targeting the use of green hydrogen in the industrial sector. However, there is significant divergence in other sectors of interest. For example, China, Germany, and the UK are focusing on utilising green hydrogen to produce sustainable aviation fuel (SAF). Similarly, certain countries are evaluating its use in transport and space-heating solutions. This varied focus on end-use applications and a combination with a specific technology could end up concentrating supply chains in early-moving countries. Additionally, focusing on limited geographies of end uses also means that the supply chains will take longer to develop. For example, the use of green ammonia (produced from green hydrogen), as a shipping fuel will require that most littoral countries be a part of the supply chain as ships travel across continents. Without fully developed supply chains globally, the use of green ammonia as a decarbonisation for the shipping industry will be limited to a few geographies.

Diversity of technologies

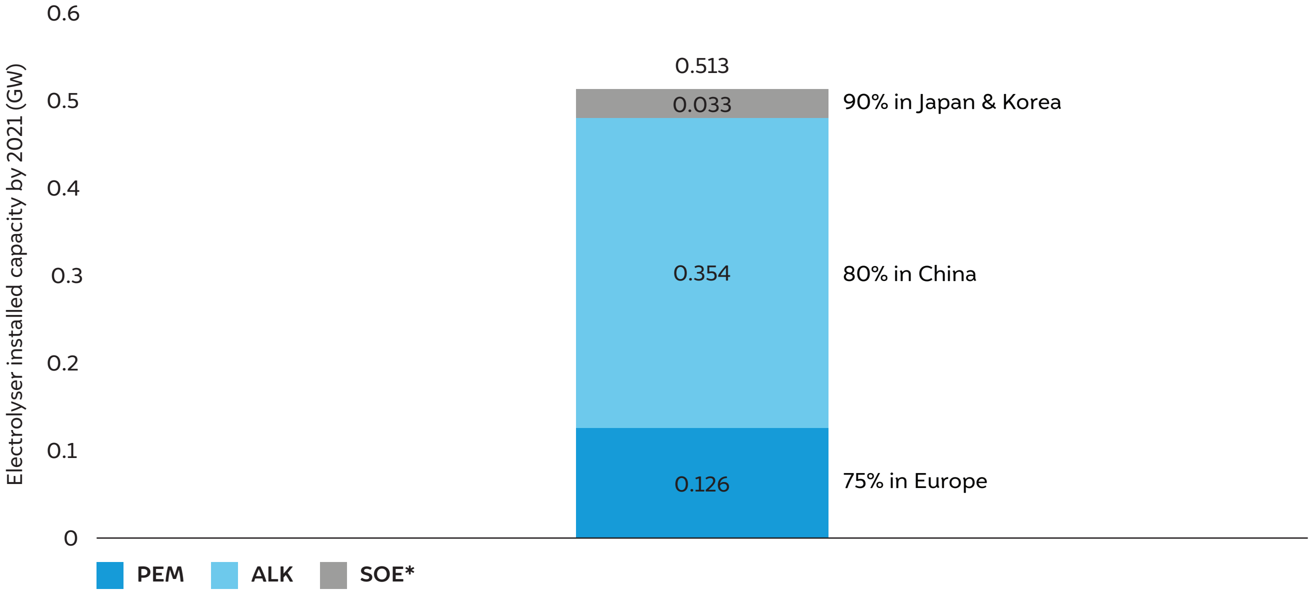
Among various electrolyser technologies available, currently three technologies are commercialised: alkaline (ALK), proton exchange membrane (PEM), and solid oxide (SOE). A newer entrant is the anion exchange membrane (AEM). There are other technologies still in the development stage, including electrochemical and capillary-fed membrane technologies.

To a large extent, the choice of technology is driven by the end-use application, geography-specific requirements, and the availability of the technology domestically. Figure 15 provides a breakdown of the electrolyser capacity deployed currently by technology type and the country/region where it is a predominant choice (IEA 2022c). A similar pattern is expected to continue in the years to come, which will result in concentrated manufacturing. Also, the interoperability of technology between countries might become a concern. For example, an internal combustion engine today can operate anywhere in the world; however, a transport vehicle with a specific type of fuel cell, which is the reverse cycle of an electrolyser, can only be operated in countries that use the same technology.

Geographic concentration in manufacturing

Manufacturing electrolysers with different technologies requires a unique combination of sub-components and critical minerals. PEM electrolysers require a specific membrane (Nafion) and SOE electrolysers utilise a specific sub-component called interconnect (for separating cells in the electrolysers), which are both manufactured by only one company, each, globally. Similarly, speciality chemicals are required in the manufacturing process and are produced only by a few companies globally. The exact number is not known because most of the chemicals are proprietary and the knowledge of use is not in the public domain.

Figure 15 Globally ~0.5 GW installed electrolysers capacity by 2021 is dominated by alkaline and PEM



Source: (IEA (2022 b)

Note: SOE* includes other unknown technology types

Annexure 4 shows the location of major electrolyser manufacturers. The electrolyser-manufacturing plants are concentrated in Canada, the US, the EU, China, and Japan. This is largely due to the limited access to sophisticated manufacturing technology and expertise in the process. The lack of access to technology will significantly limit the scaling-up of green hydrogen production globally.

Material requirement

A key input to the manufacturing of electrolysers is critical minerals and rare earths. The type of mineral or rare earth required depends on the specific electrolyser technology. Table 1 provides an estimate of the amount of critical minerals and rare earths that are required per MW capacity of electrolysers of different technologies (IEA 2021c). On one hand, it can be observed that PEM electrolysers require critical minerals whereas SOEs are primarily dependent on rare earths. Alkaline electrolysers, on the other hand, mainly require nickel and small amounts of zirconium and are hence less dependent relative to other technologies. Table 1 also provides the historical production rates of these critical minerals and rare earths. We can observe that a significant scale-up of production is required to meet the demands by 2030, let alone the orders of magnitude of higher production required by 2050 to meet the 3,500 GW requirement by 2050 (IEA 2021b). The demand for iridium will negatively impact the deployment of PEM electrolysers unless substitutes are found. Besides the availability, reserves and processing of these minerals and rare earths are more geographically concentrated than oil, gas, and coal globally. Annexure 5, 6, 7 and 8 provide the breakdown of production, resources, and processing of rare earths and critical minerals by country.

Existing bilateral and multilateral arrangements for secured supply chains for green hydrogen

The green-hydrogen supply chain is in its infancy and will evolve with time. Several countries have started establishing bilateral and multilateral partnerships with other countries to develop technology, produce and offtake green hydrogen, access finances, deploy pilots, develop standards, and overall develop the supply chain. Figure 16 depicts the network of bilateral and multilateral partnerships on green hydrogen. Germany leads the efforts in these partnerships followed by Japan, Republic of Korea, and India.

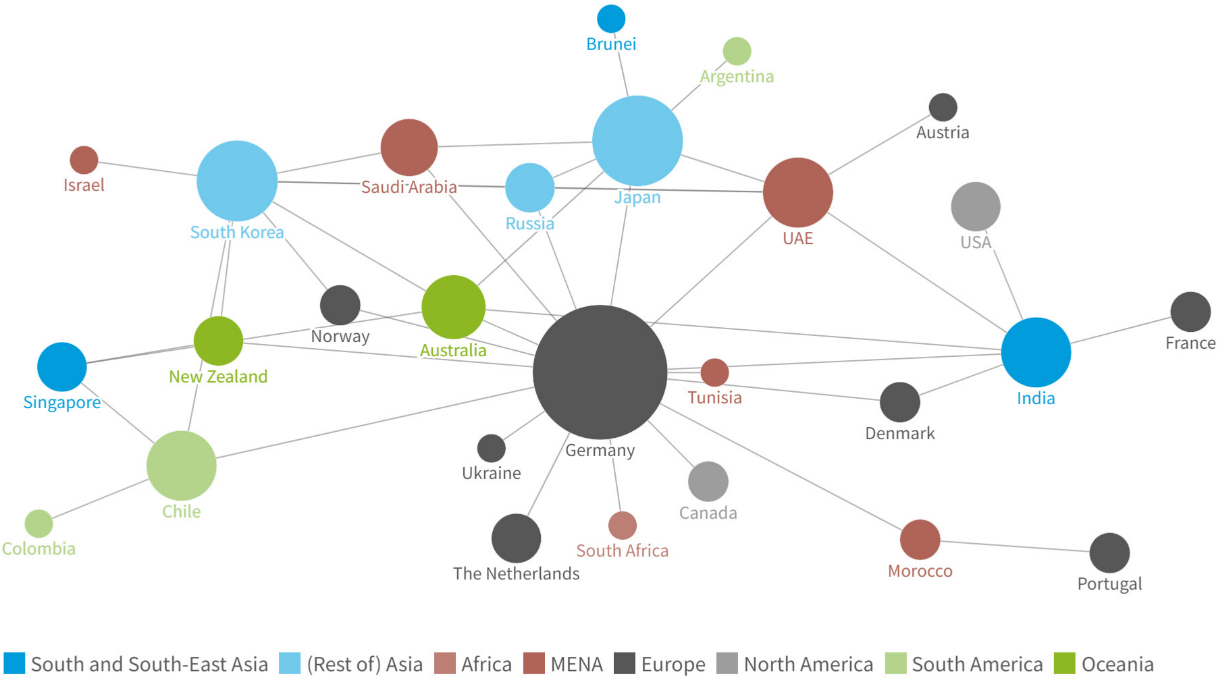
Table 1 Minerals and rare earths required per MW capacity electrolyser by technology type and quantity of critical minerals and rare earths required to meet 2030 electrolyser capacity requirement

Critical minerals and rare earths required	Current estimates			For 2030 target of 850 GW		
PEM		ALK	SOE	PEM	ALK	SOE
	Kg per MW			Tonnes		
Platinum	0.3			63		
Palladium	0.05			10.4		
Iridium	0.7			146		
Nickel		800	175		44,000	10,000
Zirconium		100	40		59,000	2,200
Lanthanum			20			1,100
Yttrium			5			

Source: (IEA 2021c), CEEW analysis and USGS (2022)

Note: Annual mine production of minerals can be referred to in Annexure 8

Figure 16 Bilateral and multilateral agreements among countries on green hydrogen are on rise



Source: CEEW compilation from World Energy Council (2022)

Box 1 Using Herfindahl–Hirschman index (HHI) to determine concentration

HHI helps in determination of market concentration. The formula is shared below:

HHI = Sum of the square of market share of each firm ($S_1^2 + S_2^2 + S_3^2 + ...S_n^2$)

Table 2 HHI for electrolyser manufacturing capacity by major geographies indicates even higher electrolyser market concentration in upcoming years

Country	Country-wise capacity (GW/year)		Share		HHI	
	2022	2025	2022	2025	2022	2025
Europe	2.1	18.3	42%	45%	0.17	0.19
China	0.85	13	17%	32%	0.02	0.10
US	1.1	4.75	22%	12%	0.04	0.01
UK	1	5	20%	12%	0.04	0.01
Total	5.05	41.05	100%	100%	**0.28**	**0.32**

Source: CEEW analysis from KGAL, 2022

Countries have formed partnerships and undertaken specific initiatives across geographies as shown in Annexure 9. Each of these has a different set of objectives. These partnerships are valuable in scaling up the green-hydrogen ecosystem. However, they also create a diverse set of competing requirements and pathways that will inhibit a common rules-based architecture that is necessary for rapid decarbonisation, especially the developing and least-developed economies.

Evaluating the resilience of existing supply chains for electrolysers

The electrolyser supply chain is in its early stages of development. Therefore, it is not possible to comment on resilience at different stages and elements. The current manufacturing capacities are concentrated in the limited geographies of the United States, United Kingdom, China, and Europe.

Table 2 provides the geography-specific electrolyser manufacturing capacity, the corresponding market share, and the HHI for 2022 and 2025. Table 2 shows that the markets are currently concentrated. If a country-level assessment is made, the market concentration can be expected to be even higher

Identifying portions of the supply chain in each product class that need strengthening

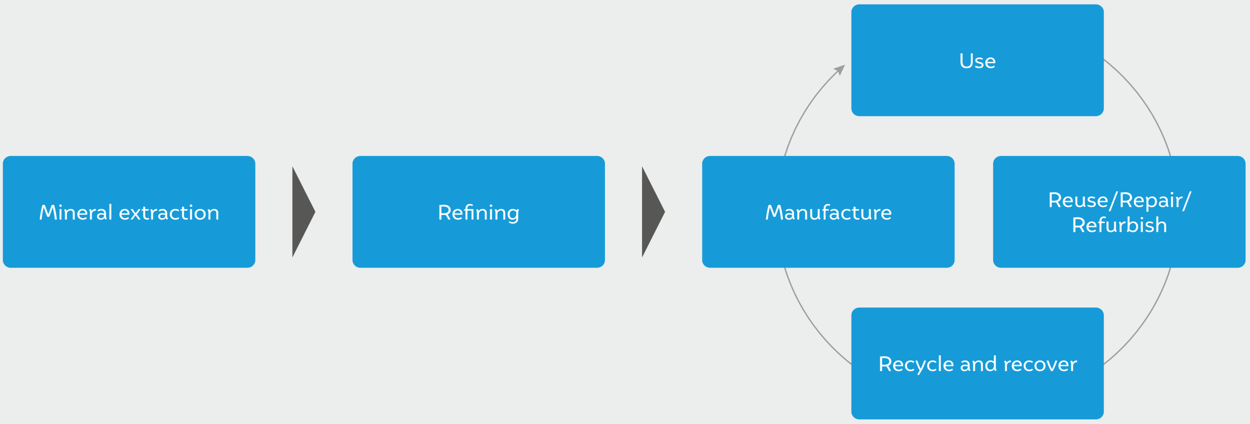
The following areas in the supply chain can be considered for strengthening the overall resilience.

- Membrane and interconnects: The membranes and interconnects (for SOEs) are critical components for manufacturing electrolysers. Developing multiple options for membrane type and manufacturing processes is necessary to ensure competition in the market and global access to the technology and products at reasonable costs.
- Critical minerals: As discussed previously, access to critical minerals is essential for the deployment of electrolysers at a large scale, especially for PEM and SOE technologies. Specific groupings and initiatives that limit open access will deter countries from deploying green-hydrogen solutions.
- Access to low-cost finance: The scale of finance required to deploy RE and green hydrogen is unprecedented. Annexure 10 lists some significant funding commitments for green-hydrogen ecosystem development. All these initiatives are focused on Europe and the United States. The developing and least-developed countries will not have access to this level of capital and will limit their adoption of green-hydrogen solutions.

Box 2 Role of circular economy in building resilient supply chains

Making supply chains circular is a vital strategy to reduce supply risks, as it aims to reduce material intensity by keeping them or the products in circulation (Ellen MacArthur Foundation 2019). Although industries can implement circular economy principles throughout the supply chain (Figure 17), the maximum potential lies at the design and end-of-life management stages. With considerations about the choice and use of raw materials, manufacturing, transportation, distribution, installation and maintenance, use, and end-of-life treatment, product design profoundly influences the environmental impact over its life cycle. End-of-life management, which includes reusing the products or functional components (with or without repair) and recovering materials from discarded products, also promotes circular strategies. This stage has also received the most attention from the industry with efforts to identify second-life applications and develop efficient recycling technologies.

Figure 17 Creating a circular economy would require changes at various stages of the supply chain



Source: Authors' representation

However, there are a few metrics for tracking and measuring circularity in supply chains. The EU directive on eco-design requirements for various energy-related products covers some aspects of defining circularity at the design stage (European Commission 2009). Similarly, the 'end-of-life recycling input rate' is also used as a circular economy indicator to denote the share of secondary sources in the total supply (European Commission 2018). However, these are staggered initiatives, and the RE industry needs universal standards to develop products on circular economy principles.

3. International trade of RE technologies

3.1 Historical trade data analysis for solar PV, wind generators, and lithium-ion batteries

This section uses international trade data to gather insights for the export and import of solar cells/modules, LIBs, and wind-powered generators. Analysis of this global trade provides a nuanced picture of the trade flows of these technologies alongside the static picture of manufacturing concentration highlighted in the previous section. This is particularly important since global manufacturing concentration does not have a uniform impact on all countries – some have been able to diversify their supplies chains better than others. Trade analysis brings to the fore these national-level discrepancies and provides a more holistic assessment of supply chain vulnerability arising from concentration for individual countries importing solar, wind and battery technologies.

A specific product or a group of products, are categorised under unique two to six-digit harmonised system (HS) codes, developed by the World Customs Organisation (WCO). These codes facilitate tracking of products being traded internationally. Trade data from UN COMTRADE was compiled for the following HS codes[2]:

- **HS 854140**: Electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes.
- **HS 850231**: Electric generating sets; wind-powered, excluding those with spark-ignition or compression-ignition internal combustion piston engines.
- **HS 850760**: Electric accumulators; lithium-ion, including separators, whether or not rectangular (including square).

In addition to tracking the data, we use

Key insights from the analysis of the trade data

- **Steady growth in global trade:** It should be noted that solar and wind deployments increased significantly between 2012 and 2021, with a CAGR of 26 per cent and 13 per cent, respectively. The deployments increased on the back of reduced prices, technology maturity, and country policies. The analysis suggests that despite a significant decrease in prices, the traded value of solar modules, LIBs, and wind generators has increased (shown in Table 3 and Figure 18).

Table 3 Steady growth in the traded value of solar, wind, and batteries

Technology	CAGR (2012–2021) (%)
Solar module	3.3
Lithium-ion batteries	22.2
Wind generators	5.6

Source: Authors' analysis from UNCOMTRADE (2023) data

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[2] Limitations of the current methodology are listed below:

The HS code of solar cells and modules are the same. This may lead to double counting when the same product is re-exported after value add.

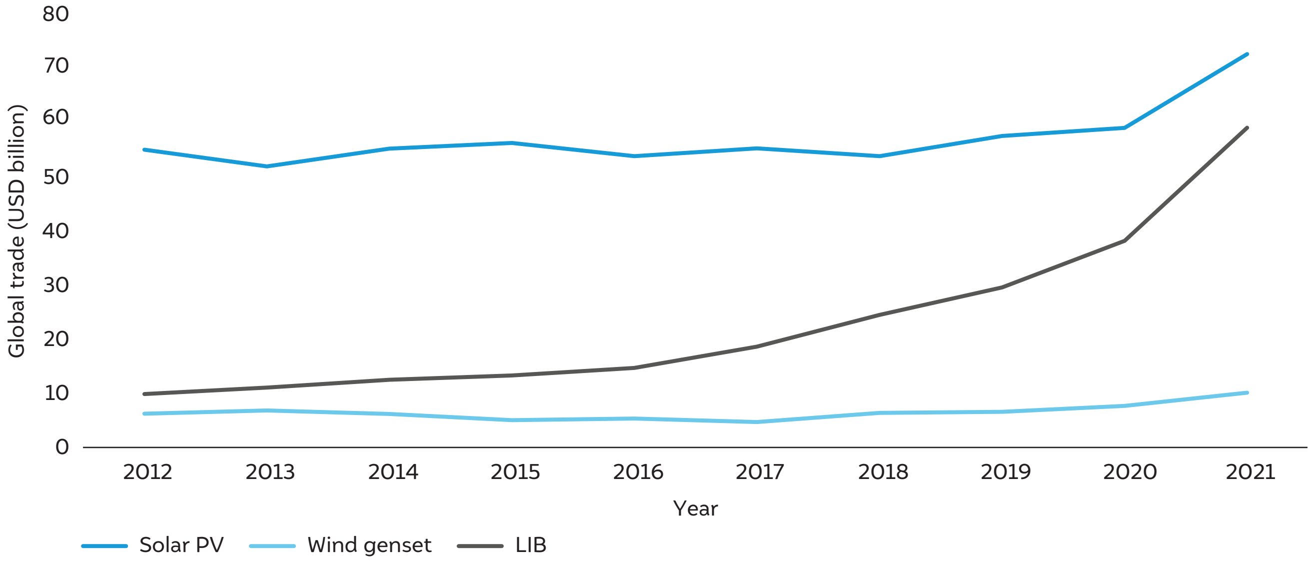
To track trade data for the wind sector, we have followed the trade pattern of wind generators. It should be noted that wind generators contribute to <5% of the overall cost; hence, trade value is significantly lower when compared to solar and batteries.

The HS code for LIBs is for both battery cells and modules. This may lead to double counting when the same product is re-exported by a country after value add. Also, it should be noted that this HS code only includes the secondary rechargeable battery.

Traditionally, LIBs have been used for consumer electronics but, in recent years, the majority of the demand comes from the transport and power sectors.

We were unable to reconcile the import and export data; hence, this analysis is only based on the import data, which means the information shared by the importing country, partner country, product, and traded amount.

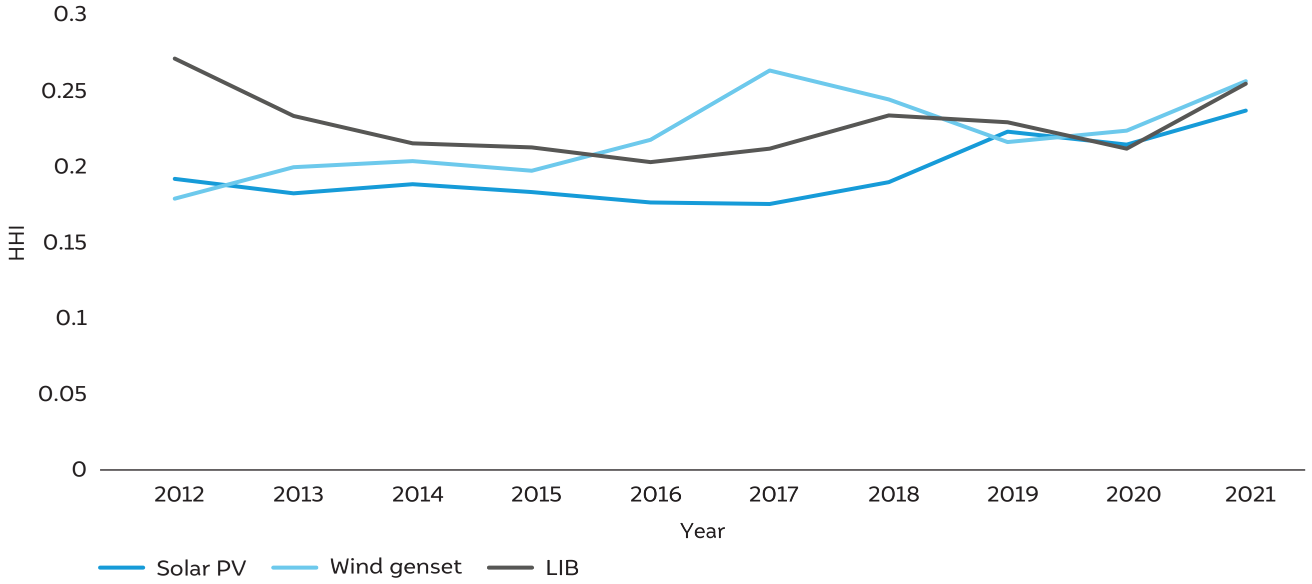
Figure 18 Annual global trade of solar, wind generators, and lithium-ion batteries have increased significantly



Source: Authors' analysis based on UNCOMTRADE (2023) data

- **Concentration of global exporters:** The historical trade patterns show that the HHI value for the global solar, LIB and wind generators exports are near 0.25.[3] While the HHI has slightly reduced for wind generators, the values have increased significantly for solar and LIB's, as seen in Figure 19. This implies that the global trade is highly concentrated and has only increased in the recent years. Currently, there are no agreed levels of HHI to determine concentration for RE supply chains. For this analysis, an HHI greater than 0.25 is considered concentrated. **However, it is important that countries decide on the threshold level of HHI so that any pre-emtive actions can be taken if required.**

Figure 19 Global HHI of solar, wind, and battery exporters



Source: Authors' analysis based on UNCOMTRADE (2023) data

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[3] Global HHI for a product = [% of imports from country 1|^2 + [% of imports from country 2]^2 + [% of imports from country 3]^2 + ...

Country-level import and export analysis of international RE trade

This section showcases the import and export trends between 2012 and 2021 in different RE supply chains. Analysis of the import data showed concentration of the imports of each country participating in the RE supply chains. In several cases, this has been done to highlight the effect that the global concentration of trade has had on individual countries. Additionally, this analysis brings to light the non-uniformity of import concentration among countries of different income levels. The export data analysed provides a picture of the top exporters participating in the international RE trade and how these have changed over the years.

Methodology to calculate the concentration of individual country imports

Importers have been categorised by the concentration of their imports of a particular RE technology in a specific year into countries with concentrated imports and countries without concentrated imports.

- The concentration of a country's imports of a specific technology each year has been assessed by calculating the HHI of its imports with its trading partners in that year.
- If the HHI of the country's imports is found to be **greater than or equal to 0.25**, the country is considered to have concentrated imports.
- Only those countries whose imports of a specific technology were greater than USD 10 million in a particular year have been considered. While this ensures that countries with negligible imports do not skew the analysis, it also excludes them because small buyers have the flexibility to choose the source.

$$\text{Importer HHI for any product} = [\text{\% of imports from country 1}]^2 + [\text{\% of imports from country 2}]^2 + [\text{\% of imports from country 3}]^2 + \ldots$$

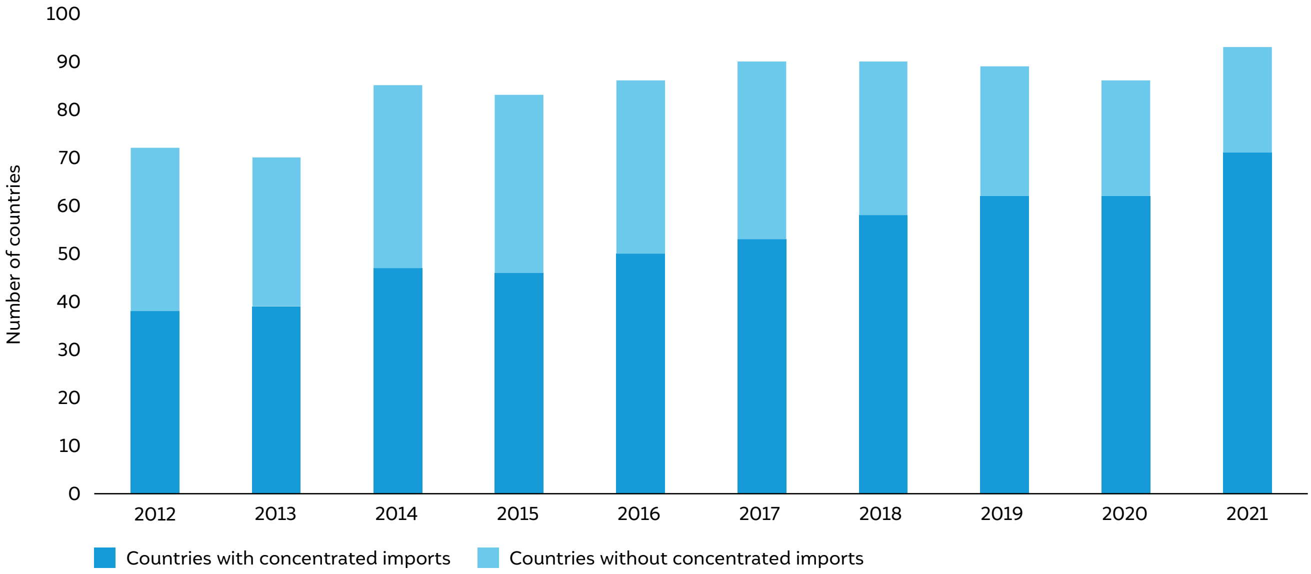
Methodology to identify the income level of importing countries

The income level of different countries was identified using the World Bank classification for 2022 (World Bank 2021). Four categories are used by the World Bank: 1. high income, 2. upper-middle income, 3. lower-middle income, and 4. low income.[4] In the import analysis, low-income countries have been excluded since a negligible number of low-income countries met the minimum-import-value criteria of USD 10 million, as discussed prior.

Solar-PV trade insights

The import data analysis for solar cells/modules provides some important insights, which are shared below in Figures 20, 21, 22 and 23.

Figure 20 The number of countries with solar PV imports greater than 10 million has increased by nearly 30 per cent in the last 10 years, with more and more countries having concentrated imports



Source: Authors' analysis based on UNCOMTRADE (2023) data

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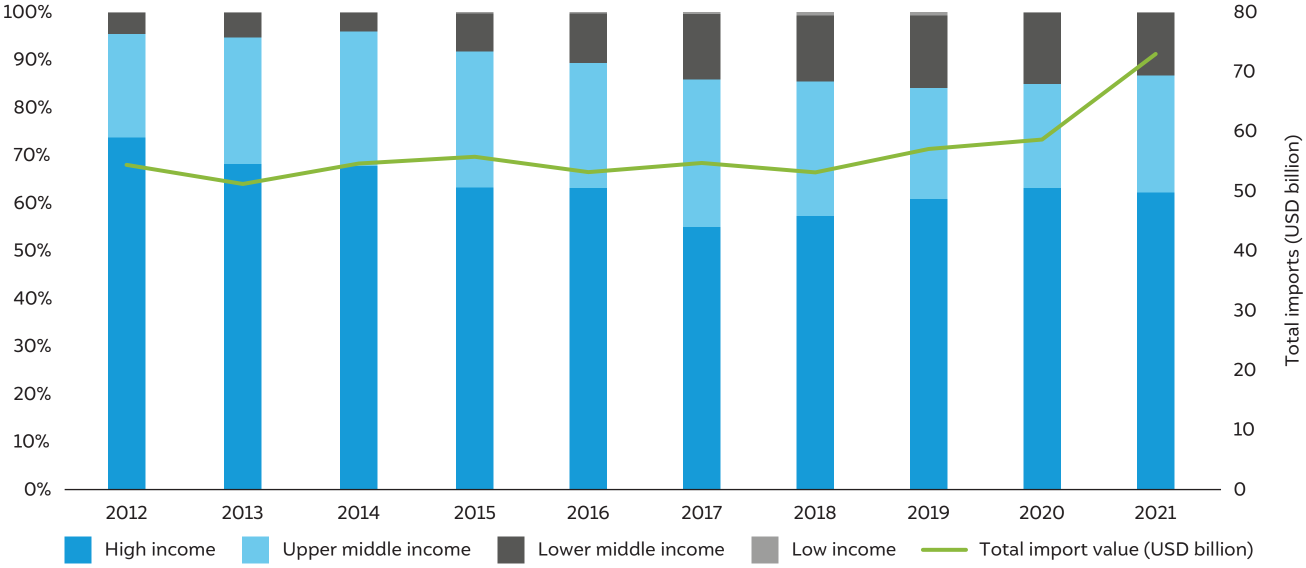
[4] Income levels are calculated in terms of gross national income per capita (GNI) in current USD rates. Low income < USD 1046, lower-middle income (USD 1,046–4,095), upper-middle income (USD 4,096–12,695), high income > USD 12,695.

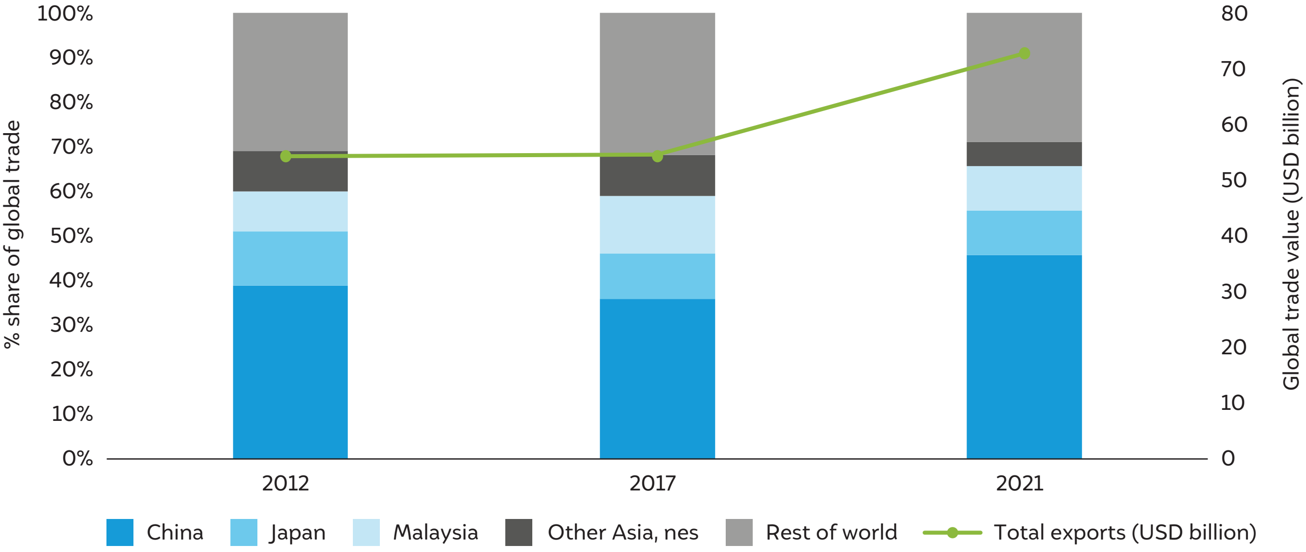
Figure 21 Share of countries of different income levels in global solar-PV imports



Source: Authors' analysis based on UNCOMTRADE (2023) data

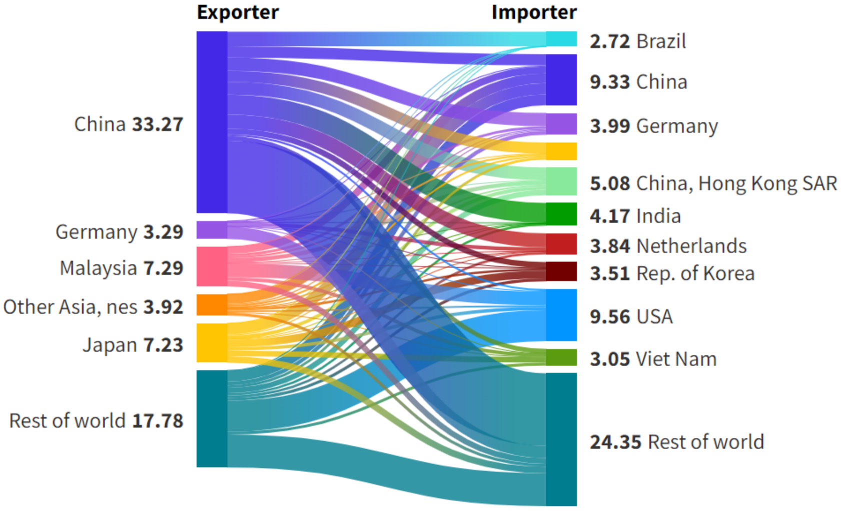
- The global trade of solar cells and modules has increased to USD 70 billion despite drastic reduction in per unit prices.
- The number of countries with imports greater than 10 million has increased by nearly 30 per cent in the last 10 years.
- The analysis shows that more countries are increasingly witnessing concentrated growth.
- Despite the increase in the export value, the number of countries supplying to the world has nearly remained constant. In the last 10 years, 70 per cent of the global exports has come from only 4 countries.
- The share of high income countries in total imports have reduced and the imports from middle and income countries are increasing.

Figure 22 In the last 10 years, 70 per cent of the global solar-PV exports has come from only 4 countries



Source: Authors' analysis based on UNCOMTRADE (2023) data

Figure 23 While some top importers had more diversified imports in 2021, countries like Brazil and India imported solar-PV cells and modules almost exclusively from China (trade flows in USD billion)



Source: Authors' analysis based on UNCOMTRADE (2023) data.

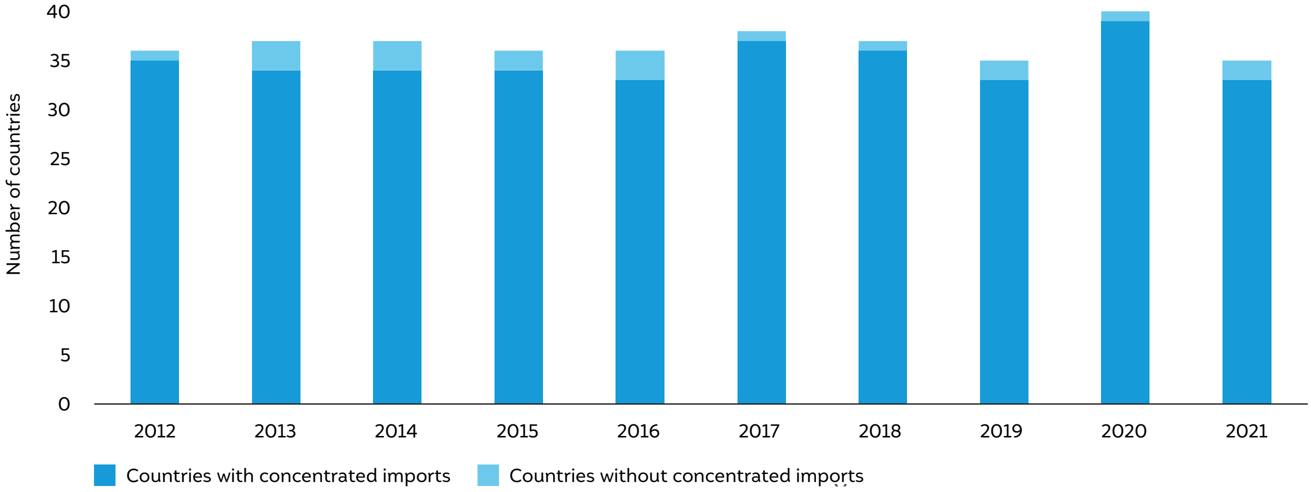
Note: Based on the trade data–recording methodology, some discrepancies in the data exist.

Wind-powered generator trade insights

The key inferences based on the trade of wind generator data is follows

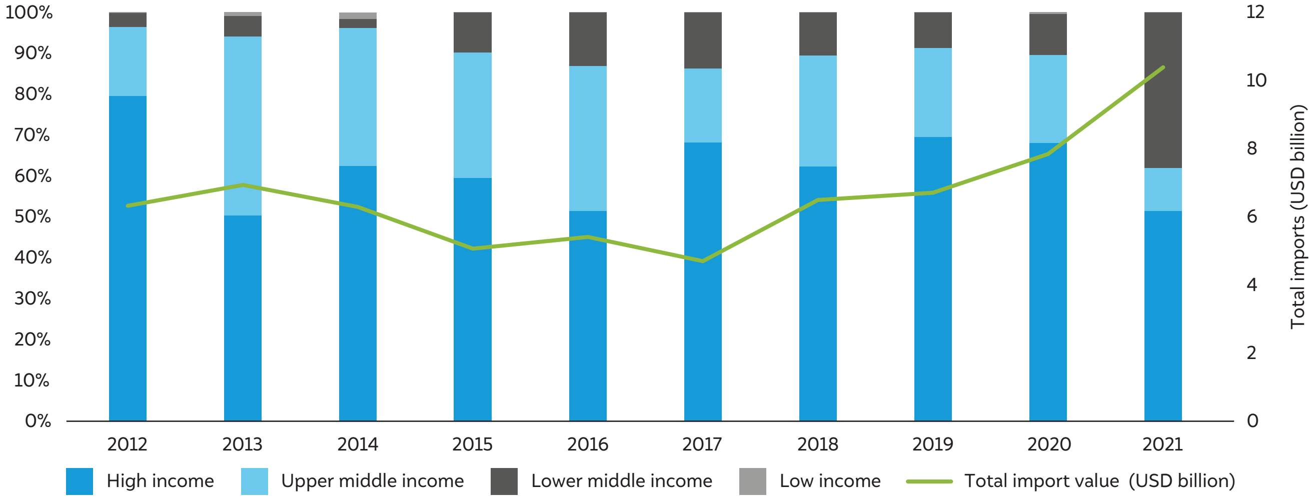
- The global trade of wind generators touched USD 10.5 billion in 2021, an increase of 1.6 times since 2012, but with a concentrated import mix for many participating countries.
- For most of the years in the last decade, more than 90 per cent of the countries have shown high import concentration (Figure 24).
- There is a drastic increase in the share of imports of lower-middle-income countries in 2021 (shown in Figure 25). This is because Viet Nam added 3.6 GW of capacity that year, which was significantly higher than the previous year (at 0.14 GW).
- Over the past 10 years, only four countries accounted for more than 80 per cent of the total global exports (Figure 26), indicating that exports have been highly concentrated.
- China and the EU also hold the majority share of manufacturing capacity. The increasing export from China indicates that, over the years, more countries have depended on China for their wind deployment.

Figure 24 In most years over the last decade, more than 90 per cent of the countries have shown high import concentration of wind generators



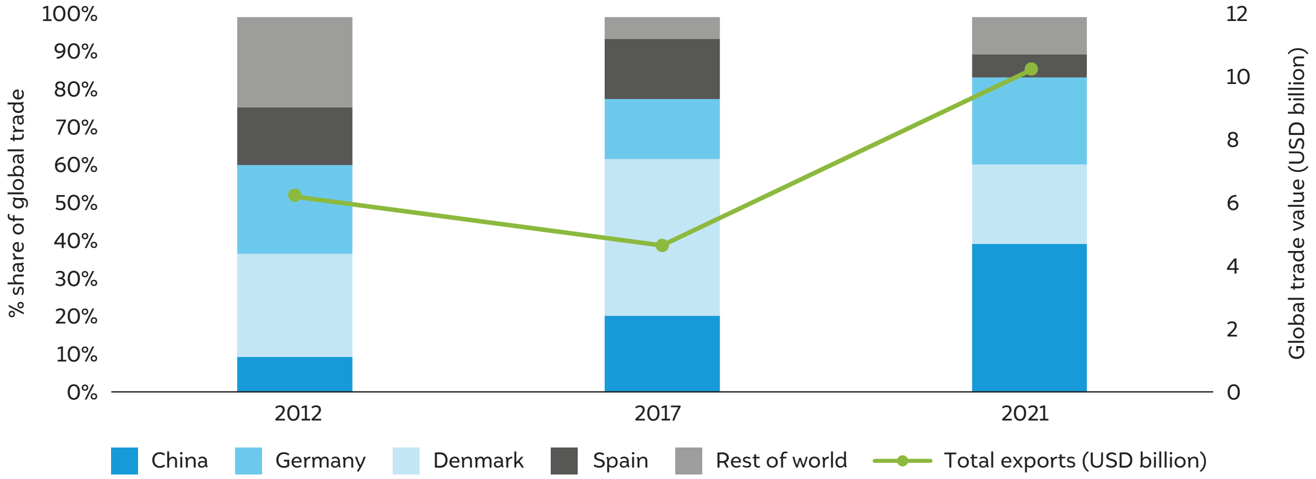
Source: Authors' analysis based on UNCOMTRADE (2023) data

Figure 25 The year 2021 saw a drastic increase in wind generator imports by lower-middle income countries



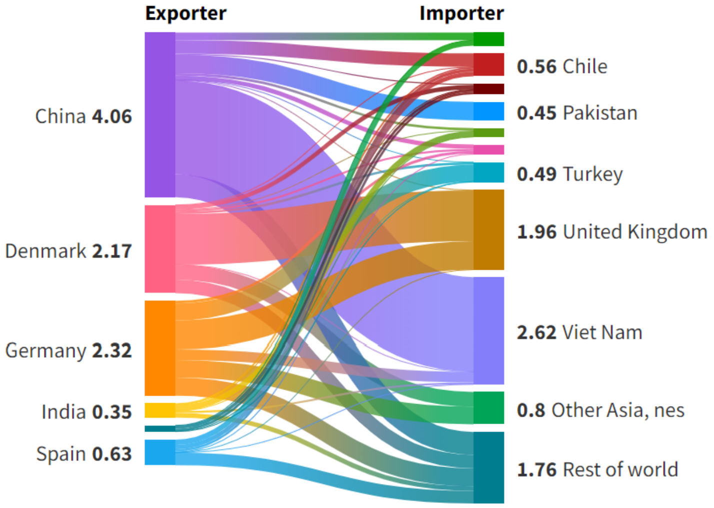
Source: Authors' analysis based on UNCOMTRADE (2023) data

Figure 26 Over the past 10 years, only four countries accounted for more than 80 per cent of the total global wind generator exports



Source: Authors' analysis based on UNCOMTRADE (2023) data

Figure 27 The major wind capacity expansion in Viet Nam in 2021 was supplemented by wind generators primarily from China, while the United Kingdom sourced wind generators primarily from Denmark (trade flows in USD billion)



Source: Authors' analysis based on UNCOMTRADE (2023) data

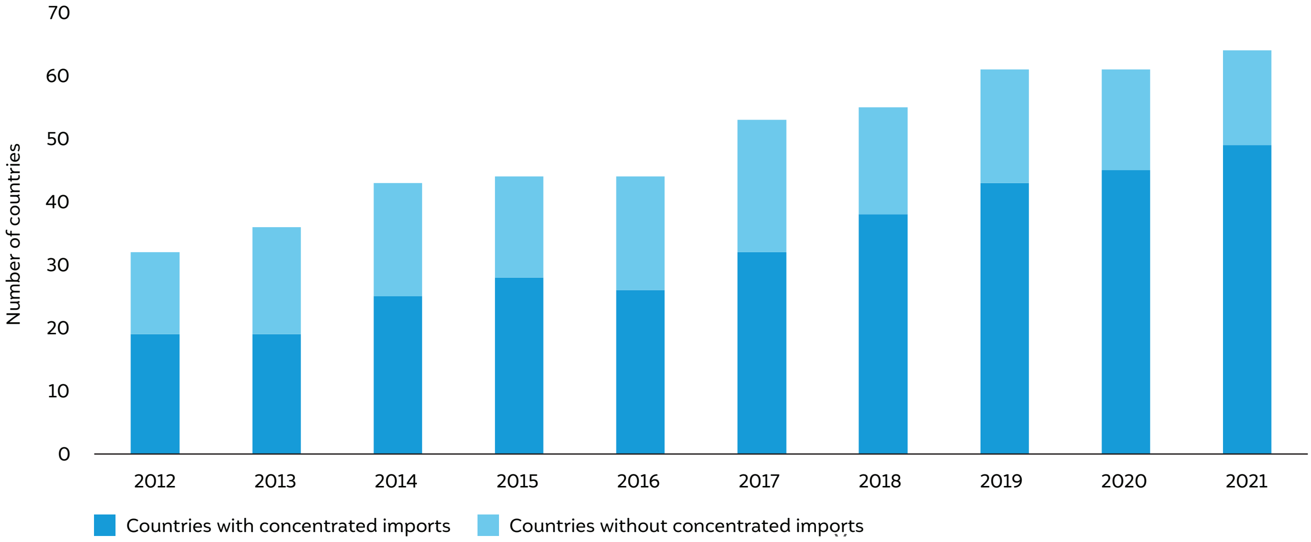
Note: Based on the trade data–recording methodology, some discrepancies in the data exist.

Lithium-ion battery trade insights

The key inferences from LIB trade data (provided in Figures 28, 29, 30, and 31) are as follows

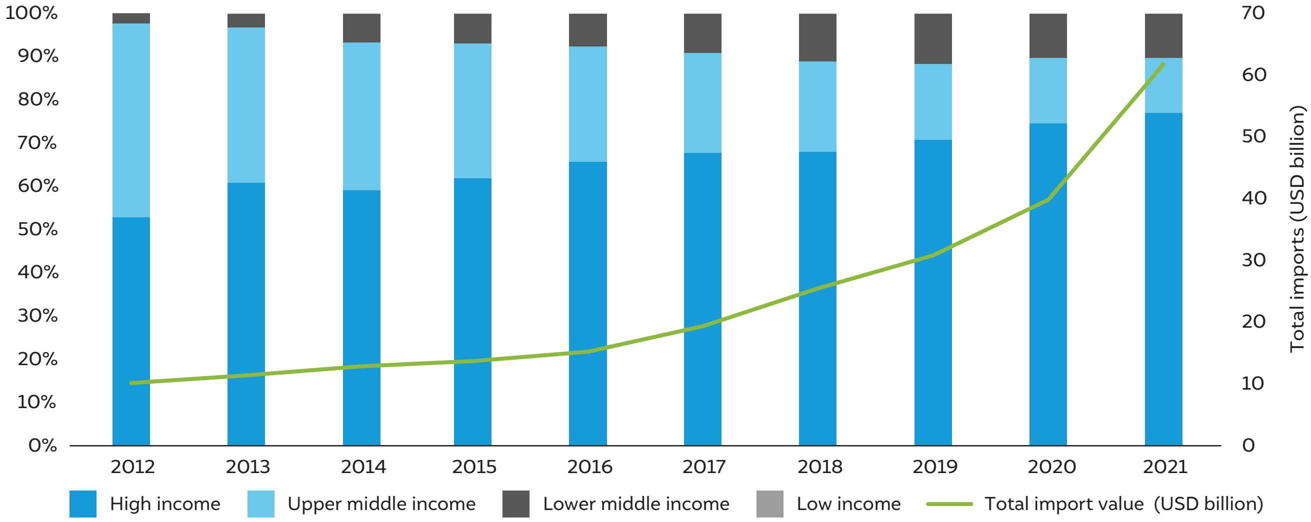
- The international LIB trade has grown by six times over the last decade, touching USD 60 billion in 2021.
- As global trade has grown, the number of importers participating in global trade flows has doubled to more than 60 countries.
- The concentration of imports from individual countries has remained high. More than half of all importers had a concentrated import basket in the last 10 years. In 2021, four out of five countries saw concentration in their LIB imports (Figure 28).
- Between 2012 and 2021, the share of high-income countries in total imports of LIBs has increased (shown in Figure 29). This has coincided with the growth in EV manufacturing and energy-storage deployment in Europe and North America. The share of imports from lower-middle-income countries has also grown accordingly.

Figure 28 In 2021, four out of five countries saw concentration in their LIB imports



Source: Authors' analysis based on UNCOMTRADE (2023) data

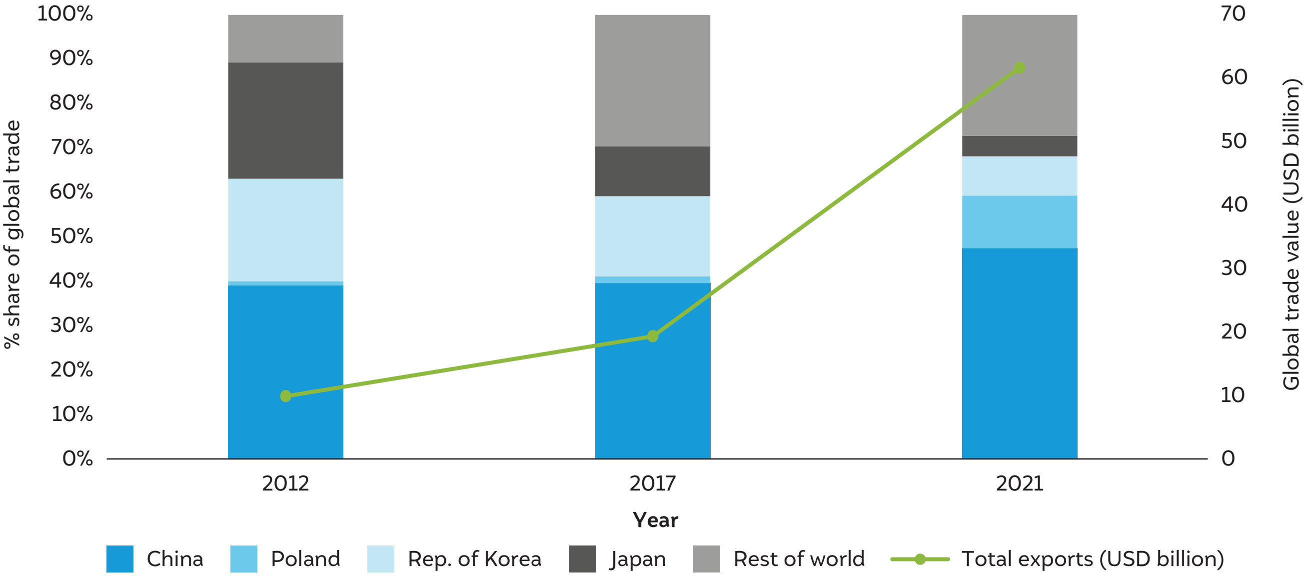
Figure 29 Between 2012 and 2021, the share of high-income countries in total imports of LIBs has increased



Source: Authors' analysis based on UNCOMTRADE (2023) data

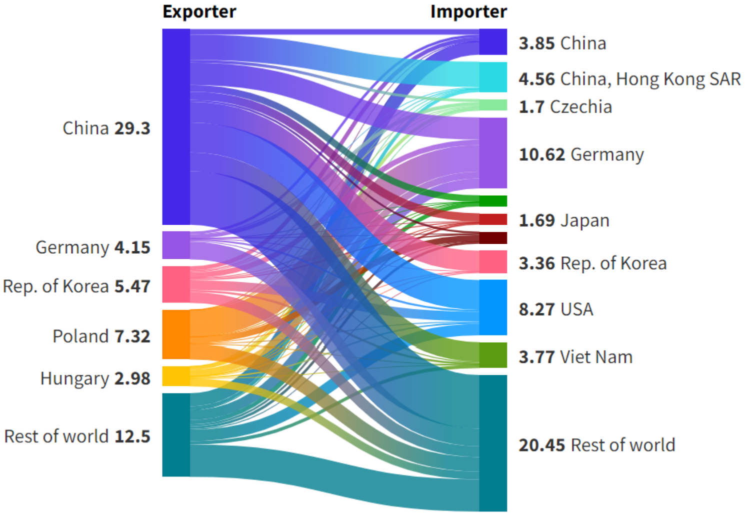
It should also be noted that a few countries dominate the global export market. In 2012, Chinese exports made up two-fifths of the total LIB exports globally (Figure 30). By 2021, this share increased to nearly 50 per cent. While China has remained the world's topmost exporter, other East Asian exporters, such as Japan and Republic of Korea, have lost their market share. In 2012, each made up around a quarter of the global battery exports, whereas in 2021, Republic of Korea's export share had reduced to just nine per cent and Japan's to six per cent. European countries, such as Poland, emerged as major exporters as new battery-manufacturing facilities were set up.

Figure 30 Between 2012 and 2021, the share of Chinese exports in the lithium-ion battery trade had increased from 40 to 50 per cent, while Japan and Republic of Korea's share declined



Source: Authors' analysis based on UNCOMTRADE (2023) data

Figure 31 European manufacturers of lithium-ion batteries primarily traded with other European countries, while for other countries China was the main export partner in 2021 (trade flows in USD billion)



Source: Authors' analysis based on UNCOMTRADE (2023) data

Note: Based on the trade data–recording methodology, some discrepancies exist in the data.

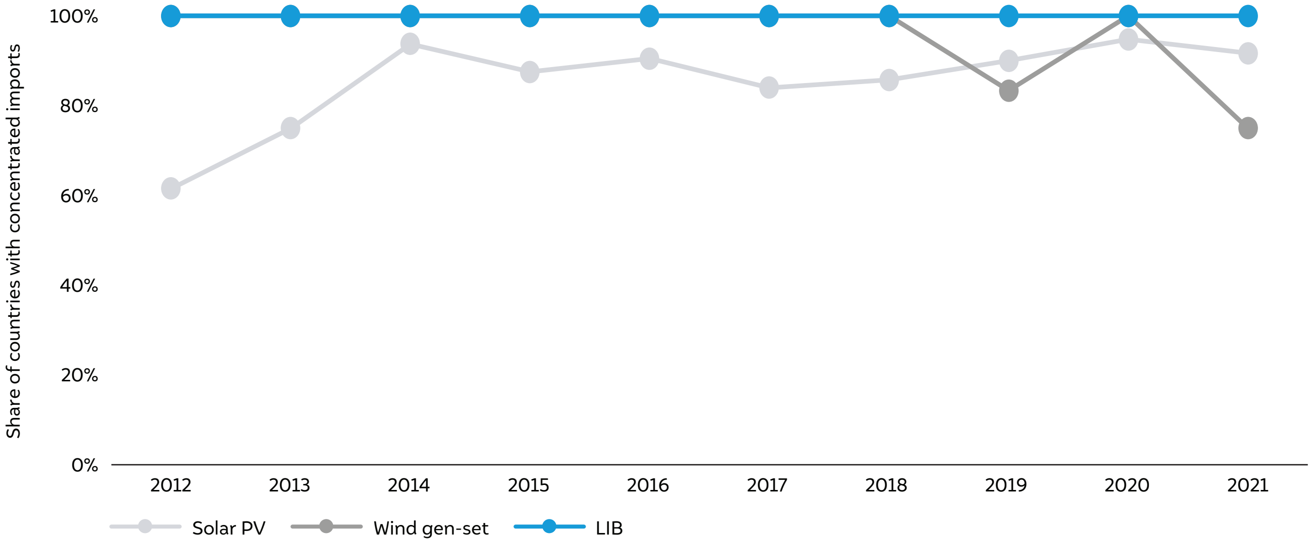
Import concentration analysis for countries of different income levels

This sub-section provided a macro-view on concentration of RE[5] imports for countries of different income levels. The analysis shows that even though concentration in imports is a major issue for many countries across the world, it is particularly a concern for lower-middle income countries; the same countries that possess smaller domestic manufacturing capabilities of these technologies.

In the global LIB trade, 100 per cent of lower-middle-income countries had concentrated imports every year over the last decade (Figure 32). For wind generators, all lower-middle-income countries saw concentrated imports till 2018. Only in the years 2019 and 2021, the concentration levels eased out for about 15 to 20 per cent of them. Even for solar PVs, the import concentration in lower-income countries has increased despite a decrease in import value.

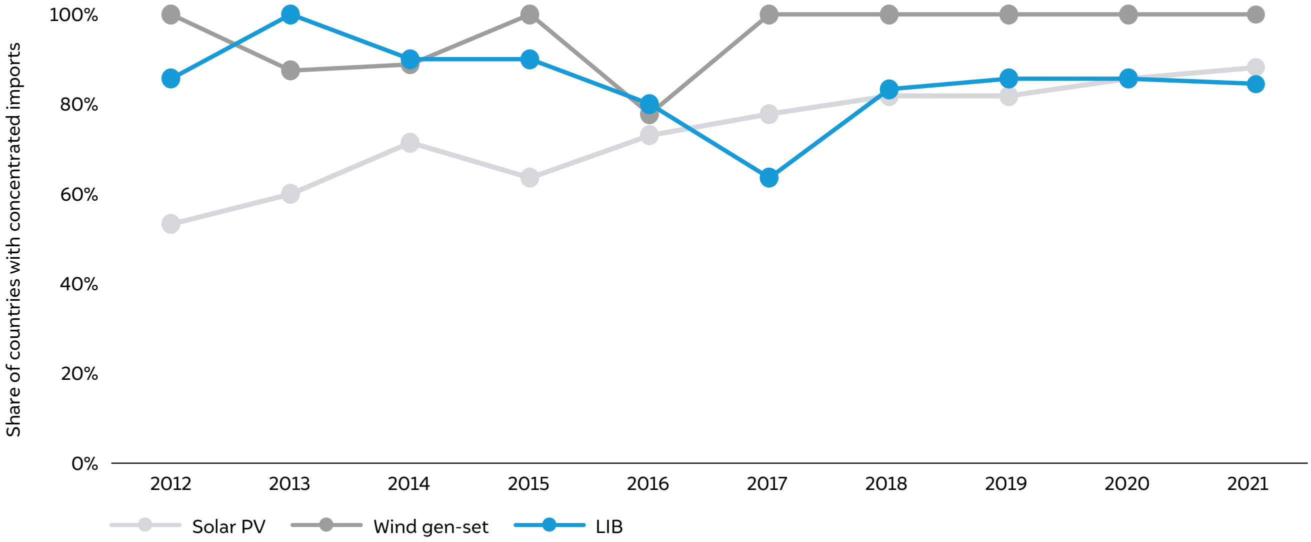
Upper-middle countries fared somewhat better (Figure 33); for solar PV imports, we see that the share of imports of upper-middle-income countries has reduced, but their import concentration has increased considerably. Eighty-five per cent of these countries had concentrated LIB imports. The percentage of high-income countries with concentrated imports was the lowest.

Figure 32 Share of lower-middle income countries with concentrated imports



Source: Author's analysis based on UNCOMTRADE (2023) data

Figure 33 Share of upper-middle income countries with concentrated imports



Source: Author's analysis based on UNCOMTRADE (2023) data

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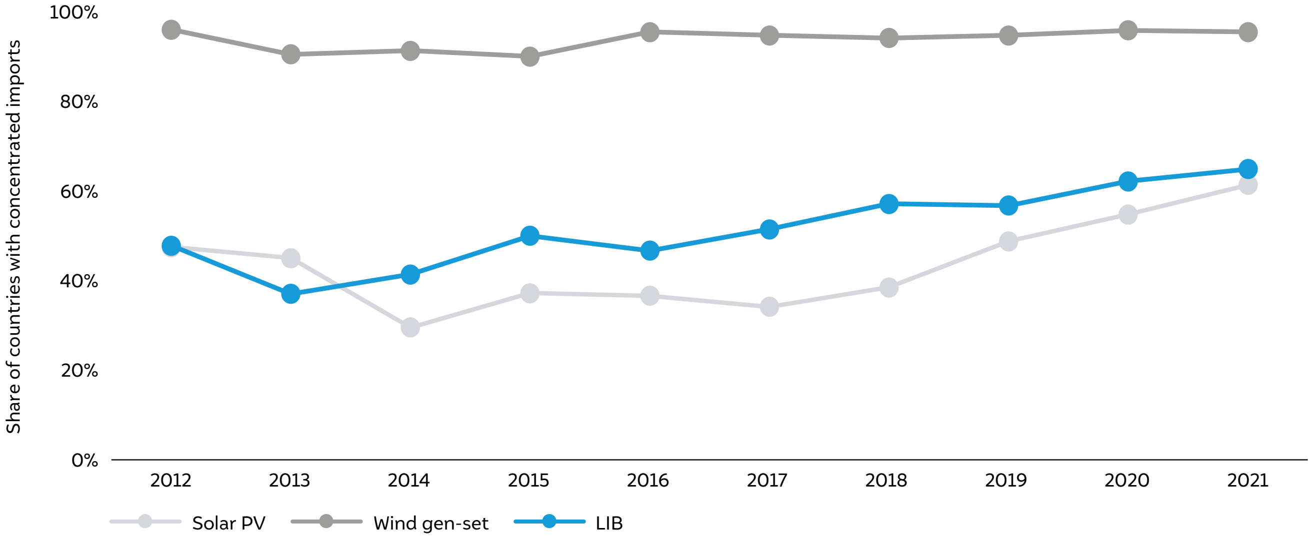
[5] Solar PV, wind generators and LIBs

Figure 34 Share of high income countries with concentrated imports



Source: Author's analysis based on UNCOMTRADE (2023) data

Almost all higher income countries saw concentration in wind generator imports (Figure 34). In the solar PV and LIB imports, on the other hand, higher income countries fare much better than their middle income counterparts. Only around half of all middle income countries had concentrated imports of solar PV and LIBs in 2012; this share has seen an increase in recent years, and in 2021 sat above 60 per cent.

3.2 Enabling future international trade for hydrogen through standardisation

Hydrogen has primarily been used in the refinery and fertiliser industry as feedstock. Consequently, the standards for the handling and use of hydrogen have been limited to these applications. Newer options for the use of hydrogen are being explored in ironmaking and combustion devices, apart from their use in making fuels. Standards need to be developed for these newer applications. The scope of existing standards is also limited by existing technologies. For example, the International Organization for Standardization (ISO) standard for electrolysers currently only covers ALK, PEM, and AEM electrolyser technologies, while horizon technologies, like SOEs and reversible fuel cells, remain out of the scope of this widely adopted standard.

When it comes to the storage of hydrogen, gaseous or liquid, many countries have adopted a modified version of the ISO standard. Bulk transport of hydrogen through pipelines remains a relatively less explored option. Consequently, only countries like the US and the UK have formulated and adopted standards for the same. In stark contrast to this, most countries that are part of this grouping have adopted relevant ISO standards for hydrogen refuelling stations and applications like fuel-cell EVs (modified in some cases).

Additionally, there are different standard-setting organisations globally, including The American Society of Mechanical Engineers (ASME), Bureau of Indian Standards (BIS), Compressed Gas Association (CGA), European Industrial Gases Association (EIGA), etc. Each of these organisations often sets its own standards for the same focus area. The possibility of varying or even conflicting requirements within the standards that limit operability across geographies is high.

Green hydrogen and derivatives will be commodities of the future with their own markets. For this to happen, there is a need to determine the equivalency of hydrogen produced across geographies and technology pathways. For example, viscosity and sulphur content are used to define crude-oil quality and heat/energy content for natural gas. The most important attribute necessary to define green hydrogen is the green attribute itself. Countries need to agree on how they define green hydrogen to ensure interoperability of hydrogen and its derivatives.

In cases when hydrogen is produced using intermittent renewable energy, the electrolyser may need to be run on part load or some form of power storage may be required to maintain a round-the-clock supply. In either case, the cost of green hydrogen goes up significantly. Therefore, green-hydrogen producers may consider supplementing the power requirement from the grid that is not completely renewable or utilising banking options. Banking refers to an accounting practice where any excess renewable power is injected into the grid during peak-generation periods, and an equivalent amount of grid power is utilised during periods of low or no generation. This may vary across countries and will have to consider the ratio of fossil versus non-fossil power generated in the country. Some countries are trying to create a market first through decarbonised hydrogen by sequestering carbon dioxide from conventional fossil-based hydrogen-production processes (blue hydrogen) or using technology that produces solid carbon as a by-product, such as natural gas pyrolysis (turquoise hydrogen). Others are utilising nuclear energy or biomass to produce hydrogen, which is only considered green by some countries. A consensus is needed to allow alternative hydrogen-production options with proper accounting of GHG emissions on a life-cycle basis.

4. Recommendations for G20

Priority Area 1: Comprehensive tracking of RE supply chains

- Tracking trade flow data for RE products and raw materials
- Periodic updates on manufacturing capacities
- Track projects and periodically assess technologies

Priority Area 2: Increase the supply of RE technologies to meet future demand

- Increase financing of manufacturing by MDBs
- Upskill individuals and institutions on scaling local RE value chains
- Improve local infrastructure for RE supply chain logistics
- Develop RE circular economy standards

Priority Area 3: Enable co-development of technologies

- Share novel technology-centric public procurement models
- Formalise international collaboration between lab

Priority Area 4: Harmonise RE standards and certification

- Establish interoperability of operational and safety standards
- Harmonise global certification systems

Priority 1: Joint efforts to comprehensively track the renewable energy supply chains

- **Action point 1: Tracking the trade-flow data with greater accuracy:** Globally, countries are undertaking several initiatives and actions to meet their sustainability goals. In this aspect, the global trade of low-carbon technologies is expected to increase exponentially in the coming years. Without concrete trade data, countries will not be able to analyse and understand their supply chains. Therefore, countries must agree to record and report the trade data of the final product and the associated input of raw materials.

  The G20 can request the trade statistics branch of the United Nations Statistics Division to recommend ways in which detailed supply-chain data can be recorded for low-carbon technologies. This will help track the flow of the raw materials from mines to processing facilities to deployment sites. Additionally, for green hydrogen, no data is publicly available on the price of green hydrogen or derivative products, which is important to foster competition and trade. Therefore, data on green hydrogen and derivative prices can be anonymised and shared on a regional basis. The price information can also be converted into an index, much in the same way that Brent crude oil, Henry Hub gas prices, or Japan–Korea Marker LNG prices are used as indices.

- **Action point 2: Tracking manufacturing capacity across the value chain:** Building manufacturing capacities and new supply chains takes time. Additionally, many processes are technically complex, capital intensive, and require significant infrastructure (roads, power, ports, etc.). Given the difficulty in building supply chains and manufacturing capacity, many countries have relied on imports for their energy transition. However, price spikes have been witnessed in cases wherein supply has been unable to meet the demand. If the data on current and future manufacturing capacity is available, then governments and private investors can use it to take proactive steps in building new manufacturing capacities or investing in supply chains that require expansion.

> Without concrete trade data, countries will not be able to analyse and understand their supply chains.

Therefore, G20 can recommend that the United Nations Industrial Development Organization (UNIDO) take the lead in tracking the RE supply chain and sharing the data in the public domain. Additionally, the UNIDO can also track the manufacturing capacities of the equipment that is used to manufacture these RE technologies. Having reliable data on manufacturing will help countries dedicate their resources more efficiently to building a resilient supply chain.

- **Action point 3: Periodic project tracking and technology assessments:** Lack of awareness and information on decarbonisation projects is a limiting factor in addressing climate change effectively. A mechanism is needed to track and list projects deployed globally for decision-makers worldwide to emulate in their jurisdictions. One way is to develop a searchable web portal that lists projects and decarbonisation solutions. The information from this portal can feed into the Paris Agreements Global Stocktake and highlight the progress made over time.

  A periodic assessment and status report of new and upcoming technologies is needed. This will allow collaborators to identify opportunities for co-development or adaptation to new use cases. Innovators can also identify gaps and new areas for technology development. Finally, transparently providing details on existing technologies, such as efficacy, suitable applications, size availability, etc., will help determine the level of decarbonisation possible or achieved through the deployment of these technologies.

Priority 2: Create new avenues of supply to meet the increasing demand for renewable energy technologies

- **Action point 1: Dedicated financing for manufacturing through multilateral development banks:** It is expected that over the next decade, hundreds of billions of dollars will be required to scale up the RE supply chain and manufacturing capacity. Given the scale, such opportunities will also lead to the creation of new jobs across the value chain which can be beneficial for lower- and middle-income countries. In this aspect, the role of G20 becomes critical to ensure that investments are made across the supply chain (from mining to the assembly of final products) of the RE technologies. Dedicated funding from multilateral development banks should be channelled towards building supply chains for the future. In addition, countries can also forge bilateral/multilateral partnerships based on complementary strengths in the RE supply chain.

> Dedicated funding from multilateral development banks should be channelled to build supply chains for the future.

- **Action point 2: Jointly develop handbooks and courses to train individuals and institutions on developing the local value chain:** To develop a global RE supply chain, individuals and institutions across the value chain (academic institutions, bureaucrats, banks, etc.) need to be trained in both technical and non-technical skills. G20 countries can take a lead and leverage their technical know-how by forming multilateral collaborations on education and training. Leading universities can create new centres of excellence to conduct training programmes and scale up efforts like the National Programme on Technology Enhanced Learning (NPTEL) in India to prepare digital courses on building hard and soft skills related to RE supply chains. In terms of safety, skilling and training on safe production, transport, and end-use of various RE technologies will be important. There is a significant potential for the deployment of RE and increased use of distributed green hydrogen. Therefore, awareness and training programmes are needed so that there are no skilling and psychological barriers to the adoption of these solutions.

- **Action point 3: Develop and prioritise infrastructure for the production and movement of raw materials and finished products:** Many steps leading to the production of finished products are highly energy intensive and may even require large parcels of land. Additionally, very few regions/countries export RE products globally, which makes it important for both the exporter and importer to continue upgrading their infrastructure to meet the increased demand. As new deployment areas open up, new infrastructure in the form of ports, pipelines, and roads may be built or upgraded. The pandemic's impact on freight rates was observed to be the greatest on trade routes to developing regions. This affected consumers and businesses in these regions and impacted the affordability of commodities. Port expansion and management across countries and regions will be key to shortening supply chains and increasing the resilience of supply chains pertaining to energy-transition technologies, among other essential goods and high-value commodities. G20 could propose that UNCTAD facilitate investments in the institutional, technological, and human capacities needed for greater penetration of electronic solutions for trade facilitation, sophisticated and automated customs clearance systems, and digital trade solutions. UNCTAD could also be directed to facilitate the development of a policy brief or assess the challenges and opportunities for the preparedness of ports in prospective RE markets to host manufacturing and procurement facilities.

- **Action point 4: Develop global standards on RE circular economy:** Currently, most countries and industries focus only on the last stage of products – end-of-life recycling. Although it has the potential to recover the intrinsic elements and support demand, its success depends considerably on product design and packaging. The design also determines the product's reparability and reusability, which can support offset the mineral demand by extending the use of the entire product or functional components. G20 countries could propose that organisations like UNIDO come up with global standards for designing RE technologies based on circularity principles. They could also set up indicators to track circularity in the RE supply chains. UNIDO may engage with sectoral organisations like Global Battery Alliance to develop such standards. UNIDO organisations could also be tasked with tracking the development of recycling technologies that improve the EoL recycling rate of materials. Science 20 engagement groups can take a lead in leading this by working with sectoral initiatives.

Priority 3: Enable co-development of technologies and innovation

- **Action point 1: Share best practices on public procurement models which scale up advanced technologies:** As the demand for RE technologies grows, the requirement of associated minerals will also increase manifold. Developing new mines and building the capability to process the minerals is a time-consuming process with a lead time of many years. Additionally, many of the key minerals are geographically concentrated, leading to an increased risk of supply-chain disruptions. In this background, G20 countries must share their best practices on procurement models that can scale up advanced technologies (like those requiring less or no critical minerals). The Science 20 and Business 20 engagement groups under G20 can take the lead and coordinate with international multilateral initiatives like Mission Innovation.

> G20 can take the lead in forming an official partnership of global technical institutions which work together to co-develop technologies and conduct studies in the RE supply chain.

- **Action point 2: Formalise collaborations between technology-development labs across the world:** RE technologies are undergoing a rapid rate of innovation globally. However, often, the development of new technologies is concentrated and may not cater to the needs of all countries. Additionally, new R&D centres cannot be immediately successful due to a lack of institutional memory. Therefore, cross-country collaborations must be prioritised, and details of previous-generation innovations (IP, patents, etc.) shared in the public domain. Additionally, concessional financing for developing countries to access technology IP may be provided. This will help many countries and institutions come up to speed and focus on developing new technologies and supply chains. G20 can take the lead in forming an official partnership of global technical institutions which work together to co-develop technologies and conduct studies in the RE supply chain.

Priority 4: Facilitate development of globally acceptable standards and certification

- **Action point 1: Establish interoperability in operational and safety standards:** Green-hydrogen supply chains will include both the deployment of electrolyser (and fuel-cell) technologies and trade in green hydrogen and derivatives. Therefore, there is a need for harmonised standards and protocols such that these do not turn into barriers to easy deployment and market creation. Most of the codes and standards relating to green hydrogen rest on a voluntary process based on consensus, but governments can encourage their progression with dedicated effort. Developing and obtaining consensuses for changes to these standards is a long process; hence, urgent action is needed on this front to avoid them becoming a barrier to supply chains. Competition among standards-development organisations can also complicate the process. An industry-driven alliance can be created to either develop or harmonise standards globally for hydrogen technologies or include it under the ambit of an already existing organisation such as the ISO.

- **Action point 2: Develop harmonised, and universally acceptable certification systems:** Varying certification systems could conflict with each other and act as trade barriers, especially on the issue of defining green hydrogen. Establishing a common certification system – or, at the very least, harmonising certification systems across geographies – will enable healthy trade in green hydrogen. A consortium of countries can design globally accepted certification norms and verification protocols that will be agreed upon by all member states. Similarly, a nodal body can be created, which can be constituted of existing certifiers across the globe and responsible for the regular update and exercise of the agreed system. The nodal body will also certify third-party auditors that will support the certification system. On the other hand, the performance of solar, wind, and battery are heavily dependent on their environmental conditions, which often leads to the development of country-/climate-specific standards. Learnings and best practices from the standard-development process should be shared to ensure better quality products with increased life and durability, making the sector more climate resilient.

> **An industry-driven alliance could be created to either develop or harmonise standards globally for hydrogen technologies.**

Conclusion

We need to accelerate the adoption of renewable energy for sustainable economic growth, but at affordable prices for millions of people, particularly in developing countries. While continuous technology advancements are reducing the cost of generating renewable energy, there are factors that impede its adoption and deployment. The current structure of global supply chains for solar PV, wind, lithium-ion batteries, and green hydrogen make transition to these technologies risky.

Manufacturing capacities of mainstream technologies such as solar PV and wind have expanded over the last decade, but are concentrated only in a few countries. This concentration of RE manufacturing facilities has had a significant effect on the import mix of individual countries, particularly those in the low-income category. This implies that countries import key components and equipment from only a handful of sources leading to concentrated supply chains, making them vulnerable to risks of climate change, geopolitics, and health and economic crises. The recent years have exposed almost all countries to these risks as the availability and prices of key technology components as well as mineral resources were hit, thus slowing down the pace of the energy transition.

However, an accelerated and risk-proof energy transition only be possible if countries can come together to comprehensively track the renewable energy supply chains, identify avenues and strategies for diversification and development of supply chains in a relatively more distributive fashion, enable co-development of technologies and innovations, and harmonise standards and certification systems for new and emerging clean technologies.

Annexures

Annexure 1 Green-hydrogen production and electrolyser capacity targets by country

Country	Colour of hydrogen in focus GH2 capacity	2030 targets			2050 target
		Electrolyser capacity	Cost reduction		
Argentina		-	5 GW+	-	-
Australia		-	-	< AUD 2/kg	-
Brazil		NA	NA	NA	NA
Canada		3 MT (low-carbon H2)	-	-	20 MTPA (low-carbon H2)
China		0.1–0.2 MT by 2025	-	USD 1.4/kg	-
EU		10 MT (low-carbon H2) 10 MT (import)	40 GW	-	-
France		-	6.5 GW	-	-
Germany		-	10 GW	-	-
India		5 MTPA	-	USD 1/kg	-
Indonesia		-	-	-	52 GW by 2060
Italy		-	5 GW	< USD 2/kg	-
Japan		3 MTPA (blue and green)	-	< USD 3/kg	20 MTPA (blue and green)
Mexico		-	-	-	-
Russia		2 MT of exports (by 2035)	-	-	15 MT (exports)
Saudi Arabia		2.9 MT	-	-	-
South Africa		0.5 MT	10 GW	USD 1.4–1.8/kg	-
Republic of Korea		1.9 MTPA (not green) 1.96 MTPA (import)	-	-	27.9 MTPA
Turkey		NA	NA	NA	NA
United Kingdom		-	10 GW (low-carbon H2)	-	-
United States		10 MTPA	-	USD 1/kg	50 MTPA
Belgium		20 TWh (imports)	150 MW (by 2026)	-	200–350 TWh (imports)
Chile		-	25 GW	< 1.5 USD/kg	-
Egypt		-	1.4 GW	USD 1.7/kg by 2050	-
Morocco		14 TWh	-	-	-
Namibia		1–2 MTPA	-	USD 1.2–1.3/kg	10–15 MTPA
Oman		1 MTPA	-	-	3.5–8.5 MTPA
Portugal		-	2 GW	-	-
Spain		-	4 GW	-	-

Source: CEEW compilation

*Note 1: Low-carbon H2: Low-carbon hydrogen is defined by the EU as blue hydrogen and electricity-based hydrogen, with significantly lower life-cycle emissions than the hydrogen produced from fossil fuels. Not green: Not-green H2 means the H2 that is not produced using RE that is either grey, brown, or blue H2.
Import: Hydrogen that will be imported by the country to meet certain demands.
Export: Hydrogen that is specially meant for exports to other countries.
Note 2: 1 MT of H2 produces 33 TWh of energy.

Annexure 2 Country-specific investment commitments for deploying hydrogen-based solutions

Major countries	Investments committed	Investment required for net zero	Source
Argentina	-	-	-
Australia	AUD 2.2 billion (hydrogen ecosystem and industrial hydrogen hubs)	-	(CSIRO 2022a)
Brazil	-	USD 200 billion (hydrogen production and RE infra)	(McKinsey & Company 2022)
Canada	-	-	-
China	USD 4.6 billion (by 2025 in hydrogen production and RE infra)	-	(Xin 2023)
EU	~ EUR 20 billion (by 2030 for electrolyser, hubs, R&D)	EUR 180–470 billion (by 2050, hydrogen production)	(CSIRO 2022b)
France	EUR 5 billion (by 2030 for decarbonised hydrogen, retrofits, PTG, mobility, and R&D support)	-	(CSIRO 2022c)
Germany	EUR 10 billion (hydrogen application, PTX, mobility, heating)	-	(CSIRO 2022d)
India	USD 2.3 billion (hydrogen production, hubs, R&D, RE)		(Ministry of New and Renewable Energy 2023)
Indonesia	-	USD 25.2 billion (by 2060 for electrolyser, RE, mobility)	(Evans 2022)
Italy	EUR 10 billion by 2030 (production asset, infra, R&D)	-	(CSIRO 2022e)
Japan	JPY 2 trillion/USD 18 billion (hydrogen energy, storage batteries and carbon recycling)	-	(CSIRO 2022f)
Mexico		USD 15.5 billion (hydrogen production)	(HINICO 2021)
Russia	-	-	-
Saudi Arabia	-	-	-
South Africa	-	-	-
Republic of Korea	-	-	-
Turkey	-	-	-
United Kingdom	GBP 12 billion (hydrogen, ecosystem, R&D, technology development)	-	(Department for Business 2021)
United States	USD 9.5 billion (by 2030 for a clean hydrogen ecosystem)	-	(DOE 2022a)

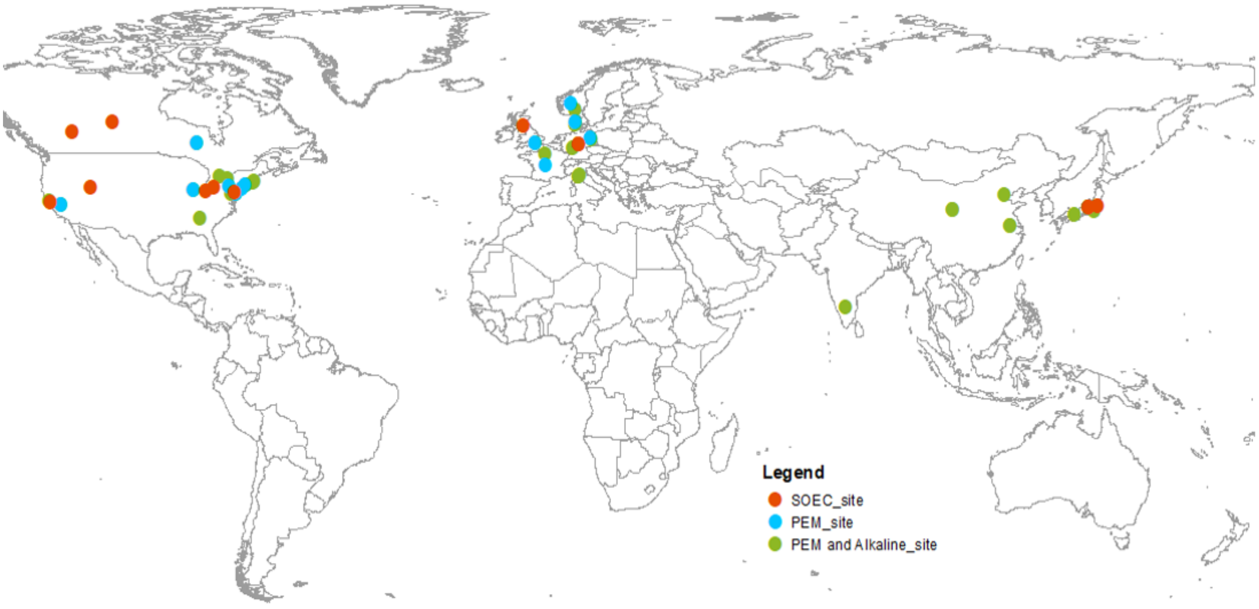
Source: CEEW compilation

Annexure 3 Sectoral focus of countries in utilising green hydrogen

Major countries	Industry	Electricity	Export	Shipping	Transport	Refining	Space heating and gas network	Aviation
Argentina	✓	✓	✓					
Australia	✓	✓	✓	✓	✓		✓	
Brazil	✓				✓	✓		
Canada	✓	✓	✓	✓	✓		✓	
China	✓		✓		✓	✓	✓	✓
EU	✓				✓	✓	✓	
France	✓				✓	✓		
Germany	✓	✓		✓	✓	✓	✓	✓
India	✓		✓			✓	✓	
Indonesia								
Italy	✓				✓		✓	
Japan	✓	✓		✓	✓	✓	✓	
Mexico		✓						
Russia	✓		✓			✓		
Saudi Arabia	✓				✓	✓		
South Africa	✓		✓		✓	✓		
Republic of Korea		✓					✓	
Turkey	✓		✓					
United Kingdom	✓	✓		✓	✓	✓	✓	✓
United States	✓	✓		✓	✓	✓	✓	

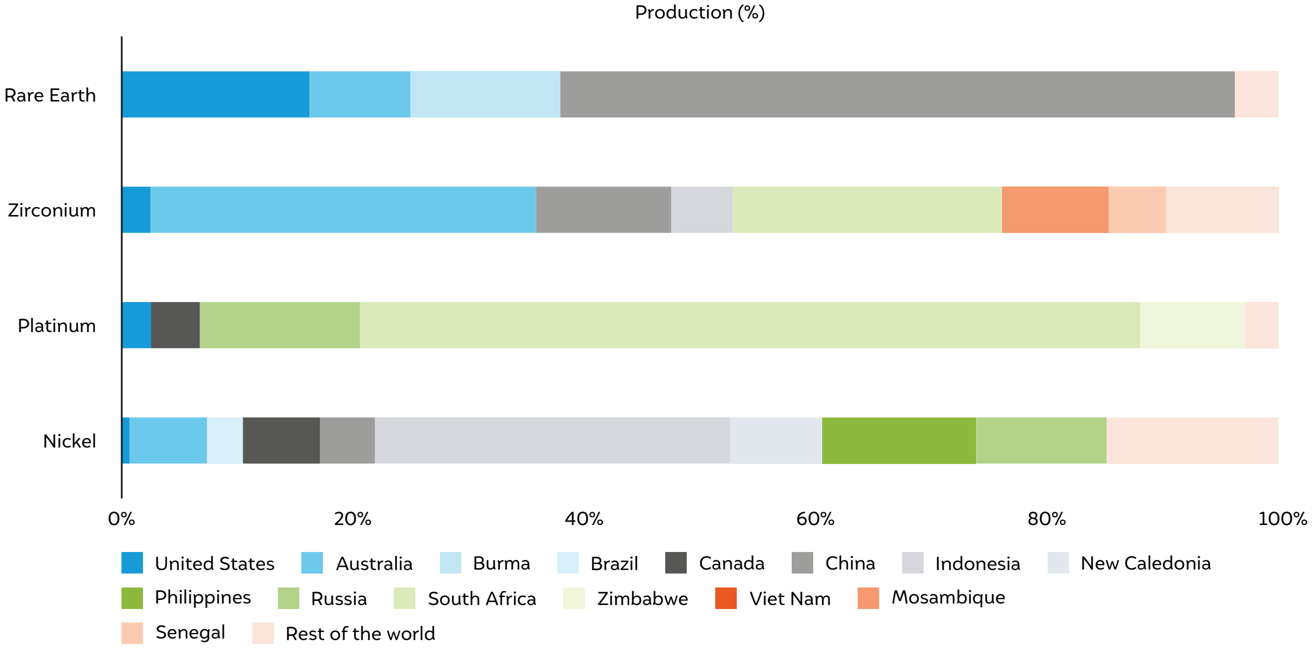
Source: DOE 2022a

Annexure 4 Location of PEM, SOEC, PEM, and ALK manufacturing plants



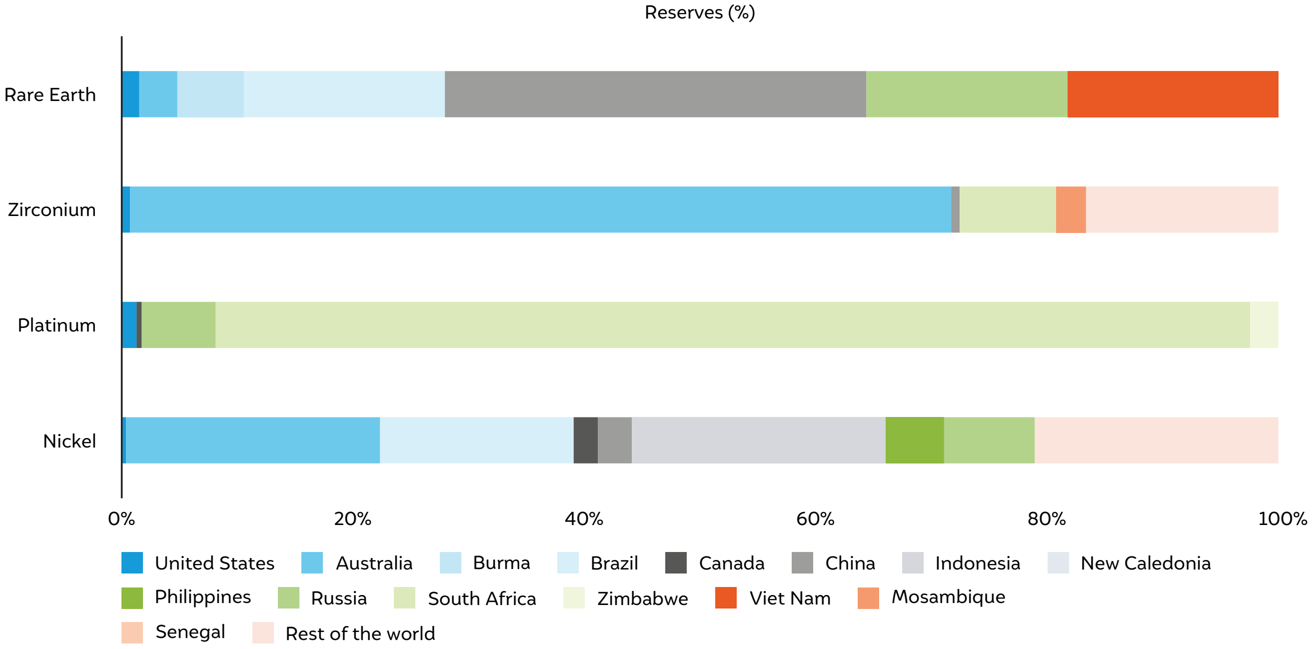
Source: CEEW compilation

Annexure 5 Production of rare earths and minerals by country in 2021



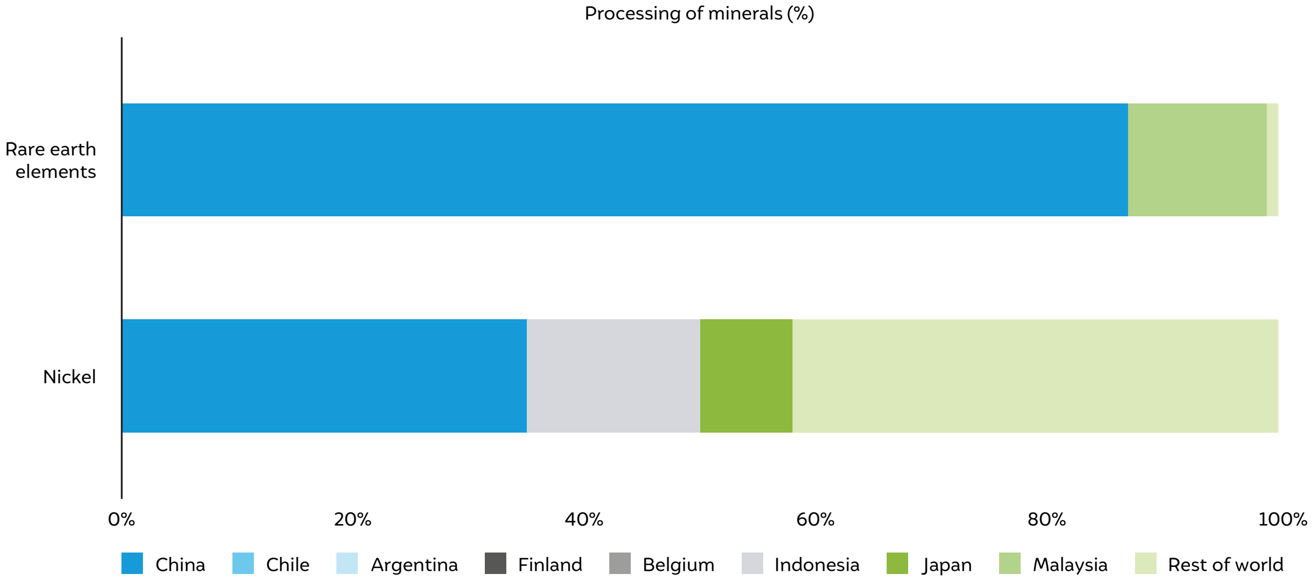
Source: (USGS 2021)

Annexure 6 Reserves of rare earths and minerals by country in 2021



Source: (USGS 2021)

Annexure 7 Processing of rare earths and minerals by country in 2019



Source: (IEA 2022d)

Annexure 8 Global mine production of clean energy technology minerals in 2021

Mineral	Mine production - World total (rounded), Unit is in thousand metric tons
Aluminium	67,960
Copper	20,980
Graphite	1038
Lithium	105
Manganese	19,950
Nickel	2,748
Palladium	0.20
Platinum	0.18
REE	277
Silicon	8,538
Zinc	12,850
Zirconium ores and zircon concentrates	1,200

Source : (USGS 2021)

Annexure 9 Partnerships and initiatives on green hydrogen globally

S. No.	Partnership	Led by	Member nations	Objective
1	Supply Chain Resilience Initiative	NA	India, Australia, Japan	Diversify supply chain
2	International Partnership for Hydrogen and Fuel Cell in the Economy	United States	Australia, Chile, France, Italy, Norway, United Kingdom, Austria, China, Germany, Japan, South Africa, United States, Brazil, Costa Rica, Iceland, Republic of Korea, Switzerland, Canada, EU, India, Netherlands, and the UAE	Hydrogen and fuel cell–technology development
3	Clean Energy Ministerial – Hydrogen Initiative	NA	Australia, Austria, Brazil, Canada, Chile, China, Costa Rica, European Commission, Finland, Germany, India, Italy, Japan, The Netherlands, New Zealand, Norway, Portugal, Saudi Arabia, South Africa, Republic of Korea, United Kingdom, and the United States	Hydrogen and fuel cell–technology development
4	The Hydrogen Technology Collaboration Programme	NA	24 countries including the EU, United Kingdom, US, China, and India, among others	Coordination in hydrogen R&D, market deployment, and technology dissemination
5	Mission Innovation's Clean Hydrogen Mission	Australia, Chile, EU, UK, US	22 countries including the EU	Development of hydrogen valleys
6	African Green Hydrogen Alliance	NA	Kenya, South Africa, Namibia, Egypt, Morocco and Mauritania	Develop a green-hydrogen value chain
7	Quad Clean Hydrogen Strategic Initiative	NA	India, the United States, Japan, Australia	Infrastructure project for clean hydrogen

Source: CEEW compilation

Annexure 10 Funding commitments for green-hydrogen ecosystem development

Organisation	Fund	Committed funding
European Union Horizon	Horizon Europe	EUR 95.5 billion
Clean Hydrogen Partnership and Mission Innovation	Hydrogen Valley Platform	EUR 39 billion
European Union Innovation	Innovation Fund	~ EUR 20 billion
US Department of Energy	Regional Clean Hydrogen Hubs	USD 6 billion
KfW Development Bank	PtX Development Fund	EUR 550 million
European Investment Bank	Green Hydrogen Fund	EUR 25 million

Source: CEEW compilation

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