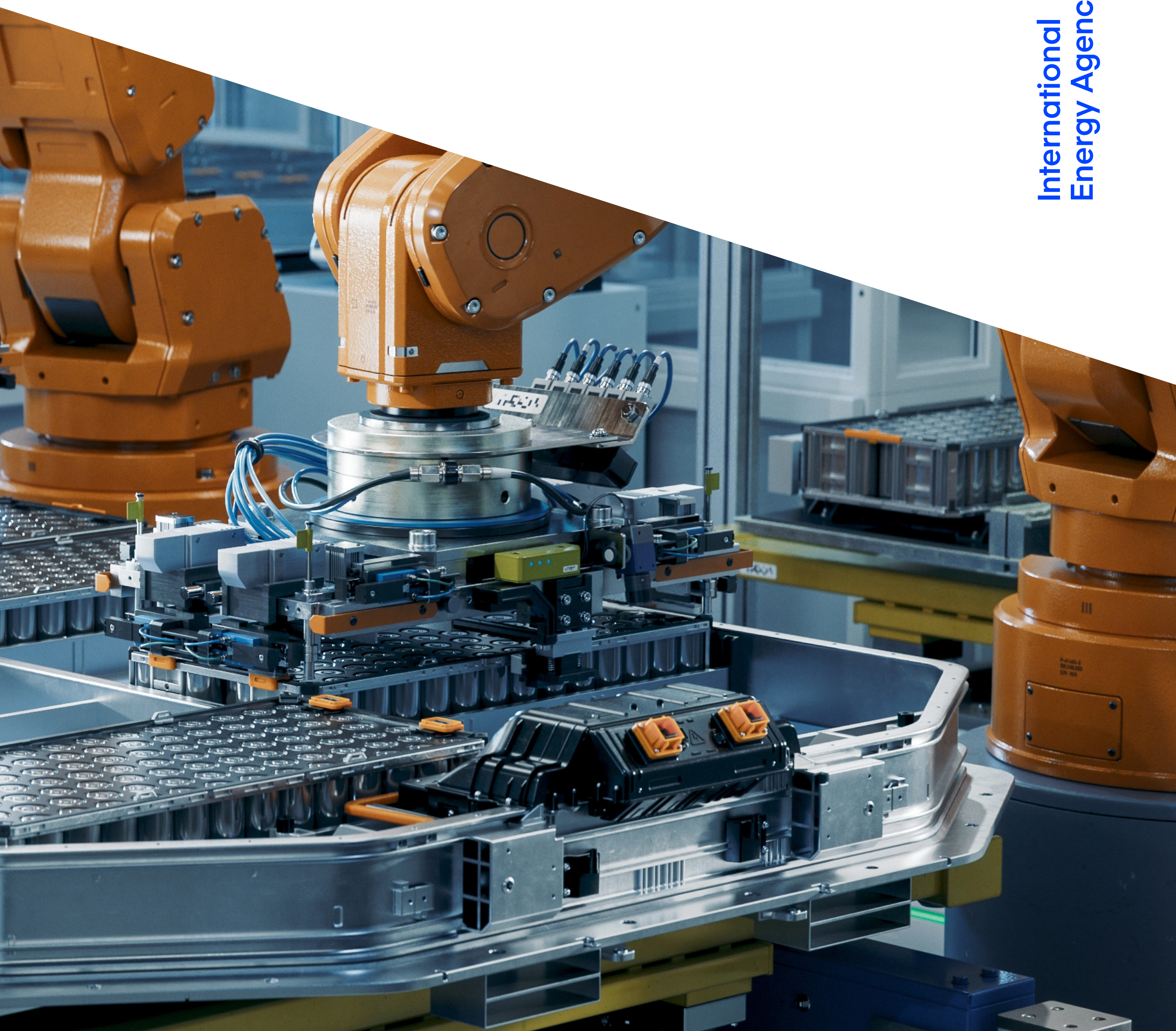
Advancing Clean Technology Manufacturing

An Energy Technology Perspectives Special Report

International Energy Agency



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Abstract

Governments and firms around the world are racing to define their place in the clean energy economy, which is growing quickly as policy makers develop new industrial strategies that also bolster energy security and address climate change. This Energy Technology Perspectives Special Report is structured to provide decision makers with an analytical toolkit to design and evaluate their strategies for clean technology manufacturing. Acknowledging that there is no “one size fits all” approach, it lays out guiding principles that can help inform future planning.

This analysis was produced in response to a request from G7 Leaders in 2023. It benefits from the insights gathered during a High-level Dialogue on Diversifying Clean Technology Manufacturing held at the IEA headquarters in Paris in November 2023. It also builds on analysis conducted as part of the latest edition of the IEA’s flagship technology publication, Energy Technology Perspectives, and two Special Briefings on the topic of clean technology manufacturing during the course of 2023.

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Executive summary

Clean technologies shine a spotlight on manufacturing

The manufacturing sector – long an engine of economic growth and development – is increasingly at the forefront of considerations on energy, climate and economic policy. Countries are racing to capitalise on benefits that clean technology manufacturing can bring to economic security, employment and the resilience of clean energy transitions. Following a request by G7 Leaders in 2023, this *Energy Technology Perspectives Special Report* is designed to aid policy makers as they prepare their industrial strategies. It focuses on five key clean energy technologies – solar PV, wind, batteries, electrolysers and heat pumps.

Investment in clean technology manufacturing is becoming so significant that it is starting to register in broader macroeconomic data. In 2023, it accounted for around 0.7% of global investment across all sectors of the economy, driving more spending than established industries like steel (0.5%). In growth terms, the contribution is even starker – in 2023, clean technology manufacturing alone accounted for around 4% of global GDP growth and nearly 10% of global investment growth.

The recent surge in investment looks set to continue

New, first-of-its-kind analysis in this report shows that investment in clean technology manufacturing stood at around USD 200 billion in 2023, growing by more than 70% relative to 2022. Investments in solar PV and battery manufacturing plants led the way, together accounting for more than 90% of the total in both years. Investment in solar PV manufacturing more than doubled to around USD 80 billion in 2023, while investment in battery manufacturing grew by around 60% to USD 110 billion.

China accounted for three-quarters of global investments in clean technology manufacturing in 2023, down from 85% in 2022, as investment in the United States and Europe grew strongly – particularly for battery manufacturing, for which investments more than tripled in these regions. For solar PV manufacturing, investments in China more than doubled between 2022 and 2023. Outside these three major manufacturing hubs, India, Japan, Korea and countries in Southeast Asia made important contributions in specific areas, while investment in regions such as Africa, Central America and South America was negligible.

Near-term momentum for clean manufacturing looks strong. Around 40% of investments in 2023 were in facilities that are due to come online in 2024; for battery manufacturing facilities, this share is nearly 70%. Committed projects –

those that are under construction or have reached final investment decisions – through 2025, together with existing capacity, would exceed by 50% the global solar PV deployment needs in 2030 based on the IEA's Net Zero Emissions by 2050 Scenario (NZE Scenario) and meet 55% of battery cell requirements. This momentum is also spreading to adjacent sectors – nearly half of committed battery manufacturing announcements in the United States will be via joint ventures with automakers.

The project pipeline is expanding rapidly, if unevenly

Existing manufacturing capacity for solar PV modules and cells could today achieve what is necessary to meet demand under the NZE Scenario in 2030 – six years ahead of schedule, with only modest gaps remaining for the upstream steps of wafer and polysilicon manufacturing. However, facilities making cells and modules are currently seeing relatively low average utilisation rates of around 50% globally. Key factors that explain this are a solar PV module supply glut, together with the rapid expansion of manufacturing capacity. While the sharp increase in supply has driven down module prices, supporting wider consumer uptake, stockpiles of solar PV modules are growing and there are signs of downscaling and postponements of planned capacity expansions, particularly in China.

Battery manufacturing also had a record year in 2023. Production totalled more than 800 gigawatt-hours (GWh), rising 45% from 2022. Capacity additions also surged, with almost 780 GWh of cell manufacturing capacity added – around a quarter more than in 2022. This raised total installed capacity to around 2.5 terawatt-hours (TWh), or almost three times current demand. Globally, battery manufacturing capacity could exceed 9 TWh by 2030 if all announcements are realised. Battery manufacturing deployment needs in 2030 under the NZE Scenario are within reach: more than 90% could be met by announced expansions that have reached final investment decisions.

New manufacturing capacity for wind and electrolysers also grew faster in 2023, although the gains were not as dramatic. Existing capacity for wind could deliver nearly 50% of NZE Scenario needs in 2030, while announced projects could meet a further 12%. Meanwhile, capacity additions for heat pump manufacturing slowed due to stagnation in the majority of leading markets. Existing capacity could deliver only around one-third of 2030 needs in the NZE Scenario – though this could change quickly given the short lead times typical of capacity expansions in this industry.

Geographic concentration in manufacturing looks set to remain high for most clean energy technologies

China, the United States and the European Union together account for around 80% to 90% of manufacturing capacity for solar PV, wind, battery, electrolyser and heat pump manufacturing. Little change to this overall concentration is foreseen to 2030, even if all announced projects come to fruition. China alone accounts for more than 80% of global solar PV module manufacturing capacity and 95% for wafers. This looks unlikely to change significantly this decade, with the country set to match or exceed the capacity additions planned in other countries like the United States and India. For battery cell manufacturing, the situation is somewhat different: Planned capacity additions in Europe and the United States look set to reduce China’s present share of global capacity, with both regions reaching around a 15% share by 2030 if all announced projects are realised. In Europe and the United States, announced battery cell manufacturing capacity is sufficient to meet the 2030 domestic deployment needs associated with their own climate goals.

The geographic concentration of manufacturing for wind, electrolysers and heat pumps also shows little change through 2030. Outside of the main producer countries, Central and South America account for a small share of global production of the main wind turbine components (4% to 6% for nacelles, blades and towers). However, virtually no clean technology manufacturing takes place in Africa today. Concentration is even more pronounced for upstream solar PV and battery components, but the prospect of surplus capacity may open up possibilities for greater diversification of production in this area.

Production cost gaps are significant, but not immutable

New data and analysis, including plant-level assessments of more than 750 facilities, provide insight into key drivers of manufacturing costs and the differences between regions. Our analysis shows that China is the lowest-cost producer for all the technologies highlighted in this report, before accounting for explicit supportive policy measures, though it also points to opportunities for reducing cost gaps.

The main upfront cost that contributes to overall production costs is the capital expenditure to set up a clean energy manufacturing plant, and the associated financing costs. Facilities in the United States and Europe are typically 70% to 130% more expensive per unit of output capacity than those in China for solar PV, wind and battery manufacturing, before accounting for the difference in the cost of capital between regions. India’s capital costs are around 20% to 30% higher than China’s, but significantly lower than those of the United States and Europe.

However, upfront costs make only a modest contribution to the overall levelised cost of manufacturing. Annualised capital expenditure amounts to just 15% to 25% of the total cost of producing solar PV modules, with a cost of capital of 8%. The proportions are similar for batteries (10-20%), wind turbines and heat pumps (2-10%) and somewhat higher for alkaline electrolyser stacks (15-30%). Operational costs, including energy, material, component and labour costs, make a far more important contribution in aggregate. Using global average commodity prices, and regional labour and end-user prices for energy inputs, ongoing operational costs account for 70% to 98% of total manufacturing costs. Reducing the costs of energy, materials and components is therefore an important lever for reducing cost gaps.

Cost is not the only factor that influences investment

Many factors besides the cost of manufacturing shape the decisions of firms to invest: the size of the domestic market, the availability of workers with the necessary skills, infrastructure readiness, permitting processes and other regulatory regimes, proximity to customers and synergies with existing industries are just some examples. Policy interventions can therefore raise the attractiveness of investing in a given region without directly subsidising the costs of manufacturing. Training and certification schemes for workers, compressing project lead times while maintaining environmental standards, enlarging domestic markets and reducing uncertainty with robust, stable climate policies are some key "low regret" measures that can increase incentives to invest, irrespective of the role of direct incentives in industrial strategies.

Innovation is another key focus for industrial strategy design; as the portfolio of energy technologies shifts towards mass-manufactured equipment, the energy sector is likely to include more R&D-intensive companies with factories and R&D hubs in their home countries and elsewhere in the world. Being at the frontier of innovation is an important opportunity to compete in the market, which is one reason why countries with relatively high labour and energy costs continue to manufacture goods in trade-exposed sectors. While private-sector R&D can be stimulated by policies that promote manufacturing investment and experience, direct innovation support is also needed. Government measures, including R&D grants or loans, project finance, support for rapid prototyping, start-ups and production scale-up, can be targeted towards specific innovation missions to advance manufacturing.

Key principles to support industrial strategy design

The purpose of this report is not to prescribe a single approach to industrial strategy or to make recommendations to a specific country, but rather to support decision-making. Alongside its analysis of competitiveness, innovation and other specific areas of policy, the report distils a set of key principles to guide policy makers.

When considering domestic actions, governments should:

- **Prioritise and play to strengths**, with clearly defined goals and metrics to gauge success, and with experimentation and the ability to change course built in.
- **Attract and support innovators**, including by creating strong links between manufacturing and each component of the broader innovation system.
- **Plug cost gaps strategically and for the long-term**, including through measures to reduce lead times and upskill workforces.

Governments should also collaborate internationally, which in turn enhances opportunities for domestic investment and global progress. To do so, they should:

- **Collect data and track progress**, including on the trade and production of clean technologies and their components.
- **Co-ordinate efforts across supply chains** to enhance resilience by sharing experiences and collaborating.
- **Identify and build strategic partnerships**, backed by clear frameworks for co-operation.

Part I. Clean technology manufacturing today

Clean technology manufacturing is increasingly in the spotlight. The production of key technologies to support the transition to clean energy has become the cornerstone of industrial policies designed to boost employment and economic development in many countries. Moreover, it is a critical enabler for meeting climate goals, such as the pledge made at COP 28 to triple the world's renewable energy capacity by 2030. The first part of this report puts clean technology manufacturing in context, considering the role of manufacturing in the global economy, and the latest progress on ramping up manufacturing capacity in line with an acceleration of clean energy technology deployment.

Chapter 1 examines how manufacturing contributes to economic development in different regions worldwide, and recent investment trends in clean technology manufacturing. Chapter 2 tracks progress being made in expanding manufacturing capacity for five key clean energy technologies: solar PV, wind, batteries, electrolysers and heat pumps. It analyses whether manufacturing capacity is on track to meet deployment needs consistent with a pathway to net zero emissions by 2050, both within countries and regions and at the global level. Finally, it considers the geographical distribution of manufacturing, examining potential to meet domestic demand and opportunities for exports, and analyses levels of concentration in the supply chain.

Chapter 1. An introduction to clean technology manufacturing

Virtually all aspects of the modern built environment are products of the manufacturing sector, or an assembly thereof. Besides those we can see and touch, there are thousands of manufactured products, materials and chemicals that most people never come into contact with, existing only as intermediates in a complex network of industrial processes that make up global supply chains. In a single year, the manufacturing sector takes in billions of tonnes of minerals and biomass and transforms them into trillions of dollars' worth of products, adding value at each processing step. The manufacturing sector is, therefore, essential to modern society and an important contributor to economic growth and development.

Clean technology manufacturing in context

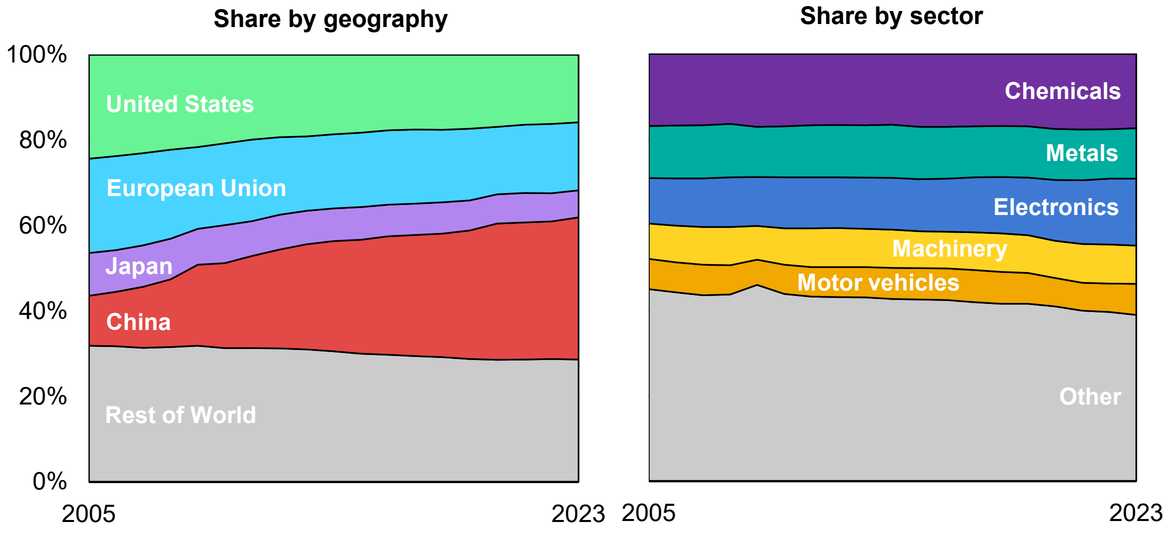
The manufacturing sector is also a critical enabler of the clean energy transition. To transform the current stock of power generation equipment, vehicles, buildings, industrial facilities and other capital stocks needed to generate and harness clean energy, the manufacturing sector will itself need to undergo a transformation. This shift is already underway, due to increasing consumer demand for clean technologies, falling costs, and supportive government policies aimed at the products of the manufacturing sector, and how it produces them. Clean technologies like solar PV panels, wind turbines and batteries together account for a small fraction of global manufacturing activity today, but they are emerging as an important contributor to the sector's growth.

This chapter introduces the manufacturing sector more broadly and provides an overview of recent trends, including the role of manufacturing in the economy. It then moves on to define 'clean technology manufacturing' using internationally recognised industrial classification systems, thereby locating its different elements within established definitions of the wider sector. The chapter concludes with new IEA analysis on manufacturing investments, providing a bottom-up, granular view of trends for individual technologies and components, filling a gap in existing top-down statistical data collection activities.

Manufacturing plays a crucial role in the global economy

Manufacturing is one of the principal drivers of economic growth, accounting for nearly one-fifth of GDP and employing around 350 million[1] people globally. The United States, the European Union, Japan and the People's Republic of China (hereafter, "China") accounted for around 70% of manufacturing value added in 2023, a share that has – in aggregate – remained almost constant over the past two decades. The United States, Japan and the European Union's combined share of output from the global manufacturing sector has declined significantly over this period, while China has emerged as the world's manufacturing hub. China nearly tripled its share of global manufacturing in monetary terms during 2005-2023, with its output increasing fivefold in absolute terms. The increase in China's share of global manufacturing output underpins a broader trend of geographic concentration. The top five manufacturing countries in terms of value added accounted for around 56% of the global total in 2005, with this share rising to around 64% in 2023.

Figure 1 Share of global manufacturing value added by geography and by sector



Note: Chemicals includes pharmaceuticals and fertilisers (ISIC Rev. 4 20-22); Metals includes basic and structural (ISIC Rev. 4 24-25); Electronics includes computer, electronic and optical products and electrical machinery (ISIC Rev. 4 26-27); Motor vehicles includes all road vehicles and parts (ISIC Rev. 4 29); Other includes all manufacturing (ISIC Rev. 4 10-33) less that covered under the other categories disaggregated. European Union corresponds to membership in 2023, held constant over the period analysed.

Source: IEA analysis based on OECD TiVA database and Oxford Economics Global Industry Service.

The sectoral composition of manufacturing has changed much more slowly than its geographic distribution. Categorised by a series of aggregated sub-sectors (see Box 1), five industries – chemicals (incl. pharmaceuticals), electronics,

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[1] Includes employment in the construction sector.

machinery, metals and motor vehicles – accounted for 61% of manufacturing value added in 2023, increasing slightly from 55% in 2005. Most of these sub-sectors have maintained relatively consistent shares of total manufacturing output over the past two decades globally, even if substantial portions of each have been relocated geographically. The automotive sector contracted by around 20% in absolute terms in the aftermath of the 2008 financial crisis, rebounding to its pre-crisis level of output in 2010. The electronics industry, including the production of electrical machinery, computers, electronic and optical products, is the only one of these five sectors to have made significant gains relative to the others, increasing its share of global manufacturing output from 11% in 2005 to 16% in 2023, in part owing to the widespread adoption of portable electronic devices like laptop computers and mobile phones.

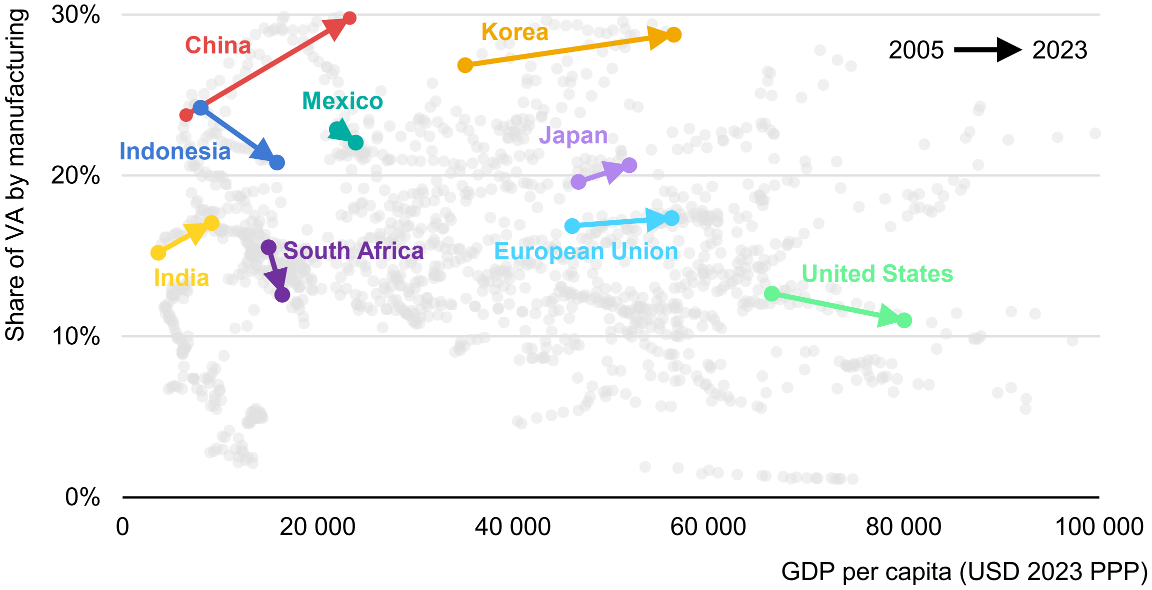
Box 1 International systems for categorising manufacturing activities and products

The International Standard Industrial Classification of All Economic Activities (ISIC) is a system administered by the United Nations Statistics Division for categorising various products, sectors and activities that contribute to a country's economy. The ISIC provides an internationally recognised structure for collecting data and statistics such that they are comparable between countries. The boundaries defined in the structure of the IEA's energy balances are based on the ISIC. The ISIC unifies national and regional statistical frameworks such as the North American Industry Classification System and the European Classification of Economic Activities. A given economic activity can be identified at different levels of specificity using its Section (letters A-U), Division (2-digit number, subset of Section), Group (3-digit number, subset of Division) or Class (4-digit number, subset of Group).

The ISIC classifies industrial activities associated with producing and transforming goods (and services and other activities), rather than the goods themselves. The Harmonized System (HS), administered by the World Customs Organization, is a classification system that is used for the classification of goods for trade purposes. Like the ISIC, the HS provides a unified architecture for use across different jurisdictions, allowing the mapping of one country's customs classifications to another. A given product – or more often a group thereof – can be identified by Chapter (2-digit number), Heading (4-digit number) or Subheading (6-digit number), with each providing an increasing level of specificity.

Manufacturing continues to be an important pillar of economic development for emerging market and developing economies (EMDEs). Few countries have achieved high and sustained levels of economic prosperity without growth in manufacturing. The role of the sector in the broader economy varies significantly by country and over time, but has been shown to rise fastest during the early stages of economic development as a country industrialises. In China, GDP per capita increased by a factor of 3.5 between 2005 and 2023, during which time the contribution of manufacturing to the economy increased from 24% to 30%. Even in India, where services made an outsized contribution to economic growth compared to other countries at a similar stage in their economic development, the contribution of manufacturing to the broader economy increased from 15% to 17% of total value added over the same period.

Figure 2 **The role of manufacturing in the broader economy at different stages of economic development, 2005-2023**



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Notes: VA = value added. Manufacturing value added includes the activities corresponding to ISIC Rev. 4 Divisions 10-33. Grey data series shows annual data for 2005-2023 for 68 countries and regions beyond those explicitly identified.
Sources: IEA analysis based on OECD TiVA database and Oxford Economics Global Industry Service.

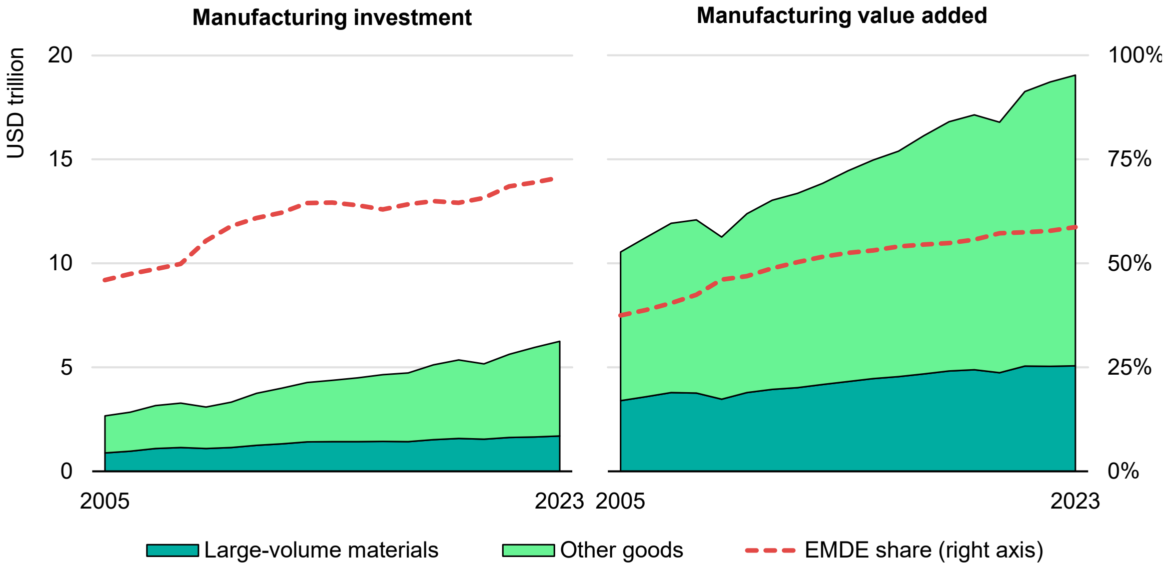
There are notable exceptions, like Indonesia's economy, whose GDP increased rapidly in size over the past two decades, but saw a decline in the share of manufacturing in total value added. In this case, growth in valued added by mining, agriculture and services outpaced the growth in manufacturing. Korea's per capita economic growth outpaced even China's in absolute terms during the period 2005-2023, and the role of manufacturing in the economy continued to grow even at relatively high levels of per capita income, in part due to supportive industrial policies. These and other exceptions aside, as countries achieve higher levels of per capita income, manufacturing tends to make a smaller contribution to the economy, giving way to services and consumption as the main drivers of growth. Even among countries with high per capita GDP there is significant variation, with the United States seeing manufacturing having just an 11% share of in total economic value added in 2023, compared with 23% in Germany and 21% in Japan.

In EMDEs, the growing importance of manufacturing in total economic output has been driven by increasing investment. Investments in factories, equipment and other fixed capital assets for manufacturing grew by nearly 30% during the period 2005-2023 in advanced economies, compared with 260% over the same period in EMDEs (including China). In 2005 the world's EMDEs accounted for little under half of global manufacturing investment. By 2023 this share had risen to over 70%.

More value is added downstream

Downstream manufacturing sub-sectors, i.e. those closer to the final consumer, tend to account for larger shares of total value added than those upstream, which produce the main input materials for the downstream industries. The production of the main large-volume materials, including metals, cement, glass, basic chemicals, timber, plastic, rubber and paper, accounted for around one-quarter of total value added from manufacturing in 2023, down from around one-third in 2005. These commodities are often traded in highly competitive markets and have limited product differentiation, leading to slim margins for their producers.

Figure 3 Global manufacturing investment and value added, 2005-2023



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Notes: EMDE = emerging market and developing economies. 'Large-volume materials' includes ISIC Rev. 4 Divisions 16-19, 22-25 and Group 201. 'Other goods' includes ISIC Rev. 4 Divisions 10-33, less the large-volume materials. Values shown in real USD 2023.

Source: IEA analysis based on OECD TiVA database and Oxford Economics Global Industry Service.

Downstream manufacturing sub-sectors have accounted for a larger share of value added over time, owing to an increase in the variety of products produced, an increase in the efficiency with which their input materials are used, and increasing product differentiation in line with consumer demands. For example, products like mobile phones and tablet computers – for which markets were still nascent in 2005 – have led to growth in the value of outputs from the 'computer, electronic and optical products' sub-sector that is disproportionate to the growth in output of key materials from the upstream sub-sectors.

There has also been a marked shift in where these downstream sub-sectors are located. Value added from downstream sub-sectors in EMDEs increased by a factor of three between 2005 and 2023, outpacing growth in value added from the main material-producing sectors, which saw a 240% increase over the same period. Even in China, which has seen unprecedented growth in the volume of energy-intensive material production – the country accounted for more than 50% of global crude steel production and aluminium production in 2023, up from 31% and 23% respectively in 2005 – the growth in value added from downstream sectors has risen 40% faster than in upstream material-producing sectors.

Tracking progress on clean technology manufacturing

The core focus of this report is on five clean technologies and their main components – solar PV, wind, batteries, electrolysers and heat pumps – as an indicative sample of key technologies for the clean energy transition, but there are, of course, many others, such as nuclear reactors; carbon capture, utilisation and storage (CCUS) technologies; and fuel cells. Clean technology manufacturing is not presently defined as an individual sub-sector in any systematic data collection or statistical frameworks. However, products and industrial activities relevant to clean technology manufacturing can be identified at varying levels of granularity in established categorisation systems (see Box 2).

Box 2 Defining clean technology manufacturing using established international classification systems

The manufacturing of these technologies and their primary components is spread across a handful of manufacturing sub-sectors, most of which are downstream of the main material-producing sectors. The electrical equipment (ISIC Division 27) and machinery (ISIC Division 28) sub-sectors account for the majority, including components of wind turbines, batteries, electrolysers and heat pumps. The computer, electronic and optical products (ISIC Division 26), chemical and chemical products (Division 20) and fabricated metal products (ISIC Division 25) sub-sectors account for the other main components (see table below).

The products themselves, as opposed to the industrial activities that produce them, can be identified in even more granular terms using the classification systems used by customs agencies for international trade. The Harmonized System (HS) administered by the World Customs Organization (see Box 1) identifies several clean technologies and their components, either individually or as part of wider groups of products. For example, HS 854143 corresponds to “Photovoltaic cells assembled in modules or made up into panels”, which matches closely with the quantities shown for “solar PV modules” in this publication. A perfect match is not available for all technologies and components within this publication’s core scope, even with the detailed six-digit HS. Electrolysers, for example, fall within a broader category of products under code 854330, “machines and apparatus for electroplating, electrolysis or electrophoresis”.

Mapping clean technologies using a selection of relevant HS and ISIC codes

Technology		HS codes (products)	ISIC codes (activities)	ISIC description of activities
Solar PV	Modules	854143, 854190	2610	Manufacture of electronic components and boards
	Cells	854142, 854190		
	Wafers	381800	2029	Manufacture of other chemical products n.e.c
	Polysilicon	280461	2011	Manufacture of basic chemicals
Wind	Nacelles	850231	2710	Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus
	Blades	841290	2812	Manufacture of fluid power equipment
	Towers	730820	2511	Manufacture of structural metal products
Batteries	Cells	850710, 850720 850730, 850750 850760, 850780	2591 2720 2790	Forging, pressing, stamping and roll-forming of metal; powder metallurgy; Manufacture of batteries and accumulators; Manufacture of other electrical equipment
	Anodes	850790, 854519		
	Cathodes	850790, 284290 284169, 382499 284190, 285390		
Electrolysers		854330	2790	Manufacture of other electrical equipment
Heat pumps		841581, 841861	2819	Manufacture of other general-purpose machinery

Note: Six-digit HS 2022 and four-digit ISIC Rev 4.

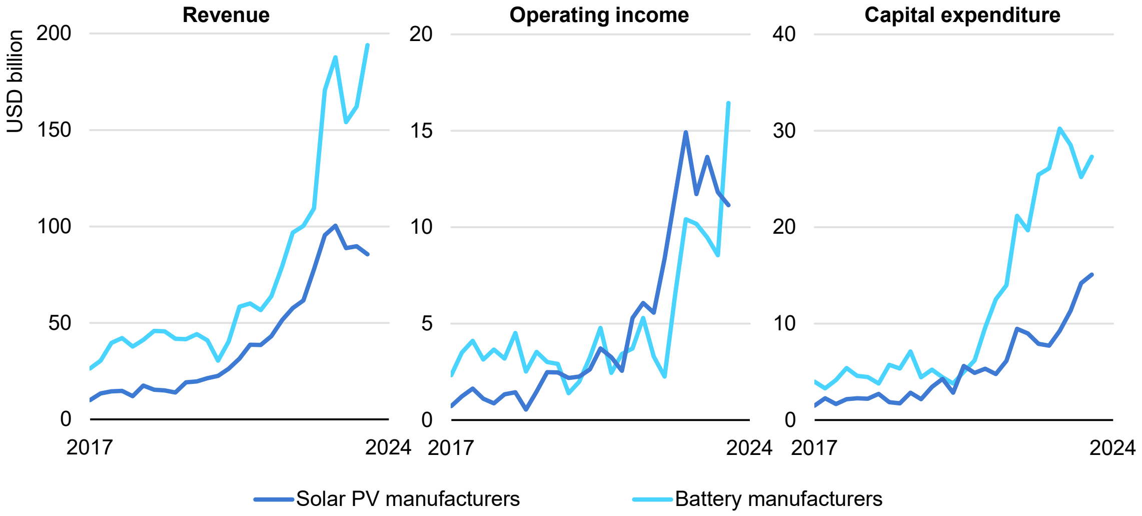
The shortcomings of existing classification schemes for providing a sufficiently granular description of the industrial activities associated with clean technology manufacturing mean that more granular data has to be assembled ‘bottom-up’ from a variety of data sources and research. Company filings are an alternative source of financial information that can be used as proxies for tracking inputs to, and outputs from, clean technology manufacturing operations, mostly in economic terms.

Aggregating investment, revenue and earnings data for companies engaged in the manufacture of clean technologies provides a glimpse at some of the latest trends.

Private sector indicators

Revenue from the top five solar PV[2] manufacturing companies surged from just USD 10 billion on an annualised basis in Q1 2017 to over USD 100 billion in Q4 2022, before falling slightly during the first three-quarters of 2023. Battery manufacturing revenue, measured on the same basis for the top five firms,[3] experienced a similar rate of growth, increasing from around USD 26 billion in Q1 2017 to almost USD 200 billion by the third quarter of 2023. Operating income, a measure of earnings after subtracting operational costs like materials and labour (but before accounting for taxes, investments and debt interest) grew even faster than revenues for the top five solar PV firms, and at a similar rate to revenues for the top five battery firms. These financial metrics indicate highly profitable operations in absolute terms, with the ten firms' earnings equating to around 15% of the global gross operating surpluses (a measure of aggregate profits) from the sub-sectors in which they are situated (ISIC Divisions 26 and 27). Most of the ten firms analysed maintained average profit margins (measured here as operating income as a percentage of revenue) in the range of 5-15-% during 2017-2023.

Figure 4 **Aggregated financial indicators for the top five solar PV and battery manufacturing companies, 2017-2024**



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Notes: Includes the top five publicly listed firms by installed manufacturing capacity for solar PV modules and batteries. Gaps in time series are filled with interpolations, and 2023 results are estimates where year-end filings are not available. Quarterly data shown on an annualised basis in nominal terms.

Source: IEA analysis based on company financials from S&P Capital IQ database.

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[2] Top five publicly listed solar PV manufacturing companies by module manufacturing capacity operational in 2023 for which complete time series data from Q1 2017 to Q3 2023 were available.

[3] As per solar PV, with the caveat that some of the largest battery manufacturers are also large electric vehicle producers. In these instances the financial indicators correspond to the overall company totals, including both battery and vehicle manufacturing operations.

Capital expenditure, a measure of overall investment by firms, which for these companies is mostly in manufacturing plants and equipment, also grew rapidly in the second half of the period analysed. To put the investment spending in context with the wider manufacturing sector explored earlier in the chapter, the combined investments from the ten firms examined – five for batteries and five for solar PV – totalled around USD 160 billion per year at their peak. When compared with total manufacturing sector investment in 2023 (around USD 6.4 trillion), the figure represents a small share, at 2.5% globally. Given that all of the firms analysed are headquartered in China – and carry out most of their manufacturing operations in the country – a more relevant comparison is with Chinese manufacturing sector investment, where the share rises to 6%. A more granular comparator still is the investment in the manufacturing sub-sectors that account for many of the activities associated with producing solar PV and battery components. At their peak, the investments by the ten firms in aggregate account for around 30% of investment in the electrical equipment and computer, electronic and optical products sub-sectors (ISIC Divisions 26 and 27) in China, and 60% when stripping out domestic appliances, consumer electronics and optical products.

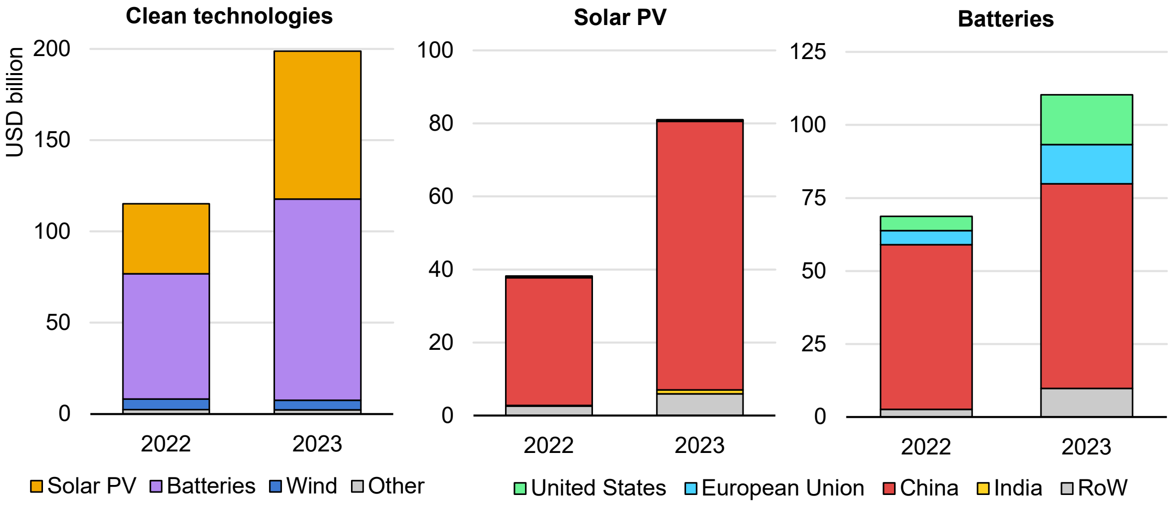
While comparisons with samples of company financial data are instructive as to broad trends in clean technology manufacturing, there are several limitations to this type of analysis with respect to tracking progress in these industries. First, a subset of companies is unlikely to be a consistent sample of a broader industry, as their combined share of sectoral activity is likely to vary over time. Second, it is difficult to obtain comprehensive data on all manufacturing entities, which can undergo mergers and acquisitions, and transfer assets to (or acquire them from) other players. Some companies are private, and not publicly listed, which generally results in less financial information being made publicly available. Third, data on manufacturing can include those corresponding to a variety of operations, and not all companies are "pure play" clean technology manufacturers. This is particularly the case for battery manufacturing, where, for example, the second largest battery manufacturer globally (BYD) is also one of the largest electric vehicle (EV) manufacturers. Tesla is also vertically integrated, with battery manufacturing operations and investments in lithium refining. Vertical integration is an increasingly common strategy in the EV supply chain, as it is for the various steps in solar PV manufacturing. Fourth, little-to-no physical data are required to be presented in company filings, which means analysis is generally limited to the use of economic measures of input, output and profitability.

These limitations underscore the need to analyse clean technology manufacturing operations on a physical basis, tracking where possible, capacity, production and investments at the facility level. Chapter 2 comprises the latest instalment of our analysis of progress in clean technology manufacturing, following Special Briefings on the topic in 2023.[4]

Clean technology manufacturing investment

New first-of-its-kind analysis by the IEA of clean technology manufacturing investment indicates that the sector is booming. Investment in manufacturing of the five clean energy technologies that this report focuses on reached USD 200 billion in 2023, up from USD 115 billion in 2022, growing by more than 70%. Investments were dominated by solar PV and battery manufacturing installations (including those for producing their main components), which together accounted for 95% of the total in 2023. China accounted for three-quarters of the investment in 2023, down from 85% in 2022. Both the United States and the European Union made significant inroads in 2023, with their combined share of total clean technology manufacturing investment reaching 16% in 2023, up from 11% in 2022. India, Japan, Korea and Southeast Asia made up most of the remaining share, with virtually no manufacturing investment taking place in either Africa or Central and South America.

Figure 5 **Clean technology manufacturing investment by technology and region, 2022-2023**



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Notes: RoW = Rest of world. Solar PV includes facilities producing polysilicon, wafers, cells and modules; Batteries includes facilities producing packs and cells, anodes and cathodes; Wind includes facilities producing nacelles, blades and towers; Other includes electrolysers and heat pump manufacturing.
Sources: IEA analysis based on InfoLink, Thomson Reuters, Bloomberg New Energy Finance, Wood Mackenzie, S&P Global Commodity Insights, EV Volumes, and Benchmark Mineral Intelligence.

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[4] IEA (2023), The State of Clean Technology Manufacturing, and IEA (2023), The State of Clean Technology Manufacturing – November 2023 Update.

There are three tell-tale signs of continued momentum in clean technology manufacturing investment going into the mid-2020s. First, we estimate that around 40% of the global clean technology manufacturing investment in 2023 was for facilities that will come online in 2024.[5] For battery manufacturing facilities, the equivalent figure is nearly 70%. Second, when looking in detail at the pipeline of announced projects for clean technology manufacturing, 85% of committed (i.e. those having reached final investment decision (FID) or under construction) solar PV manufacturing projects and around one-third of battery manufacturing facilities are scheduled to come online by 2025. Just these facilities, combined with those already installed today, could produce around 150% (solar PV) and 55% (batteries) of the global deployment levels in 2030 in the IEA's Net Zero Emissions by 2050 Scenario (NZE Scenario) (see Chapter 2). Third, a portion of the capacity that is scheduled to come online by the end of the decade is seeing some degree of financial commitment now. This momentum is also spreading to adjacent sectors – nearly half of committed battery manufacturing announcements in the United States will be via joint ventures with automakers.

This advanced spending commitment takes various forms, including land purchases, ground works, preparation ahead of manufacturing facility construction and the front-loaded investment in greenfield projects that later leads to less capital-intensive brownfield manufacturing expansion. Some of these dynamics are visible in our bottom-up investment estimates. For example, half of the global battery manufacturing capacity envisaged for 2030, including both committed and preliminary projects, is either an existing facility or a planned expansion thereof. Others only show up in macroeconomic indicators. For example, construction spending on US manufacturing facilities more than doubled between the beginning of 2021 and the end of 2023, driven by the clean technology manufacturing investments incentivised by the Inflation Reduction Act (IRA) and Chips and Science Act. Some of this construction spend is on "site preparation and outside construction of fixed structures or facilities such as sidewalks, highways and streets", which will take place well in advance of manufacturing equipment being installed. Granular data on US manufacturing investment spending from the Clean Investment Monitor shows a continuing upwards trend for each quarter of 2023, led by battery facilities.

The corollary of the current investment boom is that today's geographical concentration is set to persist, in particular for solar PV, with committed capacity potentially exceeding the 2030 deployment needs in the NZE Scenario. China continued to account for the lion's share of investments in solar PV manufacturing,

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[5] Assuming a 2-year period between FID and the plant becoming operational for all facilities analysed except solar PV module, cell and wafer manufacturing facilities where 1-year is used. An even spending profile during this period is assumed, meaning that an investment with a 2-year FID-to-operation period will see 50% of the spending take place in the year the facility becomes operational and 50% the year before.

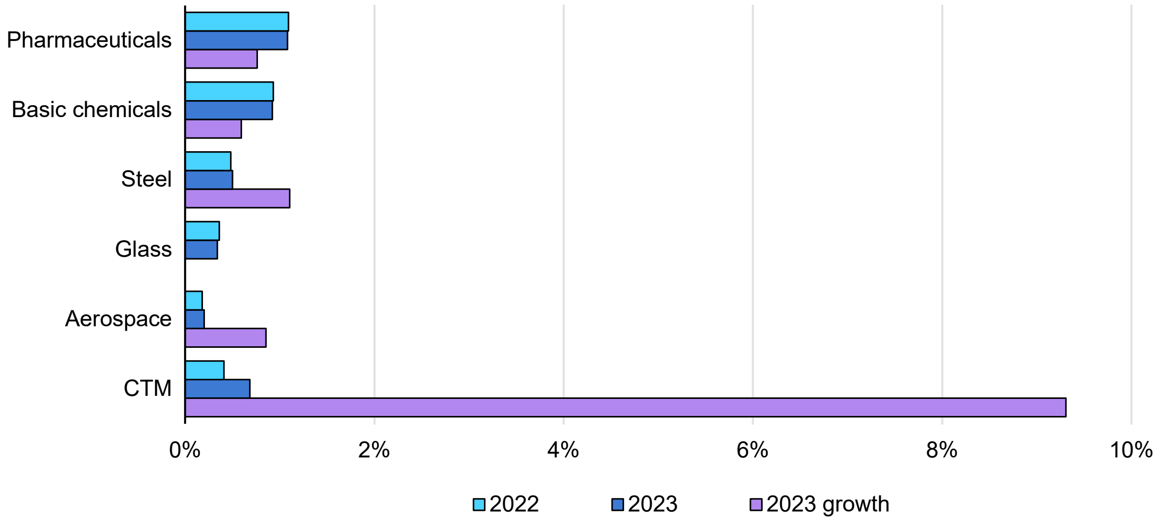
with investments growing by more than a factor of two between 2022 (USD 35 billion) and 2023 (USD 77 billion), but its share of the total remained flat at 91%, due to similar rates of increases in the rest of the world. China's high share of manufacturing investments in components was even more pronounced in the upstream steps of the solar PV supply chain, at 95% of the global total for wafer production capacity investments, and 96% of investment in polysilicon production facilities, compared with 83% for modules. This is despite the fact that China is estimated to have the lowest cost of any country for the installation of these facilities (see Chapter 3), which therefore require less investment per unit of capacity. Many of the capacity expansions in 2023 in China were brownfield and integrated (i.e. multiple process steps) facilities, which are generally lower-cost per unit of capacity than greenfield and standalone facilities, respectively.

Battery manufacturing investment – including cell, anode and cathode manufacturing – also showed strong growth in 2023, reaching USD 110 billion, up from USD 70 billion in 2022. The locations for these investments were more diverse than for solar PV. The combined investments in the European Union and the United States more than tripled in absolute terms, and together their share rose to more than a quarter of the global total, up from 14% in 2022. Given the assumption that a battery manufacturing facility takes around 2 years to construct following an FID, and a large swathe of facilities are projected to come online in 2024 and 2025 in these regions, much of this investment is attributable to facilities that are not yet operational. Looking upstream in the battery supply chain, a similar pattern can be observed as for the solar PV supply chain. While facilities outside China accounted for around a quarter of battery cell manufacturing investments in 2022, and nearly half in 2023, China accounted for 98% of investments in facilities for producing anodes in 2023 and 87% for cathodes.

Investment in other clean energy technologies – wind, heat pumps and electrolysers – accounted for a much smaller fraction of total investment, at around 7% in 2022 and 4% in 2023. Investment in wind manufacturing, including nacelle, blade and tower production facilities, fell slightly in absolute terms in 2023. China accounted for virtually all of the investment in wind manufacturing facilities. Electrolyser and heat pump manufacturing investments were the two areas where the European Union and the United States accounted for a larger combined share of investment than China in 2023, with virtually no investments in manufacturing for these technologies taking place elsewhere.

The growth in clean technology manufacturing investment in 2023 was so significant that it is starting to register in broader macroeconomic trends. Just the direct investments in the facilities described above accounted for around 0.2% of global GDP in 2023, doubling its share relative to 2022. When considering just the contribution of investment to GDP – gross fixed capital formation – these shares rise to 0.4% (2022) and 0.7% (2023). While these figures may seem small, they are larger than the shares of global investment attributable to the entire aerospace (0.2%), glass (0.3%) and steel (0.5%) industries; and approaching those of the basic chemicals (0.9%) and pharmaceuticals (1.1%) industries. Moreover, the investment in these comparatively mature industries grew only incrementally in 2023, where it grew at all, whereas investment in clean technology manufacturing grew by more than 70%. Measured as a share of overall global investment growth in 2023, clean technology manufacturing accounted for nearly 10%, and as a share of global GDP growth it accounted for around 4%.

Figure 6 Share of clean technology manufacturing in global investment and growth thereof in comparison to other manufacturing sub-sectors, 2022-2023



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Notes: CTM = Clean technology manufacturing. Shares of investment calculated as sectoral investment divided by gross fixed capital formation on a global basis. Sectors correspond to the following ISIC codes: 'Pharmaceuticals' = Division 21, 'Basic chemicals' = Group 201, 'Steel' = Groups 241-243, 'Glass' = Group 231, 'Aerospace' = Group 303.

Source: IEA analysis based on OECD TiVA database and Oxford Economics Global Industry Service.

Box 3 IEA stakeholder engagement on clean technology manufacturing

Manufacturing in clean technology industries is highly concentrated geographically, and accelerating the clean energy transition will require an expansion of global manufacturing capacity to other countries and regions. If governments are to make progress towards establishing secure, resilient and sustainable supply chains for the critical components and materials for clean energy transitions, they will need carefully designed industrial strategies that unlock investment, while at the same time maintaining competitive markets and international trade.

In light of these considerations, on 6 November 2023, the IEA hosted a High-Level Dialogue that convened experts from government, industry, research, development institutions and civil society to discuss ways to make clean technology manufacturing and its supply chains more resilient. The workshop provided a platform for stakeholders to share experience and priorities for developing and building out manufacturing bases at the country and regional level. The need for policy clarity to provide stability to attract private sector investment, and the use of trade as a tool to support progress towards climate goals, were central themes throughout the workshop. The outcomes of the discussions provided invaluable input to the design and considerations of this report.

In addition, the IEA is undertaking an industry survey to gather evidence on the factors that influence company investment decisions across the supply chain, and across the world. Initial responses to the survey have been used to inform the analysis in this report, and will be presented in various IEA publications throughout the year, notably the forthcoming Energy Technology Perspectives report.

Chapter 2. The new clean energy economy is emerging

Getting on a path to net zero emissions by 2050, in line with global climate goals, will require a substantial, accelerated expansion of clean energy technology manufacturing. This has implications for every step of the manufacturing supply chain, from mining and raw material processing, through to component manufacturing and final assembly. Against this backdrop, recent years have seen clean technology manufacturing becoming increasingly dynamic, as successive major governments have placed it at the centre of new industrial strategies.

This chapter focuses on the latest developments on manufacturing capacity through 2023 for five key technologies for the clean energy transition: solar PV, wind, batteries, electrolysers and heat pumps.[6] Together, these technologies account for almost 40% of the emissions savings that need to be achieved by 2030 in the IEA's NZE Scenario. We track announcements relating to capacity additions across different stages of development, and compare existing and announced capacity to deployment levels envisaged by government targets for 2030 and under the NZE Scenario. It builds on the analysis presented in two Special Briefings on clean energy technology manufacturing released in May and November 2023, with new data on announcements up to the end of 2023.

The project pipeline continues to expand

Global clean technology manufacturing capacity registered strong growth across several technologies and regions in 2023. Some technologies, like solar PV and batteries, saw record annual increases on the back of unprecedented development progress in recent years. Some have now become the most cost-competitive options available, such as solar PV, for which electricity generation costs are now lower than fossil fuel-based alternatives in most countries. The prices of electric cars are falling as competition intensifies, especially in China, though they remain more expensive than internal combustion engine vehicles in other markets. In addition, the global energy crisis has contributed to accelerated deployment of heat pumps, and of electrolysers for producing low-emissions hydrogen, particularly in Europe. In many instances, electrolysers and heat pumps remain more expensive than their fossil fuel counterparts. However, their role in helping to reduce dependency on fossil fuels has made them prominent targets

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[6] See the Technical annex for an explanation of the analytical boundaries used in this report.

for government industrial strategies and incentive schemes, particularly in the United States, the European Union and China.

Heat pumps are the only technology among the five covered in depth in this report for which manufacturing capacity growth slowed in 2023. This was a consequence of stagnation across the majority of leading heat pump markets, with sales and installations declining in the European Union, the United States and Japan amid higher interest rates and inflation. Sales continued to grow in China, which is currently the largest heat pump market.

Clean technology manufacturing capacity additions in 2023 were also heavily concentrated in three major markets – the United States, the European Union and China. While Central and South America account for non-trivial shares of the production of the main wind turbine components (3-8% of global production for nacelles, blades and towers), virtually no clean technology manufacturing takes place in Africa today.

Box 4 Scenarios used in this report

Analysis in this Special Report is underpinned by global projections of clean energy technologies derived from the IEA’s Global Energy and Climate (GEC) model, a detailed bottom-up modelling framework composed of several interlinked models covering energy supply and transformation, and energy use in the buildings, industry and transport sectors. The modelling framework includes 29 regions or countries covering the whole world.

The most recent year of complete historical data from the GEC model is 2023, to which year-end 2022 and 2023 manufacturing installed capacity data have been added as part of the analysis for this Special Report. For projected values to 2030, we make use of two IEA scenarios produced using the GEC model that describe possible energy system pathways:

The Net Zero Emissions by 2050 Scenario (NZE Scenario) is a normative scenario that sets out a pathway to stabilise global average temperatures at 1.5°C above pre-industrial levels. The NZE Scenario achieves global net zero energy sector CO_2 emissions by 2050 without relying on emissions reductions from outside the energy sector. In doing so, advanced economies reach net zero emissions before developing economies do. The NZE Scenario also meets the key energy-related UN Sustainable Development Goals, achieving universal access to energy by 2030 and securing major improvements in air quality.

The Announced Pledges Scenario (APS) assumes that governments will meet, in full and on time, all the climate-related commitments they have announced, including longer-term net zero emissions targets and Nationally Determined

Contributions, as well as commitments in related areas such as energy access. It does so irrespective of whether these commitments are underpinned by specific policies to secure their implementation. Pledges made in international fora and initiatives on the part of businesses and other non-governmental organisations are also taken into account wherever they add to the ambition of governments.

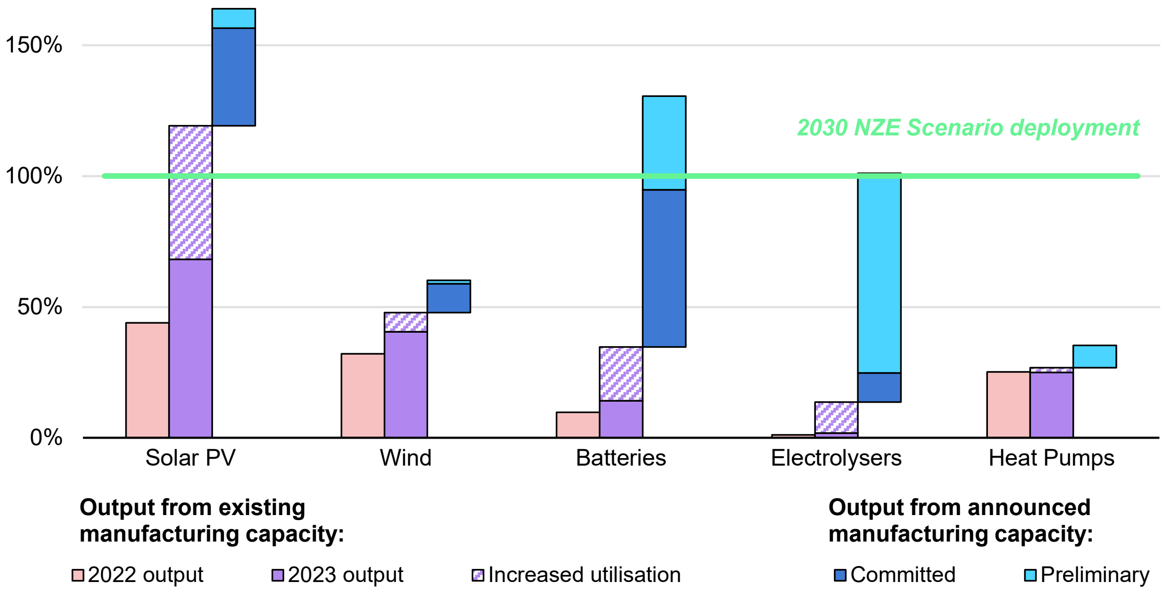
Neither scenario should be considered a prediction or forecast. Rather, they are intended to offer insights into the impacts and trade-offs of different technology choices and policy targets, and to provide a quantitative framework to support decision-making in the energy sector, and strategic guidance on technology choices for governments and other stakeholders. The scenarios and results are consistent with those presented in the World Energy Outlook 2023.

Latest announcements present a varied picture of manufacturing for net zero deployment needs

With existing solar PV module and cell manufacturing capacity alone, the deployment levels for solar PV envisaged by the IEA's NZE Scenario in 2030 could already be achieved today, were it to be run at near-full capacity across all existing facilities – 6 years ahead of schedule. Ensuring that this existing manufacturing capacity is used to its full potential would therefore require an acceleration in deployment. There are, however, still shortages at the upstream end of the solar PV supply chain: current capacity for producing wafers and polysilicon is not yet fully sufficient to meet 2030 deployment needs in the NZE Scenario.

For the other technologies considered here, existing manufacturing capacity could already deliver between 15% (in the case of electrolysers) and close to 50% (in the case of wind energy) of the NZE Scenario deployment needs by 2030 at the time of writing (Figure 7).

Figure 7 **Output from existing and announced manufacturing capacity relative to Net Zero Emissions by 2050 Scenario deployment in 2030**



Notes: NZE Scenario = Net Zero Emissions by 2050 Scenario. 2022 and 2023 output values reflect estimates of actual utilisation rates. Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.
Sources: IEA analysis based on data from Benchmark Mineral Intelligence, Bloomberg New Energy Finance, EV Volumes, InfoLink, S&P Global Commodity Insights, UN Comtrade, Wood Mackenzie and announcements by manufacturers and personal communications.

This outlook changes significantly if all announcements for manufacturing capacity expansion are taken into account. For solar PV modules, based only on announced expansions that are already committed (see Box 5), output could exceed 2030 requirements of the NZE Scenario by more than 50%. If all announced expansions are considered, including those that have not yet reached a final investment decision (FID), output rises to over 60% more than envisaged demand. This comes with both benefits and drawbacks. On the downside, it points to a significant level of surplus capacity, which may lead to stranded or under-utilised assets, and has also led to intense competition among manufacturers, resulting in a significant module spot price drop over 2023. This has already resulted in cancellations and downward revisions of planned expansions in solar PV manufacturing, especially for PV modules. However, the new manufacturing sites are likely to produce new-generation components with improved characteristics, as a consequence of growing competition and technology innovation. New capacity could therefore outcompete existing manufacturing capacity, reduce the risk of over-capacity and lead to the commercialisation of products that are cheaper and perform better. This effect could be multiplied if the prospect of new capacity leads to upgrades in existing manufacturing capacity that is based on older cell technologies.

Box 5 Manufacturing data categories

In this Special Report the manufacturing data for the focus five clean energy technologies can be categorised as follows:

“**Installed manufacturing capacity**” refers to the maximum rated output of facilities for producing a given technology. Capacity is stated on an annual basis for the final product and does not refer to the capacity for any intermediate products or components. Where available, manufacturing capacity for key components is provided separately. Annual manufacturing “**output**” is a fraction of the installed manufacturing capacity. Output depends on the utilisation rate of production capacity, for which 85% is a typical annual average target level under normal operation. However, utilisation rates for clean technology manufacturing facilities tend to be much lower on average today, reflecting significant degrees of capacity surplus globally. The year 2023 – the base year for the analysis in this Special Report – is the most recent year for which installed manufacturing capacity data has been collected.

“**Announced projects**” refers to the aggregate stated capacity – or estimated output of that capacity (assuming a default utilisation rate of 85%) – of potential manufacturing facilities that have been announced. This includes projects for building new facilities or expanding existing ones that are at different stages of development. **“Committed”** projects include those that have already reached an FID, or are under construction, whereas **“preliminary”** projects include those that have not yet reached an FID, meaning feasibility studies or earlier steps are underway. Wherever data is available, we distinguish committed projects from preliminary announcements across the key technologies in focus, which allows for more robust projections of future manufacturing capacity. Unless otherwise stated, the announced projects dataset assembled for this Special Report comprises announcements dated up to the end of 2023.

In the case of batteries and electrolysers, if all announcements for expansion are realised, it will be possible to achieve the level of deployment of the NZE Scenario by 2030, although the maturity of announcements differs. For batteries, the growth trajectory is quite clear: committed expansions (which account for over 60% of total announcements) are already sufficient to match more than 90% of the 2030 global deployment needs in the NZE Scenario. When also considering other announced (though not yet committed) projects, the pipeline of new manufacturing capacity for batteries comfortably exceeds deployment requirements in the NZE Scenario by around 30% in 2030.

For electrolysers, the outlook is less certain: all announced expansions would need to be realised to meet deployment needs in the NZE Scenario, but only 13% (19 GW) are already committed (i.e. have reached FID). This share reflects advances made in 2023, having increased from 7% (6 GW) in 2022, but uncertainty around future demand for low-emissions hydrogen continues to limit the rate of progress. In contrast to the maturing market for electric vehicles – which is resulting in more certainty about demand for batteries – the cost of electrolytic hydrogen production remains high when compared to alternative technologies. In addition, policies to support project development and stimulate demand are being implemented slowly, although a growing number of countries are moving into the implementation phase of their hydrogen strategies, which could trigger further deployment.

Wind and heat pump manufacturing currently present the least optimistic outlook. In the case of wind, the majority of announced expansions are already committed, but the output from these facilities will be able to deliver only around 60% of what is needed in the NZE Scenario. For heat pumps, announcements have slowed down in quantity and size over 2023, and even if all announcements for expansion (including those that are still preliminary) are implemented in full and on time, it will only be possible to manufacture around one-third of the heat pumps needed in the NZE Scenario by 2030. However, it should be noted that announced expansions of heat pump manufacturing capacity are only common in Europe.

Geographical concentration is expected to persist despite the growing number of expansion announcements

Level of geographical concentration is an important indicator of the robustness of a supply chain. Highly concentrated supply chains – or individual steps within the supply chain – are more vulnerable to disruption in the case of unforeseen events such as natural disasters, unexpected events or accidents (e.g. the closure of the Suez Canal due to a shipping collision) or geopolitical conflicts and price distortion by non-market conditions. In the case of clean energy technology manufacturing, geographical concentration is also an indicator of the extent to which individual countries or regions are set to reap a potential economic benefit from clean energy transitions.

All the technologies under the scope of this report currently present a high level of geographical concentration in manufacturing, with the three largest producing countries or regions accounting for around 80% or more of the capacity in all cases. If all the announced expansions are realised, the situation is expected to remain the same through 2030, with only minor variations in the relative shares of the main three producing countries or regions for each technology.

Solar PV manufacturing is the most regionally concentrated of all the key technologies analysed, with more than 80% of capacity located in China, driven by the relatively low production costs across the full supply chain. The

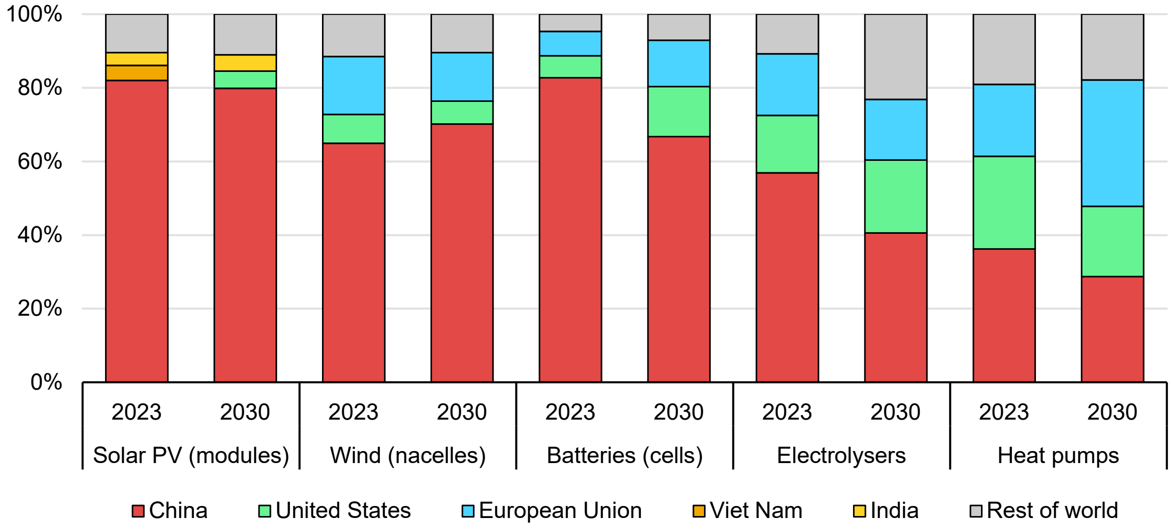
United States and India are expected to increase their share of global manufacturing capacity from now to 2030, but these expansions do not significantly dent China's share, which is likely to remain around 80%.

Battery manufacturing is also highly geographically concentrated today, with China accounting for more than 80% of the manufacturing capacity, followed by the United States and the European Union, with around 5% each. The capacity accumulated by these three regions is expected to remain above 90% through 2030, but the share of China could fall to around 60%, as the European Union and the United States nearly triple their shares, thanks to boost from ambitious policies such as the Important Projects of Common Interest (IPCEI) and Net-Zero Industry Act (NZIA) in the European Union and the US IRA. In the case of the United States, actual expenditure on EV battery manufacturing from 2020 to the end of the third quarter of 2023 totalled over USD 40 billion. In addition, half of the committed manufacturing capacity in the United States will be delivered by joint ventures between battery manufacturers and automotive original equipment manufacturers (OEMs), which demonstrates that automakers are committed to electric vehicles over the long term.

With regards to the concentration of manufacturing for electrolysers, wind and heat pumps, the 2030 outlook is little changed from today. In the case of electrolysers, despite the significant growth that would be achieved if all announcements are realised, China, the European Union and the United States will still be home to around 80% of all capacity. However, this situation could still change significantly: around 20% of all announced expansions of manufacturing capacities have no specified location.

For wind and heat pumps, the distribution of manufacturing in 2030 is little different to today, as a consequence of the very limited number of announced expansions. The share of wind manufacturing in China looks set to grow, reducing the current share of the other major manufacturing regions and countries. For heat pumps, the share of manufacturing in Europe will grow the most on the basis of announced capacity additions, although this may be a reflection of expansions being announced more prominently in Europe.

Figure 8 **Geographical concentration of current and announced manufacturing capacity, 2023-2030**



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Notes: 2030 value includes all operational capacity in 2023 together with the capacity of announced manufacturing projects through to 2030. For electrolysers, the analysis only includes projects for which location data was available. Shares are based on manufacturing capacity. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Sources: IEA analysis based on data from Benchmark Mineral Intelligence, Bloomberg New Energy Finance, EV Volumes, InfoLink, S&P Global Commodity Insights, UN Comtrade, WoodMac and announcements by manufacturers and personal communications.

Rapid – if uneven – progress

Announcements on capacity additions paint a varied picture of the potential for manufacturing to scale up in line with 2030 deployment in the NZE Scenario. We now turn to consideration of how announcements compare to government ambitions through 2030, as envisaged by their announced pledges and commitments.

Steep growth in solar PV manufacturing capacity, though utilisation rates remain low

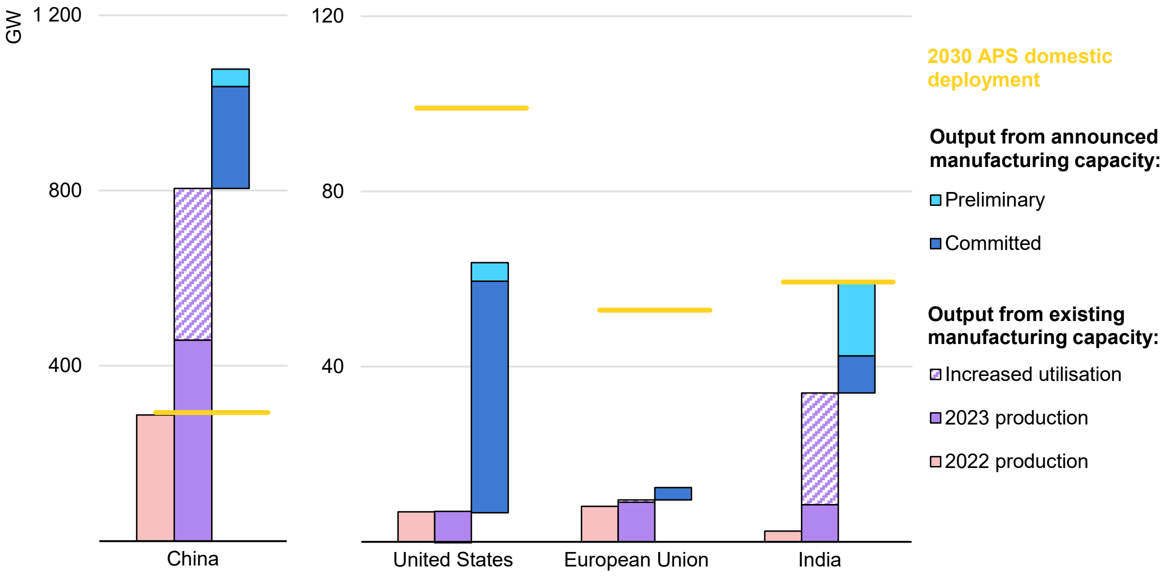
Global manufacturing capacity for solar PV modules increased dramatically in 2023, by almost 500 GW, with the vast majority – nearly 440 GW – added in China. Output also grew to around 560 GW, compared to around 360 GW in 2022. However, there was a slight decrease in average utilisation rates across PV module manufacturing facilities, which hovered around 50% in 2023, with facilities for newer technologies, like Tunnel Oxide Passivated Contact (TOPCon) cells, having higher utilisation rates than older ones.

The extensive capacity added or announced in recent years has allowed output to grow substantially, outpacing demand. This has driven down prices, and reduced utilisation rates, meaning that production costs per unit increase. The result has been a downscaling of expansion plans, including delays and cancellations, as well as job cuts. Indicatively, most of the global downscaling appears to come from China. For example, the solar panel maker Changzhou EGing Photovoltaic Technology announced it would put on hold the expansion at its TOPCon solar cell manufacturing base in Anhui province, and companies from other sectors that planned to diversify into solar have abandoned their plans. Recently, the world’s largest solar manufacturer, Longi, revealed that it will reduce its workforce. However this downscaling is not limited to China, as evidenced by other facilities that have been cancelled or shut down, like the Meyer Burger plant in Germany or the CubicPV startup in the United States.

Furthermore, low-priced solar PV module imports, primarily from China, and to a lesser extent from Southeast Asia and destined for the United States, have led to the accumulation of significant inventories by European and North American developers, leading to concerns about the future competitiveness of upcoming production.

Overall, announced capacity additions have been revised downwards across the supply chain (with the exception of polysilicon, at least for the time being, as further detailed below). Despite this, the picture varies depending on the region: India will be able to achieve levels consistent with the APS in 2030 on the basis of announced capacity, and China already exceeds the APS levels in 2030 today, indicating significant capacity for exports. As a consequence, China is likely to remain the lead exporter of solar panels (and their subcomponents) in the near term. China currently produces twice as much solar PV (modules) as it installs, supplying regions in which manufacturing capacities are expected to remain well below their deployment needs in the APS, such as the United States and the European Union. The projected Chinese surplus output in 2030 (i.e. beyond output required to meet its domestic needs in the APS) alone could easily accommodate the global APS demand for installations in the same year.

Figure 9 **Output from existing and announced solar PV manufacturing capacity in selected regions relative to deployment in the Announced Pledges Scenario in 2030**



Notes: APS = Announced Pledges Scenario. 2023 production values reflect estimates of actual utilisation rates. Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on data from InfoLink and Bloomberg New Energy Finance.

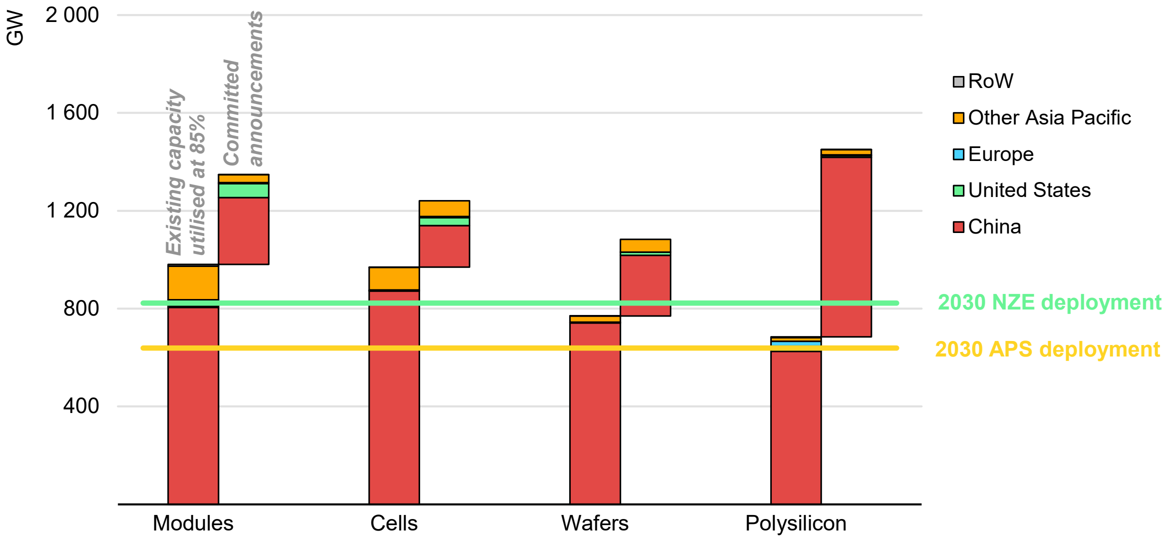
Solar PV component-level concentration intensified in 2023

Solar PV is a paradigmatic example of a technology that presents a high level of geographical concentration across the whole supply chain: China accounts for more than 90% of cell, wafer and polysilicon manufacturing. Concentration intensified in 2023 across almost all steps, even though it was already high in 2022. Indicatively, more than 90% of existing polysilicon manufacturing capacity is in China, whereas 5 years ago the share was less than 60%.

The geographical distribution of prospective manufacturing capacity did not change significantly on the basis of announcements made in 2023, with China continuing to account for around 80% of planned and existing capacity for modules, followed by the United States and India with 5%, and Europe with just 1%. However, both India and the United States are mostly expanding in module and cell manufacturing, and to a lesser extent in the upstream components of the solar PV supply chain.

The high geographical concentration of the full solar PV supply chain is unlikely to change significantly on the basis of announced projects, with China's share of capacity for modules, cells and wafers decreasing marginally (e.g. to 90% for wafers) and increasing for polysilicon, to reach close to 95% in 2030. Locally controlled polysilicon manufacturing can provide a competitive edge, as the energy-intensive commodity is traded internationally. Companies therefore have an incentive to expand vertically in order to cover multiple steps of the supply chain and reduce their exposure to fluctuations in prices for key inputs.

Figure 10 Output from existing and announced solar PV component manufacturing capacity and 2030 deployment levels in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario



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Notes: APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; RoW = Rest of World. A utilisation factor of 85% is assumed for all regions. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on data from PV InfoLink, Bloomberg New Energy Finance, IEA PVPS, SPV Market Research, and RTS Corporation.

China accounts for the largest share of announced wind manufacturing capacity additions

Manufacturing output for the nacelles, towers and blades that make up both onshore and offshore wind turbines remained largely unchanged through 2023, with China alone significantly increasing production. Across all components, China saw an average year-on-year increase of more than 30%, and remains the largest producer of nacelles, blades and towers. The world's second largest manufacturer, the European Union, saw no increase in manufacturing capacity from 2022 to 2023.

China also accounts for the largest share of announced capacity additions to 2030, with 42 GW announced for nacelles, 35 GW for blades and nearly 20 GW for towers. Across all components, nearly all of the announced capacity in China is already committed – over 90% for nacelles, 85% for blades and 100% for towers. There were very few announcements of capacity additions for blade and nacelle manufacturing outside of China in 2023. However, there were notable announcements for tower manufacturing in the European Union and United States. Towers are more likely than other components to be manufactured closer to demand centres, due to the difficulty of transporting such large structures over long distances.

In the European Union, offshore towers account for the largest share of manufacturing, with around 10 GW of offshore tower manufacturing capacity compared to 6 GW and 8 GW for offshore blade and nacelle manufacturing, respectively. In contrast, in China, offshore nacelle and blade manufacturing capacity is over 30 GW for each, whereas offshore tower manufacturing capacity reaches 20 GW. It is likely that many of these tower manufacturing facilities are local steel companies fabricating these structures on demand, as the number of facilities dedicated to these components specifically is lower than blades and nacelles facilities.

China's manufacturing capacity is tracking ahead of 2030 wind deployments envisaged by announced policies, by 50 GW for blades and 65 GW for nacelles. Notably, China's 2030 target for cumulative solar PV and wind capacity was close to being reached in the first quarter of 2024, 6 years ahead of schedule. This opens up potential for exports to other markets, especially given that other countries and regions largely do not have the manufacturing capacity across different components to meet their deployment pledges by 2030 on the basis of existing capacity and announced additions. By 2030, China would be able to provide 50% of the blades and almost 60% of the nacelles needed to close the gap between deployment needs in the rest of the world in the APS and the manufacturing capacity in those regions.

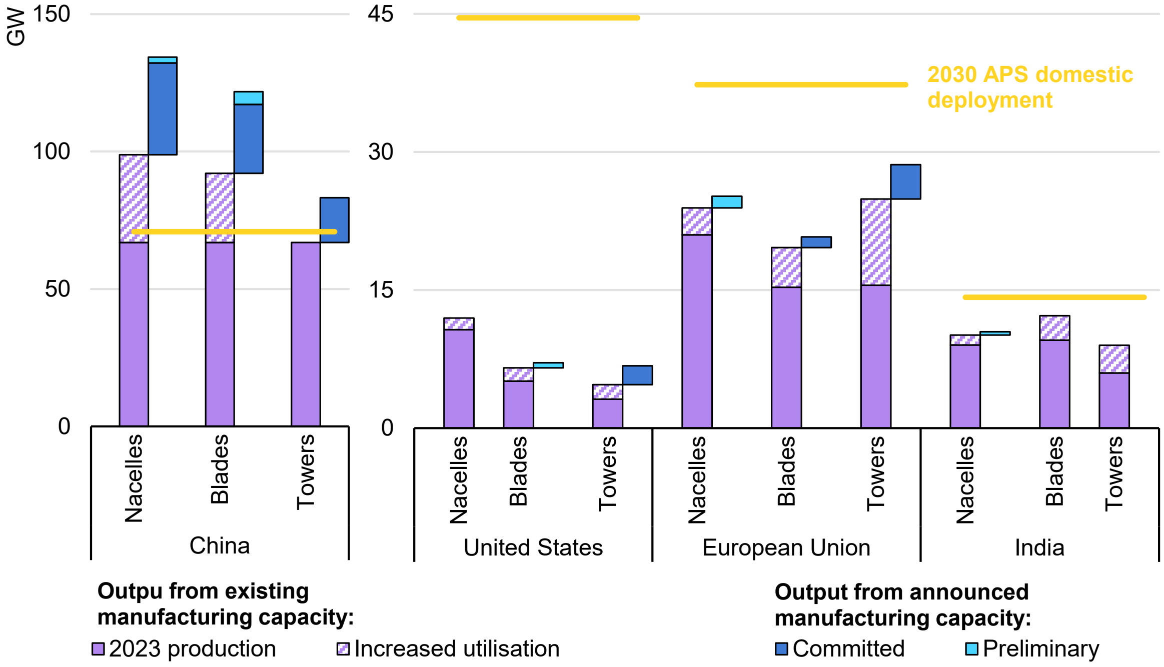
This gap is most prominent in the United States, where existing production and announced capacity additions for blades and nacelles would result in a shortfall of more than 30 GW (over 70%) between total output and deployment needs consistent with announced targets in 2030.

In the European Union, existing and announced capacity for blades and nacelles is almost 30% lower than would be needed to meet 2030 deployment needs envisaged in the APS, leading to a gap of 12 GW and 17 GW for nacelles and blades, respectively.

However, after a challenging 2022, the early signs from 2023 annual financial reports released to date suggest that several European OEMs may have turned a corner, with Vestas and Nordex confirming a return to growth. In early 2024, Vestas broke ground on a new factory for manufacturing offshore nacelles and hub assembly in Poland, expected to begin operation in 2025. Vestas also announced plans to establish a new blade factory. Furthermore, in the United Kingdom, a new Offshore Wind Industrial Growth Plan details actions to triple current manufacturing capacities, highlighting the opportunities for expanding tower and blade manufacturing capabilities, while expanding nacelle assembly is made a lower priority.

While China, the European Union and the United States remained the largest manufacturers for wind in 2023, India also increased production, and has more than 60% of the capacity needed to meet 2030 domestic deployment needs in the APS for nacelles and towers. India is also emerging as an alternative export hub for blades in the near term, as it is currently oversupplied for the deployment needs of coming years, although it would come 2 GW short on its domestic targets for 2030. Elsewhere, many Chinese and European OEMs have made investments in wind manufacturing facilities in Latin America in recent years, principally in Argentina and Brazil. Attention is turning to capacity for recycling wind turbines at the end of their lifespan, with six dedicated factories in Europe for recycling blades announced by Continuum in early 2023.

Figure 11 **Output from existing and announced wind manufacturing capacity in selected regions relative to Announced Pledges Scenario deployment in 2030**



Notes: APS = Announced Pledges Scenario. The figure includes data on facilities which are specifically dedicated to wind manufacturing for blades, nacelles and towers, except for tower manufacturing in China, where an implausible shortfall is assumed to be met by additional generic fabrication capacity. 2023 production values reflect estimates of actual utilisation rates. A utilisation rate of 85% is used for both existing and announced dedicated manufacturing capacity in 2030. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on data from S&P Global Commodity Insights.

Battery manufacturing capacity reaches new highs, mostly in major electric vehicle markets

Battery production has ramped up quickly in the past few years to meet increasing demand resulting from growth in electric car sales. In 2023, battery manufacturing capacity reached 2.5 TWh, with 780 GWh of new capacity added relative to 2022. The capacity added in 2023 was 25% higher than that added in 2022.

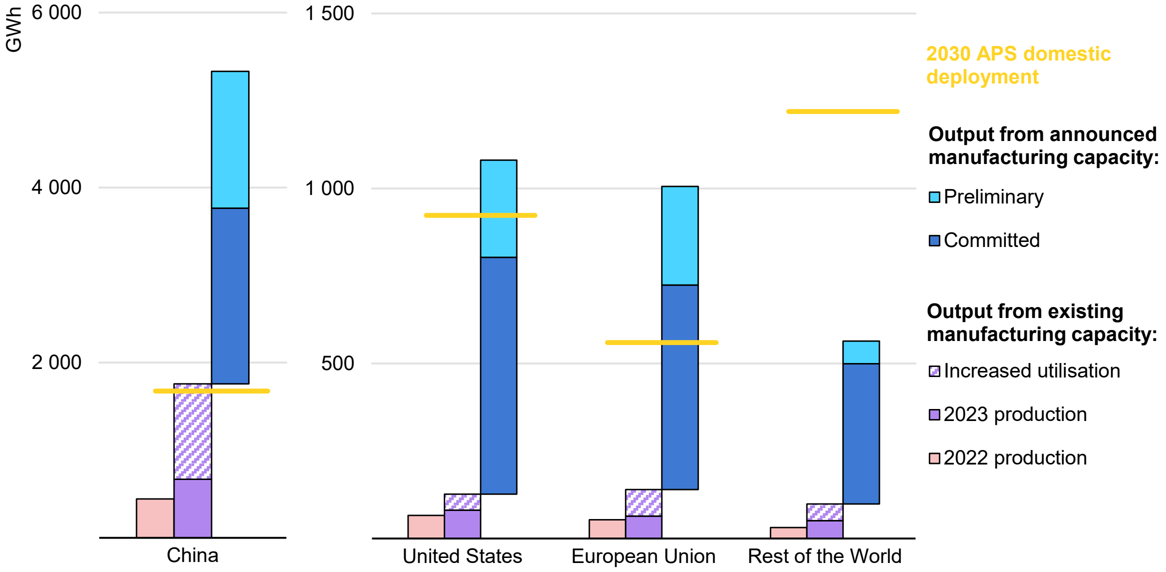
Global battery manufacturing capacity could exceed 9 TWh by 2030 if all announcements are completed in full and on time. About 70% of the 2030 projected battery capacity worldwide is already operational or committed, though announcements differ across regions. Over 40% of future manufacturing capacity in China relies on the expansion of current plants, indicating the strengthening of industrial actors that are already part of the Chinese market. In contrast, 80% of US and EU manufacturing capacity is expected to come from new plants, with a significant number of new actors entering those markets in the coming years.

Much of the currently announced battery manufacturing capacity remains concentrated in today's major EV markets – China, the United States and the European Union – which are all set to have enough capacity to reach their announced pledges for 2030. Of course, as EVs and battery storage increasingly reach global markets, and battery demand diversifies geographically, there will be new opportunities to be seized around the world to produce batteries near demand centres. Locating battery manufacturing close to EV manufacturing hubs would reduce exposure to import/export tariffs, as well as insurance costs associated with shipping lithium-ion batteries.

Outside of today's major EV markets, announced manufacturing capacity – of which 85% is already committed – meets around half of APS needs in 2030 in those regions. Almost all of this committed manufacturing capacity is divided among other European countries and Canada (with about 35% each), India (12%), other Southeast Asian countries (8%), like Malaysia, Viet Nam, and Singapore, and Japan and Korea (5%). Korea and Japan, however, also account for over 80% of today's capacity in these regions.

There is considerable space for growth in South American countries, which today have no significant announcements for battery manufacturing capacity through 2030, and for countries with manufacturing capacity that falls short of their pledges, such as India, whose announced capacity would cover only one-quarter of its 2030 demand in the APS. These gaps could increase the risk of countries failing to meet their long-term decarbonisation targets, and could have important implications for future battery trade.

Figure 12 **Output from existing and announced battery manufacturing capacity in selected regions relative to Announced Pledges Scenario deployment in 2030**



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Notes: APS = Announced Pledges Scenario. 2023 production values reflect estimates of actual utilisation rates. Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030. Demand refers to both EV battery and stationary storage demand. Battery capacity refers to battery cells. Battery refers to lithium-ion batteries. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on data from Benchmark Mineral Intelligence, Bloomberg New Energy Finance and EV Volumes.

China currently has a leading role in battery production, accounting for over 650 GWh in 2023, or almost 80% of the global total. However, this also comes with surplus capacity: In 2023, China used less than 40% of its maximum battery cell production capacity. China's projected battery manufacturing capacity alone in 2030 could cover global demand in the APS in the same year. If only its already committed capacity is considered, China could cover about 85% of 2030 global demand under the APS. China is currently the world's largest exporter of EV batteries, accounting for about 70% of total exports in 2023, but surplus capacity has also significantly reduced producers' margins, which may put some at risk if they do not find enough customers outside of China.

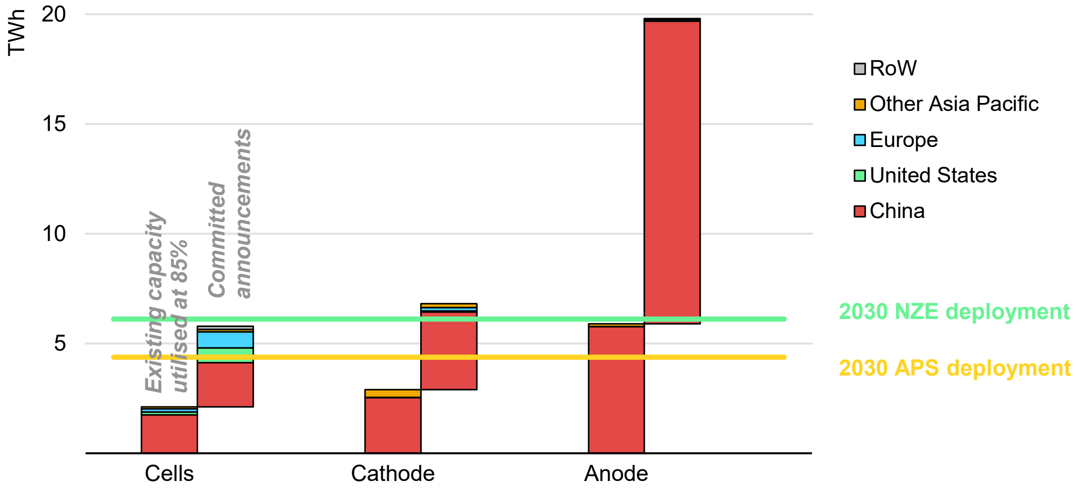
High levels of capacity over the entire battery supply chain, above and beyond levels of demand, can put downward pressure on prices. This is attractive for end consumers and can help boost uptake towards a level needed to meet climate targets, but it also lowers cash flows and provides smaller margins for mining, refining and manufacturing companies. For example, the drop in battery material prices in 2023 led to a 14% decrease in average battery pack price, but it also put at risk several mining companies, with many of them now struggling to stay afloat and announcing spending and job cuts in 2024.[7]

Battery component manufacturing remains heavily concentrated, but capacity surplus may lead to greater diversification by 2030

While final battery manufacturing becomes less geographically concentrated through 2030, the project pipeline for battery components shows little sign of diversification. The manufacturing of lithium-ion batteries requires a stable, high-quality supply of cathode and anode materials. Their production is heavily concentrated in China, which currently accounts for nearly 90% of global capacity for cathode active materials, and over 97% of capacity for anode active materials. China also accounts for more than 85% of both committed and preliminary capacity additions announced for cathodes and anode active materials by 2030.

Different supply chains are, however, required for different battery chemistries, with lithium-iron phosphate (LFP) dominating the Chinese market and lithium nickel manganese cobalt oxide (NMC) the European and North American markets. China is home to about 100% of the LFP production capacity, and more than three-quarters of the installed production capacity for NMC, followed by Korea, with about 20%.

Figure 13 **Output from existing and announced battery component manufacturing capacity in selected regions relative to Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario deployment in 2030**



IEA. CC BY 4.0.

Notes: APS = Announced Pledges Scenario; NZE = Net Zero Emissions by 2050 Scenario; RoW = Rest of World. A utilisation factor of 85% is assumed for all years and regions. Battery capacity refers to battery cells. Calculations for cathode and anode assume a cathode and anode materials energy density of around 670 Wh/kg (NMC and lithium nickel cobalt aluminium oxide cathode active material), 465 Wh/kg (LFP cathode active material) and 1 500 Wh/kg (graphite anode active material), respectively. Demand refers to both EV battery and stationary storage demand. Battery and battery components refer to lithium-ion batteries. Cathode and anode refer to cathode and anode active materials. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on data from Benchmark Mineral Intelligence, Bloomberg New Energy Finance and InfoLink

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[7] See: IEA (2024), Global EV Outlook 2024.

The 2030 projected manufacturing capacity for cathode active materials is about two times greater than the projected battery cell manufacturing capacity in the same year. In the case of anode active materials, this ratio increases to five times greater, raising doubts about whether all manufacturers will be able to remain competitive in the face of such a surplus.

The prospect of capacity surplus may also open the door to a more diversified supply chain: In 2030, cathode and anode active material manufacturing capacity outside of China can potentially cover up to 70% of the maximum demand for battery production within those regions. Nonetheless, this cannot be taken for granted: of the installed capacity and announcements outside of China, over 60% of the cathode active material capacity, and over 90% of the anode active material capacity, is still at the announcement stage and has not yet started construction, underlining the need for close attention to this part of the battery supply chain.

Of course, manufacturing capacity is not the only parameter determining whether battery manufacturers choose one supplier rather than another. The main challenge for Chinese manufacturers in the coming years will be finding big enough export markets to use their massive manufacturing capacity surplus and increase currently low margins, while manufacturers in regions like the European Union and the United States will need to demonstrate their cost competitiveness. The quality, cost and characteristics of the cells and components provided by different suppliers, together with regulations on local content requirements, and environmental, social and governance (ESG) standards, will be key to determining the winners and losers in these markets.

Sustained interest in electrolysers is encouraging, though the outlook remains uncertain

Current manufacturing capacity for electrolysers increased to about 23 GW per year at the end of 2023, up from more than 12 GW in 2022 (Table 1). However, this figure is based on the announced nominal capacity of each facility, which in some cases may only be reached after a few years of operation. Manufacturing capacity remains geographically concentrated, with China accounting for 60% of 2023 capacity, followed by Europe with 20% and the United States with 16%.

Table 1 Selected electrolyser manufacturing facilities commissioned in 2023

Company	Location	Country	Announced capacity	Technology
Cummins	Fridley	United States	500 MW	PEM
Plug Power	Rochester	United States	1.2 GW	PEM
Siemens Energy	Berlin	Germany	1 GW	PEM
HydrogenPro	Tianjin	China	500 MW	ALK
Sunfire	Solingen	Germany	500 MW	ALK
E-Gen Energy	Shanghai	China	100 MW	SOEC

Notes: PEM = proton exchange membrane electrolyser; ALK = alkaline electrolyser; SOEC = solid oxide electrolyser cell.

Based on announcements made in 2023, almost 170 GW of cumulative installed manufacturing capacity could be reached by 2030, an increase on the 102 GW that had been announced at the end of 2022. However, close to 90% of the announced capacity is at a preliminary stage of development, and more than 40% of this capacity has been announced without a target year of commissioning. Only 13% of the announced capacity has reached FID or is under construction, half of which is in China. Today, capacity that is committed accounts for 19 GW, compared with 6 GW at the end of 2022, and 17 GW at the time we published the November 2023 Special Briefing.

This progress is encouraging, though there are reasons to remain cautious about the expansion of electrolyser manufacturing capacity. Firstly, the manufacturing output in 2023 has nearly doubled compared to 2022, but utilisation rates remain very low. Output of manufacturing capacity in 2023 is estimated at 2.5 GW, mainly from projects under construction in China, where the majority of the electrolyser deployment is taking place.[8]

Secondly, many of the announced factories are assembly facilities that will require a supply of components (membranes, cathodes, anodes, bi-polar plates, power electronics, etc.) to produce the electrolyser stacks and the final electrolyser system. Many of these components are also used in other technologies with more mature markets (such as power electronics for batteries). There is currently limited visibility on the expansion plans for these components, and on whether manufacturers will be able to serve the competing needs of both markets. Reaching the capacity expansion envisaged by announced projects will depend on the scale-up of manufacturing capacity of all these components in parallel, to prevent bottlenecks occurring in certain parts of the supply chain.

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[8] This estimation includes manufacturing of electrolysers for the chlor-alkali industry, which has been traditionally the core market for electrolysers, as well as electrolysers manufactured for dedicated production of hydrogen, which is now the largest market for electrolysers.

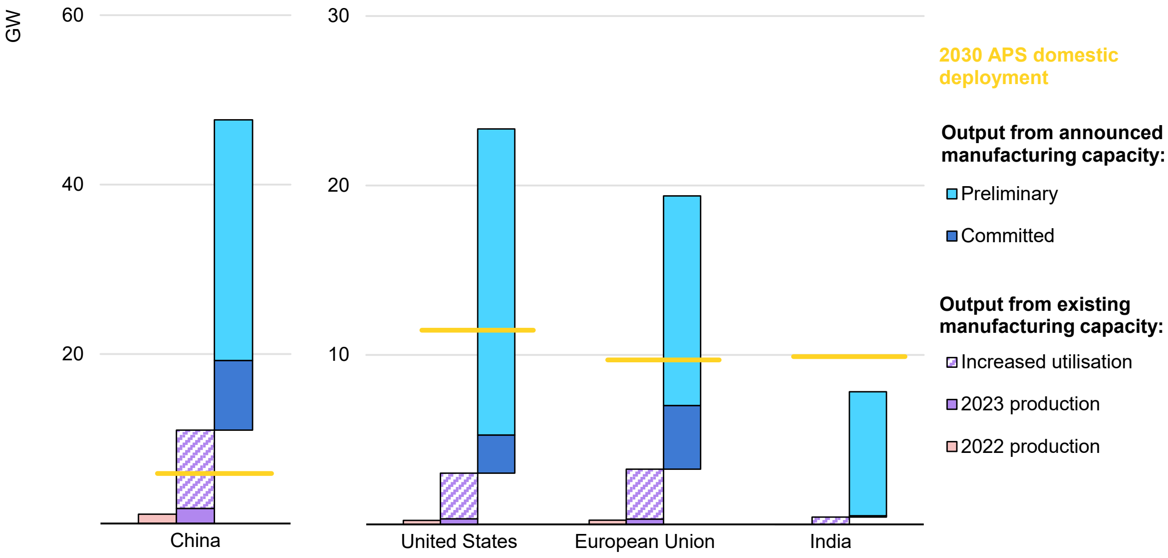
China, with 56 GW, today accounts for one-third of the total manufacturing capacity that could be operational by 2030. This level of deployment is significantly above the level of deployment needed in the APS. Moreover, with only the capacity that the country has available today (13 GW, about 60% of the global capacity), if fully utilised, China could already meet the deployment needed to reach its climate objectives by 2030. This could lead to a situation similar to that of solar PV, where capacity that is surplus to the needs of the domestic market can enable exports to other regions. In fact, almost 45% of global APS needs by 2030 could be met just by the surplus of manufacturing output from China. However, for this to happen, Chinese manufacturers will need to modify their current designs to comply with the standards required in other regions, and to respond to doubts about equipment reliability that have arisen from the operational challenges experienced with the largest project to date.

The European Union accounts for 14% of the total capacity that could become operational by 2030. If only the committed capacity is considered, this share rises to about 25%. If fully utilised, the committed capacity could be enough to meet the level of deployment needed in the APS, but this would require faster implementation of support schemes for low-emissions hydrogen production projects, as well as policies for demand creation and the development of hydrogen infrastructure to link producers and users. Sluggish implementation of the announced programmes has led to delayed FIDs, which is translating into slower growth in demand for electrolysers.

The United States accounts for about 16% of the total capacity that could be operational by 2030, or 15% of all committed capacity. After the IRA was signed into law in 2022, there were high expectations about the United States becoming a particularly attractive location for capacity additions, but delays in providing the final guidelines on provisions are resulting in subsequent delays in manufacturers reaching FID. Consequently, less than 3 GW of manufacturing capacity (11% of the announced manufacturing expansions) in the United States is at least at the FID stage, which, added to the existing capacity, accounts for around half of what would be needed in the APS in 2030.

Another 20% of the announced manufacturing capacity currently has no specified location, and the final decision on project siting could be influenced by policies and subsidies. In addition, a large part of the announced manufacturing capacity – more than one-third of the 145 GW – has been announced without a specific target year of deployment. The realisation of this capacity will depend on the demand for electrolysers, and therefore on the deployment of announced electrolytic hydrogen production projects. Under 4% of electrolytic hydrogen production projects around the world have reached FID.

Figure 14 Output from existing and announced electrolyser manufacturing capacity relative to Announced Pledges Scenario deployment in 2030



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Notes: APS = Announced Pledges Scenario. 2023 production values reflect estimates of actual utilisation rates. Increased utilisation refers to the gap between 2023 production levels and existing capacity being utilised at 85%. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on announcements by manufacturers and personal communications.

Announced capacity additions for heat pumps have slowed, but could see a quick turnaround

New announcements of manufacturing projects for heat pumps slowed in 2023 relative to 2022. Global heat pump sales declined by 3% in 2023, after two consecutive years of double-digit growth fuelled by the energy crisis. Most major markets showed negative trends in sales, with the exception of China, and heat pump markets in general were hit by rising interest rates and inflation. This global trend increased uncertainty among manufacturers, undermining potential investment decisions in the short term in some regions.

In line with the decline in sales, manufacturing output in the European Union, United States and Japan also fell, with an average reduction of 10% in the utilisation rates of existing manufacturing facilities. In contrast, China's manufacturing capacity slightly increased to accommodate growing domestic demand (12% increase relative to 2022), which compensated for a 20% decrease in heat pump exports.

In the United States, heat pump sales fell by 15%, but sales of fossil fuel-based heating systems plummeted even further, by a record 20%, indicating a slowdown in the national heating market. However, these trends could be reversed in the short term thanks to recent policy developments, such as the allocation of

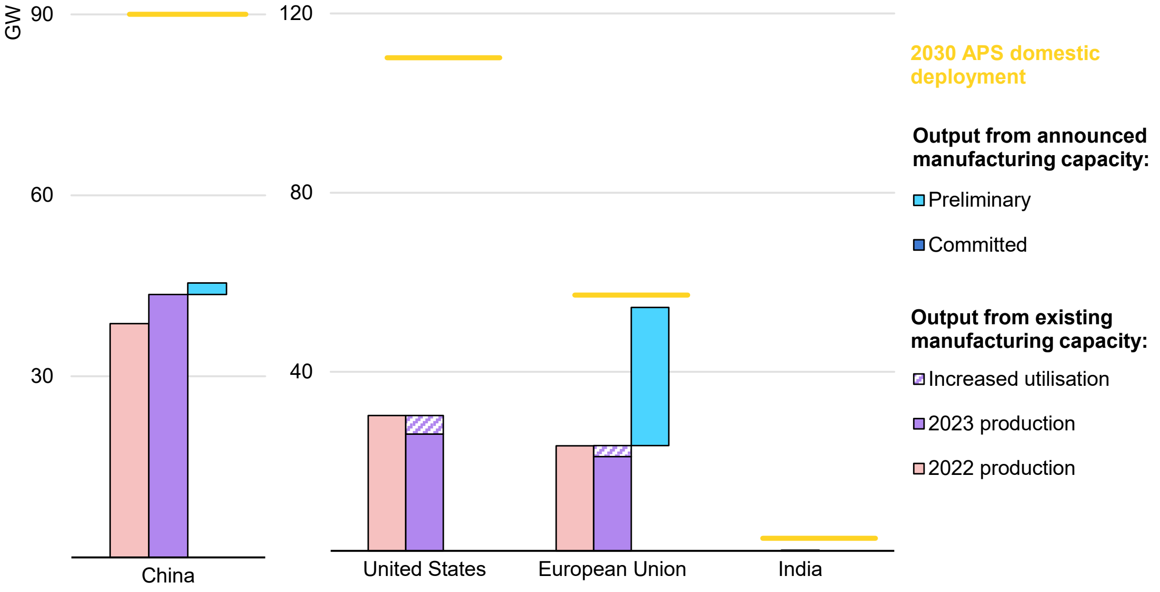
USD 250 million under the IRA to support the expansion of domestic heat pump manufacturing. Further, nine states (accounting for almost a quarter of residential energy use) set a target for heat pumps to account for around two-thirds of heating and cooling equipment sales by 2030.

In the European Union, sales fell by 5% after a decade of steady growth. The EU market was particularly affected by a slowdown in the construction of new buildings, which accounts for a large share of heat pump installations. In addition, the fall in natural gas prices from their peak in 2022 has favoured the operation of natural gas boilers, and there is continued uncertainty about policy support schemes and regulations in some countries. The European Union remains the only global region where manufacturers tend to announce their expansion ambitions on a large scale, with over 30 GW of manufacturing capacity expected to come online during this decade.

China was the only major market where sales increased, driven by demand for air-source heat pumps for space heating, while heat pumps for domestic water heating, a segment where China is the world leader, stagnated. In Japan, one of the most mature markets for heat pumps, sales were down 10% due to low consumer spending.

Sales of heat pumps in the European Union, Japan and the United States fell by 5%, 10% and 15%, respectively. In line with this decline, manufacturing output in these regions also fell, with an average reduction of 10% in the utilisation rates of existing manufacturing facilities. In contrast, China's manufacturing capacity slightly increased to accommodate growing domestic demand (13% increase relative to 2022), which compensated for a 20% decrease in heat pump exports.

Figure 15 Output from existing and announced heat pump manufacturing capacity in selected regions relative to Announced Pledges Scenario deployment in 2030



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Notes: APS = Announced Pledges Scenario. 2023 production values reflect estimates of actual utilisation rates. A utilisation rate of 85% is used for both existing and announced manufacturing capacity in 2030. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Source: IEA analysis based on trade data from UN Comtrade and announcements from manufacturers.

Overall, announced manufacturing projects for heat pumps currently meet around 40% of deployment needs in the APS in 2030. However, manufacturing capacity for heat pumps can typically be adjusted or expanded quickly in response to growing demand, by either increasing the utilisation of existing lines, adding new production lines, or building entirely new manufacturing sites. Any policies designed to support an expansion in heat pump manufacturing should therefore prioritise action to stimulate sustained market demand. Moreover, manufacturing expansion plans for heat pumps are not announced as prominently as those for other technologies, so the slowdown in capacity additions may be less significant than it appears.

The European Union is today the only region with sufficient announced manufacturing capacity to come anywhere close to meeting the 2030 deployment needs of the APS, if announcements are realised in full and on time. However, the decline in sales in 2023 has created uncertainties for manufacturing investment decisions, as domestic manufacturing capacity by 2025 would be 50% greater than sales in 2023 if all announced expansion plans are completed in full and on time. Manufacturers in Europe are responding to this slowdown by downsizing some production lines and, according to the European Heat Pump Association, nearly 3 000 employees in Europe were affected by either job cuts or significant shift reductions between September 2023 and February 2024.

Part II. Advancing clean technology manufacturing

Part I of this report illustrates some of the ways manufacturing contributes to countries' economic development, and how clean technology manufacturing – and the surging levels of investment it is attracting – is today making an important contribution to the global economy. Part I also shows that rapid – if uneven – progress is being made on the deployment of manufacturing facilities. More looks set to come if governments follow through on their climate pledges.

The emergence of clean technology manufacturing as a pillar of the new energy economy presents clear opportunities in the form of expanding markets and sources of employment, but also some important challenges. As with any structural change to the economy, the growth of new sub-sectors disrupts the status quo for incumbents, posing risks for workers and economic security. Part I also shows that the high levels of geographic concentration in clean technology supply chains identified in early 2023 in Energy Technology Perspectives, and in follow-up Special Briefings in May and November, persist in virtually all manufacturing steps analysed. This poses further risks to the security and resilience of clean technology supply chains.

Countries across the world are already responding to these risks. When designing their industrial strategies, governments have several options at their disposal: boosting domestic production, forming strategic partnerships, stockpiling, resource efficiency and input substitutions are some of the oft-cited examples. Some of these options come with trade-offs for industrial competitiveness, while others necessitate international collaboration. The purpose of this report is not to prescribe a single approach, or make recommendations to a specific country, but rather to provide a 'toolbox' for governments when examining some of the key considerations of their industrial strategies.

Part II explores three categories of these considerations in turn. Chapter 3 examines some of the fundamental cost drivers for clean technology manufacturing. Chapter 4 focuses on innovation, specifically the links between energy and manufacturing innovation, the opportunities innovation can unlock and the value of innovation as an exportable good. Chapter 5 explores other key areas of government policy, identifying 'low regret' actions governments can take to advance clean technology manufacturing.

Chapter 3. Cost fundamentals of clean technology manufacturing

The clean energy transition offers many opportunities for growth and employment in new and expanding industries, including in the manufacturing of clean energy technologies. As countries strive to meet their climate goals at the same time as maintaining energy security and affordability through designing resilient clean energy technology supply chains, they are also inherently competing to capture some of this economic opportunity. Understanding the key determinants of manufacturing costs can help to inform the development of fit-for-purpose industrial policies to achieve these goals while maintaining a competitive edge and creating value domestically.

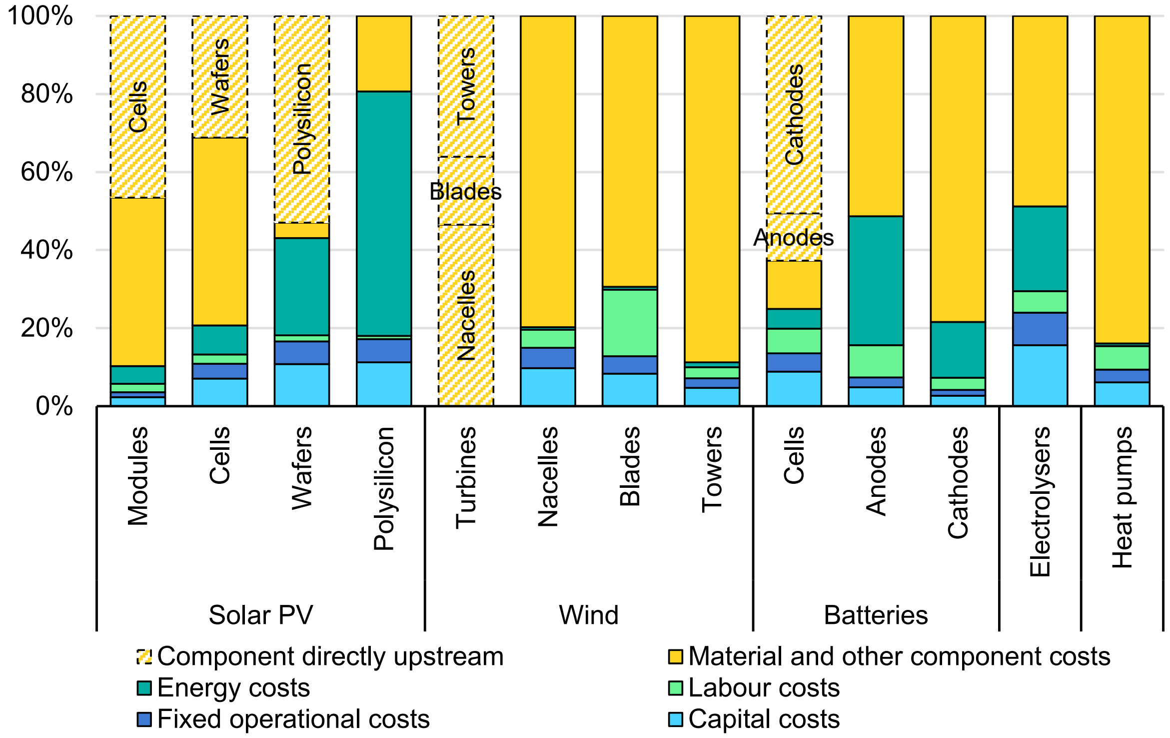
Manufacturing costs for clean technologies are highly company- and facility-specific. Individual contracting arrangements, overheads to fund R&D and corporate expenses, financing terms, tariffs, taxes and levels of profitability across the supply chain all have an impact on actual realised costs, as do government subsidies and incentives. *Prices* for clean technologies will be influenced by all the factors affecting *costs*, and more; in particular the extent to which supply and demand are in equilibrium, which is very challenging to predict accurately. However, an assessment of the main components of manufacturing cost – and the principal factors contributing to differences across technologies and regions – is an important tool for policy makers designing industrial strategies, in order to gauge the impact of any proposed action.

Levelised cost of manufacturing

Levelised cost is a good proxy for overall manufacturing cost per unit of output (e.g. the cost of producing 1 kW of solar PV modules), capturing both upfront and operational costs, together with some of the main sources of regional variation in each of its components. This section presents an overview of levelised cost estimates for manufacturing key clean energy technologies in different regions, based on the best data currently available. The Technical annex provides more details on the analytical boundaries and methodologies used in the underlying analysis.

Explicit policy incentives for manufacturing are intentionally excluded from this analysis in order to provide policy makers with *a* baseline for comparison. However, it is important to note that this does not mean the costs presented are exclusive of all subsidies (e.g. subsidies for electricity generators), which can be embedded – intentionally or otherwise – in all of the main components of levelised cost explored here. Subsidies and manufacturing incentives are explored separately in a dedicated section below.

Figure 16 Breakdown of total levelised costs of manufacturing for key clean technologies and components in 2023



Notes: 'Electrolysers' refers to the stack of an alkaline system, and 'Heat pumps' refers to the final assembly step. Cost shares presented here are calculated using energy prices, capital costs and other region-specific factors for China, and so can differ for other countries. Values exclude any explicit policy incentives for manufacturing, transportation, profit margins, taxes and tariffs, and therefore may not match market prices for these units. A depreciation period of 25 years, a weighted average cost of capital (WACC) of 8%, a utilisation rate of 85% and an annual fixed operational cost set at 5% of initial capital cost are used for all technologies and all manufacturing steps. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Solar PV module manufacturing costs are estimated to be around 35-65% lower in China than in the United States and Europe when considering region-specific values for capital, energy and labour costs. Absolute values of cost are highly sensitive to material and energy prices, which together account for around three-quarters of the total levelised cost of production, with annualised capital costs and labour costs making up less than 15% and 5% respectively. Energy costs for solar PV manufacturing are mainly incurred at the polysilicon production step, at the upstream end of the value chain, given the high temperatures required. In contrast, in the downstream steps of cell and module production, material costs have a proportionately much greater impact on manufacturing costs.

Using illustrative values for the weighted average cost of capital (WACC) (8%) and capital costs (USD 190/kW), average industrial end-user prices for electricity in China (USD 90/MWh) and global average material prices, our bottom-up estimates indicate a manufacturing cost of around USD 160/kW in 2023. However, lower production costs are achievable for facilities with lower financing costs, and for those that have access to electricity and materials at lower prices than the national and global average values considered in our indicative figures. A recent estimate[9] for best-in-class facilities in China puts total production costs at around USD 125/kW in March 2024. These production cost figures are significantly lower than global weighted average selling prices for modules during 2023 of around USD 250/kW, which include the impact of costs and margins associated with several intermediate transactions, and a variety of different contracting terms.

The cost of manufacturing the main components (nacelles, blades and towers) of onshore wind turbines is estimated at around USD 385/kW in China, compared to between USD 485/kW and USD 525/kW in Europe and the United States. Offshore units are around 20% more costly per kW to produce on average, mostly as a result of the more complex and material-intensive towers required. Based on the indicative costs for onshore turbine components, material costs can account for up to 60% and labour between 5% and 10%. At the component level, labour costs make up a larger share of the costs of manufacturing blades than for any other technology, whereas tower manufacturing cost is governed largely by material costs (mostly high-strength steel). The manufacturing costs for nacelles are largely determined by the costs for the other components (the generator and gearbox), which are assumed in this analysis to be manufactured by external facilities rather than in the nacelle assembly facility.

Anode and cathode active materials account for around 10% and 50% of the manufacturing cost for battery cells, respectively, and therefore make up the majority of overall battery manufacturing costs, which also include the electrolyte and cell casing as additional components in this analysis. A total manufacturing cost of over USD 100/kWh is estimated for the United States and Europe, if the battery cell and its components are all produced locally, with costs being between 20% and 35% lower in China. These calculations assume that the prices of the key input materials do not vary regionally, given that they are globally traded commodities. In reality, manufacturers procure materials under different contract terms, and integrated producers – which are more common in China – are likely to benefit from lower prices for key inputs, which could mean the manufacturing cost gap is even wider (see section “Synergies from supply chain integration” in Chapter 5). Moreover, Chinese battery manufacturers currently mainly produce

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[9] ‘Solar Supply Chain Index March 2024: Pitched Battle’ accessible via BNEF subscription. USD 125/kW is an average of values estimated for TOPCon and PERC technologies, including overhead expenses (sales, general administration and R&D) but excluding profit margins.

LFP cells, which are up to 30% cheaper to produce than high-nickel chemistries that are more common in the United States and Europe.

Our bottom-up estimates suggest that the costs of manufacturing alkaline electrolyser stacks could range between USD 45-65/kW, with the upper end of the range corresponding to costs in the United States and Europe, and the lower end in China. However, these illustrative figures are more representative of the levels that could be achieved once the industry is mature, and do not account for several factors that lead to much higher costs for manufacturers in what is currently a nascent industry. First, global average utilisation rates today are around 10%; much lower than the value of 85% used in this analysis to obtain comparable figures between technologies. Just accounting for this difference in manufacturing facility utilisation would lead to a three to fourfold increase, to a range of USD 130-260/kW. Second, these costs exclude manufacturers' recuperation of R&D and other overhead costs that could equate to as much as 100% of the total stack cost, when distributed among the small volumes of units currently produced. Furthermore, comparisons with electrolyser system costs would not include other components that comprise the balance of plant (e.g. rectifier, gas treating equipment etc.).

Heat pump manufacturing is estimated to cost around USD 200-250/kW in Europe and the United States today, which is around twice the cost estimated for China. Manufacturing is assessed in this analysis at the final assembly step, so components (e.g. compressors) and their materials make up the bulk of manufacturing costs. In aggregate these inputs account for around three-quarters of the total in the European Union and the United States, and over 80% in China. Energy, labour and capital costs make up relatively small shares of the total compared with other technologies such as solar PV modules. Heat pump manufacturers that are vertically integrated tend to have a competitive advantage over those more dependent on purchasing their components from other firms. Similarly, those that specialise in air-to-air heat pump units can benefit from synergies with the manufacture of air conditioners. Chinese manufacturers tend to benefit from both of these advantages, together with lower labour and capital costs relative to those seen in the other main manufacturing centres (the United States, Europe and Japan).

The cost gap between the manufacturing of clean energy technologies in China and in other countries is not set in stone. The real cost differences seen across different regions today – which our estimates provide an indication of – are a function of many factors, including surging energy prices in the aftermath of the Russian Federation's (hereafter, "Russia") invasion of Ukraine, lingering supply chain disruptions and currency inflation following the Covid-19 pandemic, increased interest rates, fierce competition in a race for market share for nascent technologies, a variety of subsidy regimes supporting manufacturing, and uncertainty about future demand, all of which are subject to change in the future.

Upfront costs

The main upfront cost that contributes to overall production cost for clean energy technologies is the capital expenditure on the manufacturing facility. We have carried out a detailed analysis of data on the cost of manufacturing facilities for this report, focusing on regions that account for the majority of global manufacturing output today. In addition to the cost of the manufacturing facility itself are the financing costs and, in particular, the cost of capital. While the cost of capital is highly project-specific, there are significant variations between regions, in particular between advanced and developing economies.

Box 6 New IEA analysis of capital costs for manufacturing facilities

Data on the cost of manufacturing facilities are scarce. When data are collected or reported, it is quite often not clear what is included (e.g. equipment costs, construction costs, land purchases, financing costs). Information on certain attributes of facilities is not always available to identify comparable costs, for example whether the facility was a greenfield (i.e. no existing facility at that site) or brownfield investment (i.e. a sizeable expansion of an existing facility), or whether all process steps in a supply chain are included, or just a subset.

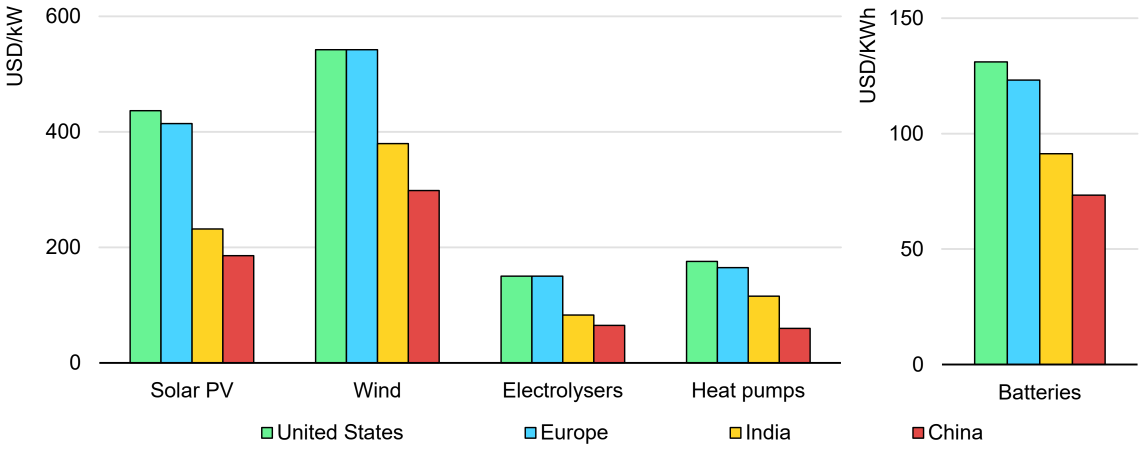
Our analysis focuses as much as possible on the overnight facility costs, including the core equipment and construction costs, but excluding land purchases and financing costs (financing costs are revisited separately below). 320 facilities were analysed for solar PV, 340 for batteries and 90 for wind, with China accounting for the largest share of plants where both cost and capacity data were available. Significant variation is present in these underlying data, which have been distilled into country/region averages for the United States, Europe, China and India.

The data on capital costs presented in this section are used both in the levelised cost and the manufacturing investment calculations. See the Technical annex for more details on the methodologies and data sources used.

Capital costs of manufacturing facilities

Wind turbine manufacturing, including nacelle, blade and tower production facilities, is the most capital-intensive among the five clean technologies we focus on in this report, with costs for manufacturing facilities in the range of USD 300-540/kW for the countries and regions we examine (average of facilities for manufacturing onshore and offshore components). These facilities require large buildings to house the huge components, and heavy-duty machinery for manoeuvring them around the site. The steadily increasing size of wind turbines in recent years has also limited the ability to standardise – an issue that impacts not only the cost of the finished components and their installation, but also to some extent the manufacturing facilities, as amortisation of specialised equipment is spread over fewer units. Recent wind manufacturing facility data for Europe and the United States are limited, due to the small numbers of manufacturing capacity additions in recent years, hence the same average capital cost shown for both.

Figure 17 Estimated overnight unit capital costs for clean technology manufacturing facilities in selected countries, 2023



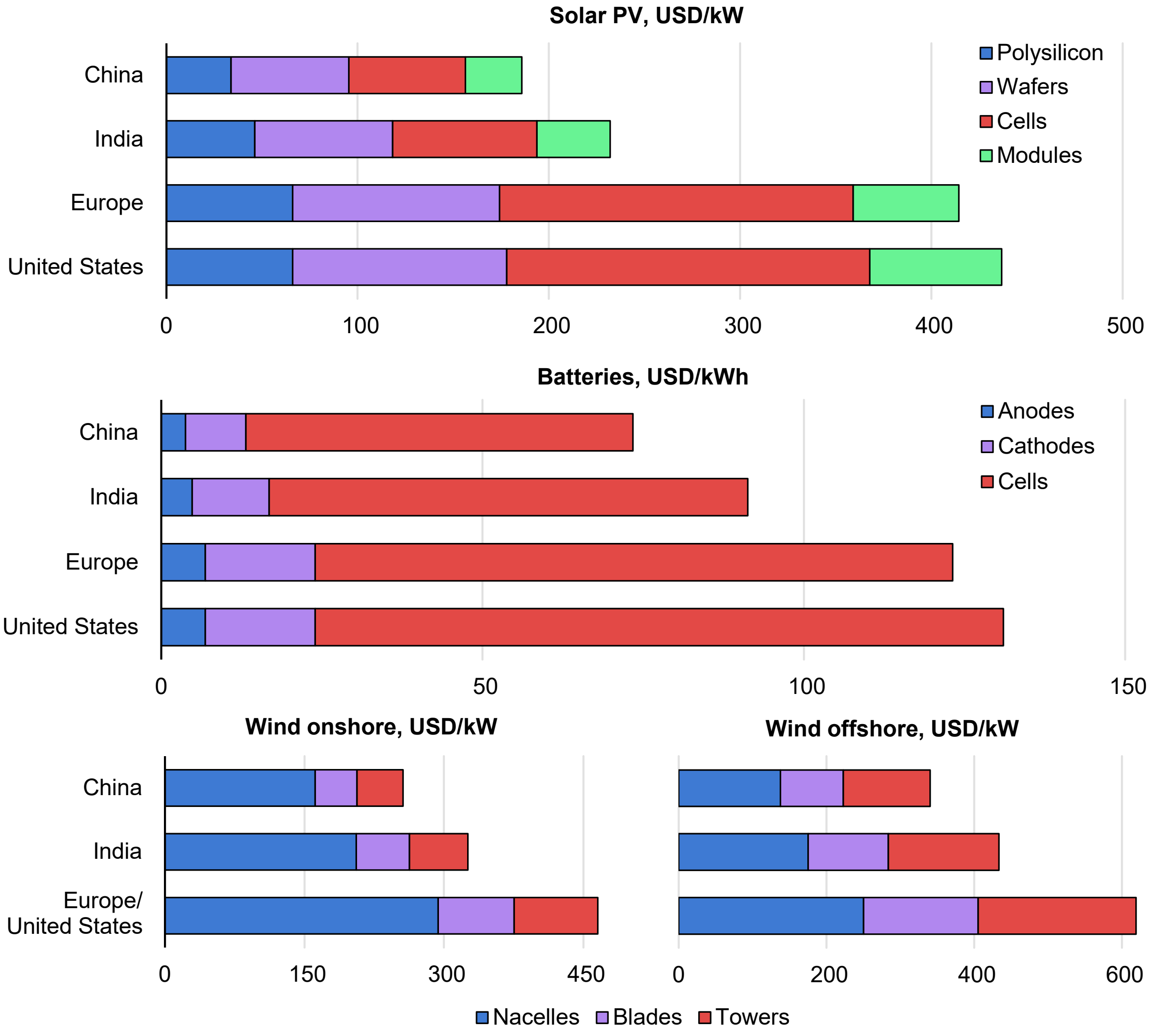
Notes: Capital costs are shown per unit of annual rated capacity. Solar PV includes polysilicon, wafer, cell and module production facilities; Batteries includes cell, anode and cathode production facilities; wind includes nacelle, tower and blade facilities. Electrolysers and heat pumps include only the final assembly step. Costs refer to greenfield, non-integrated facilities where these attributes could be isolated in the data and constitute averages across plants of different sizes today. Data gaps filled using regional multipliers based on differentials in cost for constructing other facilities where more data are available. No explicit policy incentives (e.g. investment tax credits) are applied in this assessment. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Sources: IEA analysis based on data from Clean Investment Monitor, InfoLink, Ofweek, Black Hawk Solar, InnoEnergy, ITDCW, IN-EN, Benchmark Mineral Intelligence, IPCEI, S&P Global Commodity Insights, GWEC and BNEF.

Facilities for solar PV manufacturing are similarly capital-intensive to wind (USD 190-440/kW), owing to the multiple processing steps and complex nature of the processing equipment needed, particularly for manufacturing cells and polysilicon. Module assembly, cell and wafer production are more amenable to economies of scale and short cycles of innovation, given the modular nature of the technology. Much the same is true for battery cell manufacturing facilities, which, however, cannot be compared directly in capital intensity terms given the difference in output unit (kWh vs. kW).

For electrolysers and heat pump facilities, capital costs lie in the ranges of USD 65-150/kW and USD 60-175/kW, respectively. These estimates are based on far fewer data points than those for solar PV, wind and batteries, due to the nascent (electrolysers) and slower-growing (heat pumps) nature of these supply chains and consequently more limited data availability (see the Technical annex for details on this analysis).

Figure 18 Estimated overnight unit capital costs for solar PV, battery and wind technology manufacturing facilities in selected countries, 2023



Notes: Capital costs are shown per unit of annual rated capacity. Costs refer to greenfield, non-integrated facilities where these attributes could be isolated in the source data. Investments in metallurgical grade silicon manufacturing for solar PV are not included, nor are those associated with electrolyte, separator, or foil manufacturing for batteries. Data gaps are filled using regional multipliers based on differentials in cost for constructing other facilities where more data are available. No explicit policy incentives (e.g. investment tax credits) are applied in this assessment. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Sources: IEA analysis based on data from Clean Investment Monitor, InfoLink, Ofweek, Black Hawk Solar, InnoEnergy, ITDCW, IN-EN, Benchmark Mineral Intelligence, IPCEI, S&P Global Commodity Insights, GWEC and BNEF.

China is the lowest-cost region for manufacturing facility capital investment for all technologies and for all manufacturing steps. Costs of clean technology manufacturing facilities in the United States and Europe are between 70% and 195% more expensive per unit of output capacity. India's capital costs are around 20-90% more than China's for the five technologies analysed, but still significantly lower than in the United States and Europe. These cost differentials are likely due to differences in underlying labour, material and construction costs. China also benefits from the experience gained in building its large stock of existing facilities, as well as the economies of scale from larger facilities, industrial clusters covering the full value chain, lower interest rates and a deflationary environment. A facility that can be built more quickly at a larger scale and with less uncertainty will yield cost reductions throughout the construction and procurement process.

Capital cost makes a modest contribution to the overall levelised cost of manufacturing clean technologies, accounting for – once annualised – 15-25% of the cost of producing solar PV modules, 5-10% for heat pumps, and 10-20% for batteries, wind turbines and electrolysers. However, the variation in capital cost between regions accounts for a significant share of regional variation in total manufacturing cost; for example, around half of the difference in cost between producing solar PV in China and the United States.

For battery and wind manufacturing facilities, similar differences in unit capital costs between regions can be observed at each step of manufacturing. Cell production is the most capital-intensive step in solar PV manufacturing for the boundary considered, accounting for 35-45% of total capital costs of manufacturing. The same is true for batteries, but more so, with cell production accounting for around 80% of total facility costs for cells, anodes and cathodes. Wind manufacturing facilities are more expensive per unit of capacity for the larger offshore turbines, particularly for blades and towers, owing to the greater complexity and scale of equipment needed to assemble individual components over 100m in length.

Regional average cost figures mask plant-specific variation. For instance, all capital costs presented here are estimates for greenfield facilities – to aid comparability – but some significant differences in the cost of greenfield and brownfield installations can be observed for certain components of clean technology supply chains. Polysilicon manufacturing is a case in point, where greenfield facilities in China – the only region where the distinction can be made based on the data available – cost around two-thirds more per unit of output than brownfield facilities. A recently announced JinkoSolar manufacturing facility illustrates the lower costs that are achievable for a specific plant relative to the national average values we have compiled. At 56 GW, it is larger than any plant that exists today and is fully integrated (i.e. polysilicon to modules in a single facility), factors which lead to economies of scale and lower running costs. While estimates are not outturn costs, the facility is projected to come in at USD 7.8 billion, or USD 140/kW for full-chain solar PV manufacturing, compared with our national average figure of USD 185/kW for China.

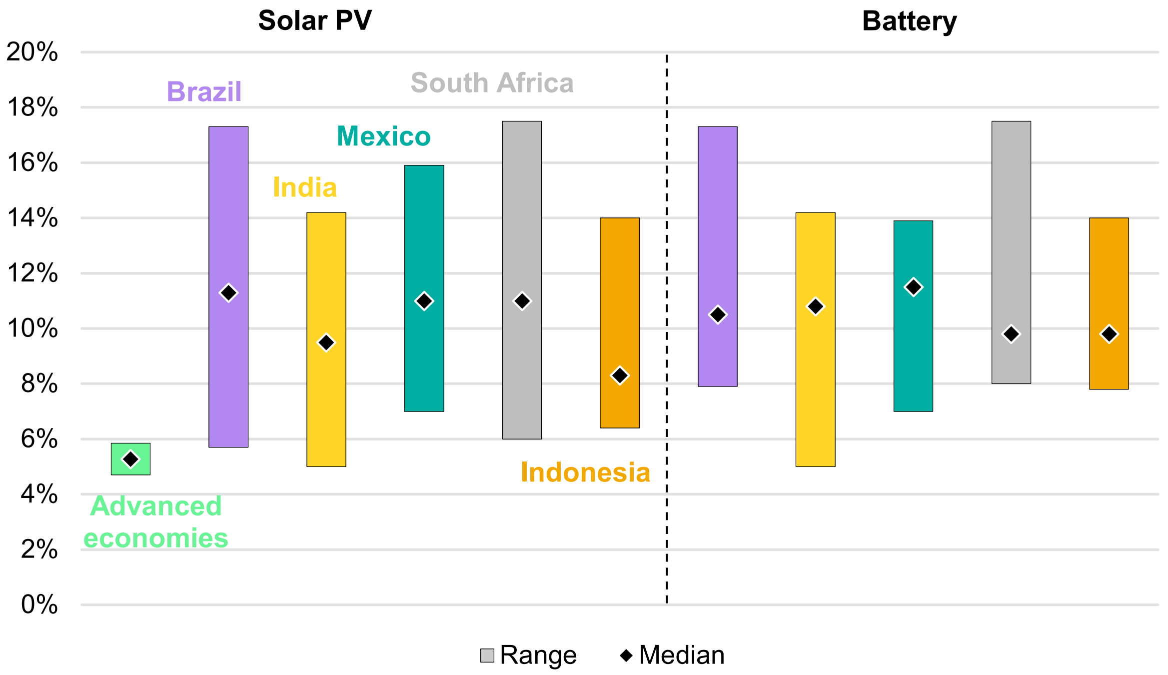
The regional average figures are also static and aimed at capturing costs of the most recently constructed facilities, thereby concealing any variation in costs over time. Most of the data in this assessment are for facilities that have begun construction over the past 5 years, a period in which costs and prices have declined significantly for technologies like solar PV modules and batteries. It does not necessarily follow that manufacturing facilities have undergone the same capital cost declines, as more expensive facilities could lead to production cost decreases for other cost components. However, some cost declines can be observed directly in the plant-level data. In China, for example, capital costs for solar PV cell and module manufacturing capacity both declined on a weighted average per unit basis by around 35% over the period 2020-2023, whereas costs for greenfield polysilicon and wafer production facilities appear to be broadly flat over the same period.

Cost of capital

The cost of capital is the minimum return that a company requires to justify a decision to invest. As such, it is also a measure of real and perceived risk: the riskier the project, the higher the rate of return that would be required to justify investing. Today, the cost of capital for clean energy projects is considerably higher in developing economies than in advanced economies and in China. This explains to a significant degree the variations in capital flows to clean energy seen across these regions. Mobilising more capital to manufacturing projects in developing economies will largely depend on reducing risks that push up the cost of capital. The IEA's report on Reducing the Cost of Capital explores ways in which these risks can be reduced, and the Cost of Capital Observatory provides an on-going analysis of the current cost of capital in EMDEs, together with tools and analysis to help governments understand the main underlying risks.

The weighted average cost of capital (WACC) is a function of the cost of debt capital, cost of equity capital, and the proportions of debt and equity used for financing. Together with the length of the period over which an asset is depreciated, the WACC directly influences the calculation of the annual contribution of capital costs in the levelised costs presented above. Small percentage point increases in WACC make a big difference in annualised capital costs. For example, a billion-dollar investment with a WACC of 5% and a 25-year depreciation period results in an annualised capital cost of around USD 70 million per year. If the WACC is increased to 15%, this increases the annualised capital cost by more than double, to around USD 155 million. This spread of values for WACC (5-15%) is illustrative of the gap seen between advanced economies and emerging economies today for renewables deployment projects in the power sector.

Figure 19 Cost of capital for solar PV and battery power plants in selected regions, 2022



Notes: Solar PV corresponds to a 100 MW plant and Battery to a 40 MW plant.
Source: IEA (2023), Cost of capital observatory.

Weighted average cost of capital (WACC) can also be very sector dependent. A manufacturing facility is likely to have a different financing structure to that of the power plant in which its finished units may be installed. For example, the WACC of a solar power plant in the United States can be around 5-6%, whereas a WACC of 9% is more typical of PV module manufacturers, and latest reported company-levels of WACC for US module manufacturers lie between 8-10%. In polysilicon production, WACC values of 15% and above have been observed in the United States. Similar trends are observed in China, with polysilicon producers reporting higher company-level WACC ranges (7-17%) than PV module manufacturers (2-13%).

Today, virtually all clean technology manufacturing capacity is located in advanced economies and China, with solar PV manufacturing installations in India and Southeast Asia being notable exceptions. Therefore the cost of capital is likely to be more project- and company-dependent than region-dependent, for regions currently active in clean technology manufacturing, with variations driven by differences in debt-to-equity ratios, costs of debt, and cost of equity across projects. Nonetheless, given that governments may identify strategic partnerships or foreign direct investment as features of their industrial strategies, the WACC for manufacturing facilities in developing economies – and ways to reduce it – are important factors to consider.

Operational costs

Important differentials in total manufacturing cost can arise from differences in operational costs, i.e. those incurred after upfront costs are met and once a facility is up and running. Three important categories of operational costs are energy, materials and labour, which together account for 70-98% of total manufacturing cost for the key technologies examined in this report. There are many other ongoing expenses that accrue or may be allocated during the operation of a manufacturing facility, such as company overheads, infrastructure charges, transport of finished goods, quality control and assurance, wastage and warranty processing, to name but a few. Here we focus on energy, materials and labour as three major contributors that would need to be examined as part of a wider assessment of the viability and competitiveness of manufacturing operations at a given site or in a given jurisdiction.

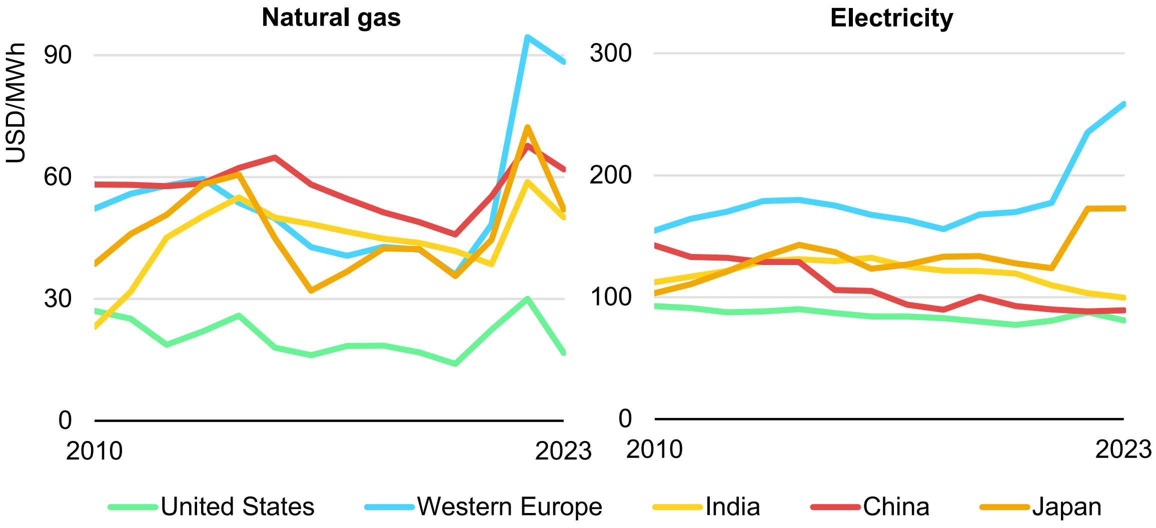
Energy costs

Natural gas and electricity are the two main energy inputs for clean technology manufacturing today, the prices of which, including taxes and excises for industrial users, vary significantly between countries. The prices of coal and oil products, which are more easily traded internationally (as transport costs represent a smaller share of the price), vary much less between regions, excluding the impact of taxes and duties like CO_2 pricing. None of the major manufacturing regions today have an industry CO_2 pricing system that covers clean technology manufacturing directly, but several have policies that cover electricity generation, including China, the European Union and certain states in the United States. The indirect impact of these policies will mostly be captured in electricity prices.

Thermal energy needs are much lower for clean technology manufacturing than for heavy industries like steel and cement, and natural gas – together with coal, particularly in China – tends to be the energy source used today to generate the direct process heat required. Countries with abundant domestic natural gas reserves (e.g. the United States) tend to have much lower industry end-user prices for natural gas, whereas regions that are dependent on imports tend to see higher prices. Higher prices still are seen for countries that rely on liquified natural gas imports as opposed to pipeline gas. Over the period 2013-2023, industry users in the United States saw the lowest natural gas prices among major clean technology manufacturing regions, with prices fluctuating within the range of USD 15-30/MWh. Industrial gas prices in China and India tended to be two to four times higher during this period. In the aftermath of Russia’s invasion of Ukraine, which sparked a global energy crisis, prices in Western Europe shot up to levels three to five times higher than the United States during the period 2022-2023.

Industrial electricity prices also vary significantly between regions, and some clean technology manufacturing operations are electricity-intensive. The United States has some of the lowest industrial end-user prices for electricity, and Europe some of the highest, particularly since Russia's invasion of Ukraine. Price differentials between regions are similar to those for natural gas, which is intuitive, given that natural gas is often the price-setting mode of generation in liberalised electricity markets. In China, electricity prices are strongly regulated for many users, which – together with the fact that a large share of electricity is generated from domestic coal supplies – has led to falling prices for industry customers even during a time when wholesale energy prices have been rising. Industrial end-user prices for electricity in China reached levels similar to those of the United States in 2022-2023.

Figure 20 Industry end-user prices for natural gas and electricity in selected regions



IEA. CC BY 4.0.

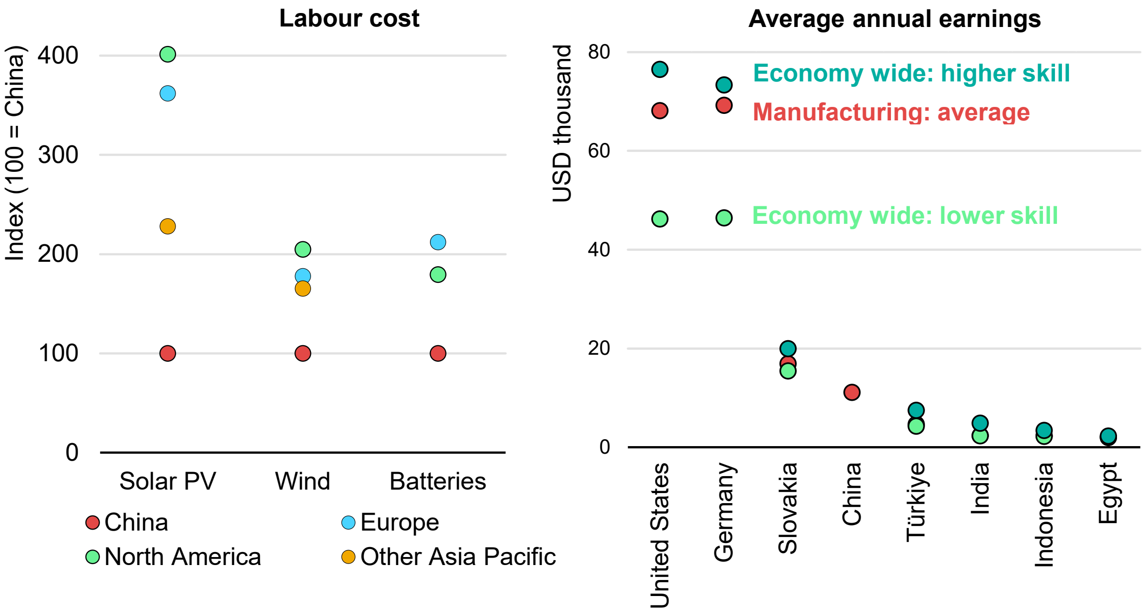
Notes: Prices are shown in 2023 US dollars using market exchange rates on an annual average basis. End-user prices include taxes (such as VAT), subsidies and tariffs.
Sources: IEA analysis based on the IEA Energy Prices database.

Energy can be an important component of operational costs for clean technology manufacturing, accounting for 1-30% of the total manufacturing cost of components excluding polysilicon and up to 75% for polysilicon, depending on the region, and the step in the supply chain. Energy costs tend to account for a larger share of production costs for upstream supply chain steps, like anode and polysilicon production. For example, in solar PV manufacturing, energy costs remain an important driver of the differences in module cost between countries, particularly for the energy-intensive polysilicon and wafer production steps, which consume around two- to three-times more energy per unit of production than cells and modules. For wafers, electricity is estimated to account for around 25% of overall production costs in China today, and for polysilicon, more than 60%. For heat pumps and wind turbines, which are typically less energy-intensive to manufacture, energy prices – and regional variations thereof – have less of an impact on the total manufacturing cost in one region relative to another.

Labour costs

Manufacturing wages, one of the primary determinants of labour costs, along with labour intensity, are a significant source of regional variation in manufacturing costs. In the United States and Western Europe, manufacturing earnings can be 6 times higher than in China, and around 30 times higher than in Southeast Asia and the Middle East. Important variations can also be observed within regions, with earnings in Eastern Europe on average four times lower than those in Western Europe. Beyond differences in economy-wide earnings, variations are also driven by differences in the distribution of skills in the manufacturing workforce. Labour productivity levels vary by region, driven largely by greater uptake of mechanisation and automation in advanced economies or manufacturing centres. This in turn reduces the magnitude of the workforce and the share of lower-skilled labour as simpler manual tasks are automated. For example, while economy-wide earnings are on average higher in the United States than in Germany, the opposite is true for manufacturing earnings, as Germany has a lower share of lower-skilled (ISCO-08 Level 1) employees[10] than the United States.

Figure 21 Current average wage expenses for key clean energy technologies and average annual manufacturing earnings and skill distribution by region



Notes: Average earnings represent the gross remuneration in cash for employees, excluding employers' contribution to social security or pension schemes. All values are for 2022, except the average earnings in China, which is for 2021. 'Lower skill' refers to the ILOSTAT ISCO-08 occupations classification levels 1-2; 'Higher skill' referring to levels 3-4. Information on wage per skill level is not available for China.

Sources: IEA analysis based on ILOSTAT.

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[10] Skill levels are defined according to ILOSTAT ISCO-08 occupations classification.

Similar differences can be observed at the sectoral level, with factors including industry maturity, degree of labour representation, local skilled labour availability, degree of automation and mechanisation, and role of government incentives all contributing. China, the leading clean technology manufacturing country globally, typically has the lowest average manufacturing wages, but there are some important differences at the level of individual technologies. For solar PV manufacturing, for example, wages in Europe and North America can be as much as four times higher than those in China, while the same gap decreases to a factor of two for wind turbines and EV battery manufacturing. On a per unit output basis, wage premiums in advanced economies or regions with more mature industries can also be offset to some degree by greater labour productivity. This effect can be clearly observed with heat pump manufacturing: In Japan, the average wage in this sector is about 60% greater than in China, but fewer workers are required for each unit produced, leading to relatively comparable total wage expenses per GW.

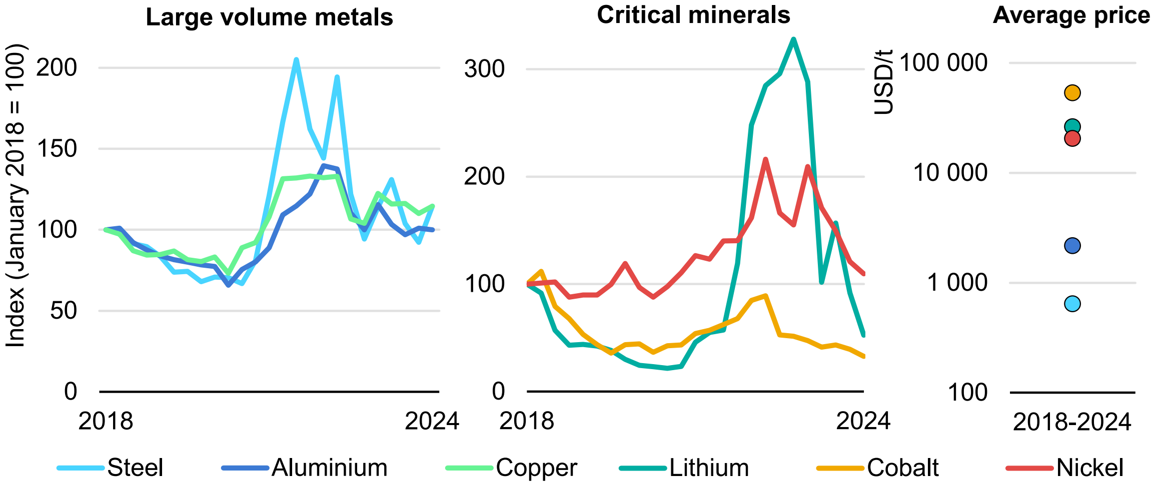
The availability of skilled workers must also be considered alongside costs. In theory, the levelised cost of battery production is similar in India and in China, but the lack of qualified workers (see Chapter 5) constitutes a barrier to scale-up of manufacturing facilities.

Materials costs

Materials make up around 25-80% of the total manufacturing cost for the key clean technologies examined in this report. For several technologies and supply chain steps thereof, materials are the single largest contributor to overall costs. Materials tend to be priced in international markets, with small variations between regions compared to energy (natural gas and electricity) prices. However, prices over time can be highly volatile, and/or cyclical, like many commodity markets. Prices for large-volume metals used in the manufacture of clean technologies – steel, aluminium and copper – have shown significant variation over the last 5 years, with prices increasing by as much as 100% for steel relative to their levels at the start of 2018. At the start of 2024, aluminium prices were up 2% relative to their 5-year average, whereas steel prices were up 5%.

Prices for critical minerals such as lithium, cobalt and nickel have shown substantially more volatility than those of the larger-volume metals over the past 5 years. Prices are directly impacted by the manufacturing demand for clean technologies, which make up 10-45% of the global total for these metals. Prices of cobalt have fallen by around 70% since 2018, returning nearly to their 2018 level in 2022, but then falling sharply again thereafter. Lithium prices fell by 75% between the beginning of 2018 and late 2020, before rocketing by a factor of 10 during 2021-2022. Prices then crashed during 2023, leaving the commodity priced at around half its early 2018 level. Nickel prices showed similar – albeit more muted – swings.

Figure 22 Commodity prices for key inputs to clean technology manufacturing, 2018-2024

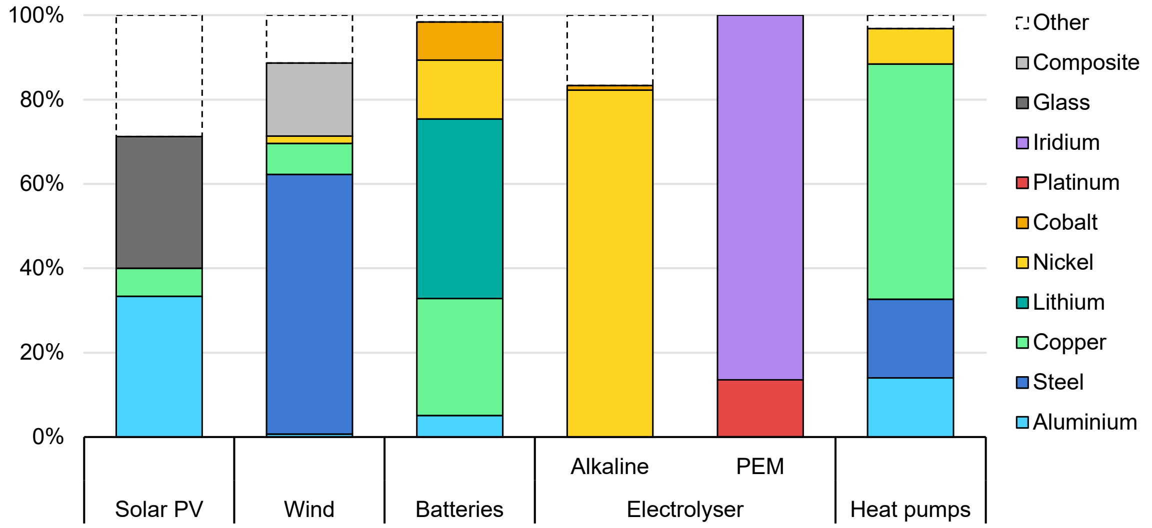


Notes: All figures based on contracts and price markers in China.
Sources: IEA analysis based on price information from Bloomberg Terminal.

The impacts of material and critical mineral costs are felt very differently between clean technologies. On a price-weighted basis using the average prices for materials over the period 2018-2024, metals produced in large volumes, like copper, aluminium, steel and glass, together account for 70-90% of the material costs of solar PV modules, wind turbines and heat pumps. The remainder of the material costs are composed of silver (solar PV), nickel (wind and heat pumps) and a variety of other materials including composites. Material costs for batteries and electrolysers depend to a great degree on the prices of specific critical minerals.

Taking a price-weighted average of the material requirements for the battery chemistries currently in use today, lithium is by far the largest contributor to material costs, followed by copper, nickel and cobalt. The remainder of battery material costs is composed of much smaller contributions from aluminium and graphite, the latter being the main input to anode manufacture. Electrolyser material costs depend almost entirely on the cost of nickel (for alkaline models), or iridium and platinum (proton exchange membrane models). Based on the differing levels of volatility seen in recent years for large-volume metals (steel, aluminium, copper) and critical minerals (lithium, cobalt, nickel), and the proportions in which they are used in each technology, batteries and electrolysers are significantly more exposed to material cost volatility than wind and solar PV technologies.

Figure 23 Share of individual material costs in total material cost for key clean technologies



IEA. CC BY 4.0.

Notes: PEM = proton exchange membrane. Composite includes carbon fibre, fibreglass and other composite materials. Solar PV covers the finished module, including the interim steps for producing cells, wafers and polysilicon. Wind covers the nacelle, tower and blades on a deployment weighted average basis for onshore and offshore turbines. The figures for batteries are calculated using the weighted average of battery chemistries based on their current market share in the electric vehicle market. For Alkaline and PEM, the material costs refer to the stack and exclude balance of plant components. For Alkaline, a nickel intensity of 800 kg/MW is assumed; for PEM, an iridium intensity of 0.4 kg/MW is assumed. None of the materials required for installation of these technologies in power plants or vehicles are included. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Sources: IEA analysis based on price information from Bloomberg Terminal.

Policy incentives for manufacturing

Financial and other incentives for manufacturing increasingly feature as components of governments' industrial strategies. The aim of these policies is to reduce the cost of production – and thereby increase the attractiveness to invest – for firms, usually by transferring aspects of cost to governments' balance sheets. Explicit measures include direct grants to projects or firms, government loans, government equity purchases, loan guarantees, investment and production tax credits, among others. These measures can be deployed on an ad-hoc basis (e.g. one-off government support for a specific facility or project) or on a systematic basis (e.g. codified in policy documents).

Beyond explicit measures, there are many ways embedded financial support can influence manufacturing costs, whether intentionally or not. A vast literature has identified and measured various subsidy mechanisms across a range of industries, sectors and activities including studies published by the World Bank, the International Monetary Fund, the Kiel Institute, the Centre for Prospective Studies and International Information, Center for Strategic & International Studies and the OECD. Such an examination is beyond the scope of this report, but it is an important consideration for policy makers that any notion of "pure" cost for industries like those producing clean technologies is challenging to interrogate in practice. The measures used to deliver these embedded financial support schemes can be similar to those comprised by explicit incentive regimes, but can be deployed on upstream inputs like labour, capital and energy costs, and therefore may be harder to observe and/or quantify.

As noted, the levelised cost estimates and their components examined above should be considered as a guide to the observable costs for firms, including embedded financial support where they exist. These figures may well be the most appropriate tool for policy makers looking to examine the potential impact of explicit policy support domestically, as they are a better starting point for assessing cost gaps than theoretical estimates of unsubsidised costs. Explicit manufacturing incentive regimes should be considered on top of these levelised cost estimates. Some highlights of the latest developments in this area are provided below.

United States

In the United States, the Inflation Reduction Act (IRA) provides production tax credits for the manufacturing of components across solar PV, wind and battery supply chains through to 2032. An investment tax credit for manufacturing facilities is also available for a wider range of technologies, including electrolysers and heat pumps. In April 2024, USD 1.14 billion was made available for clean energy technology manufacturing projects in a first round for this tax credit, with around 60% of the total allocated during that round, which also included funding for grid modernisation, critical minerals production, and industrial decarbonisation. The Defense Production Act was also extended through the IRA to provide grants and loans to strategic domestic clean energy manufacturing projects.

Further provisions under the IRA to stimulate demand for clean energy technologies could also indirectly incentivise domestic technology and component manufacturing. For example, the Clean Vehicle tax credit, which provides up to USD 7 500 for the purchase of new electric vehicles, does not apply to vehicles containing battery components or critical minerals that come from select “Foreign Entities of Concern” (FEOC).[11] In December 2023, the US Department of Treasury published further guidance around FEOC-related restrictions, with an impact for some Chinese battery and component manufacturers. The Clean Hydrogen production tax credit is an incentive to increase demand and potentially boost electrolyser manufacturing.

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[11] The United States defines a FEOC as an actor that potentially poses economic or security threats. This includes businesses that are significantly influenced by selected governments (China, Russia, North Korea and Iran).

Table 2 Examples of the funding available for clean energy technology manufacturing through the Inflation Reduction Act

Technology		Value	Description
Solar PV	Modules	USD 0.07/W	• Advanced Manufacturing Production Tax Credit (45X MPTC). • Available through to 2032 for clean energy components manufactured in the United States. • The value of the tax credit starts decreasing from 2030 (75% of credit in 2030, 50% in 2031, 25% in 2032). • Cannot be combined with Advanced Manufacturing Investment tax credit (48C ITC).
	Cells	USD 0.04/W	
	Wafers	USD 12/m^2	
	Polysilicon	USD 3/kg	
Wind	Nacelles	USD 0.05/W	
	Blades	USD 0.02/W	
	Towers	USD 0.03/W	
Batteries	Battery modules	USD 10/kWh (cells) USD 45/kWh (no cells)	
	Cells	USD 35/kWh	
	Cathodes Anodes	10% of costs	
Cross-cutting		Up to 6% of investment (30% if apprenticeship and wage requirements are met)	• Advanced Energy Project credit or Advanced Manufacturing Investment tax credit (48C ITC). • USD 10 billion available. • Covers manufacturing of solar PV, wind, battery, electrolyser and heat pump components.
			• Enhanced use of the Defense Production Act to correct domestic manufacturing shortfalls. • USD 500 million in grants and loans available until September 2024. • Covers manufacturing of solar PV, electrolyser and heat pump components.

European Union

Policy support schemes for clean technology manufacturing have also moved forward in the European Union. In April 2024, the members of the European Parliament adopted the Net-Zero Industry Act (NZIA). Unlike the IRA, the NZIA does not provide financial support to specific projects, but rather aims to boost investment in clean energy technologies by simplifying permitting procedures, enhancing the skills of the European workforce, and creating favourable frameworks to boost innovation. The NZIA is part of the broader Green Deal Industrial Plan which aims to improve regulation, access to funding, skills building, and establish trade partnerships to boost net zero industry in the European Union. The plan is complemented by the Critical Raw Materials Act, adopted in March 2024, which aims to support recycling and environmentally friendly supply of critical minerals to the European Union. Other EU-level programmes are in place to provide support to manufacturing more directly, such as the IPCEI programme that facilitates grants to EU electrolyser and battery manufacturing.

The European Union is in the process of implementing its carbon border adjustment mechanism (CBAM), which may indirectly support domestic manufacturing and prevent "carbon leakage" by shielding producers of low-emissions materials, components and technologies from competition with more emissions-intensive goods imported from other jurisdictions. The scope of the CBAM, which was passed in May 2023 and will enter into force in 2026, is currently limited to a selection of goods and precursors including cement, iron and steel, aluminium, fertilisers, electricity and hydrogen, but could be extended to all sectors covered under the EU Emissions Trading Scheme by 2030.

Individual member states are also taking action at the national level to support clean technology manufacturing. Country-level subsidy schemes such as direct grants may be approved by the European Union if they are in line with the Temporary Crisis and Transition framework. This can, for example, include aid towards relevant equipment for the transition to a net zero industry. In the Netherlands, the government just closed a public consultation on the new Manufacturing Industry Investment Subsidy Climate Neutral Economy programme, which targets the production of solar panels, batteries and electrolysers. In Spain, public consultation opened in March 2024 on a EUR 750 million grant scheme to support manufacturing of clean energy technologies, including solar panels, batteries, heat pumps, wind turbines and electrolysers. In October 2023, the European Commission approved a EUR 100 million scheme in Italy for grants for electrolyser manufacturing.

In addition to grants and loans, subsidy schemes based on lifecycle performance of technologies can also favour domestic manufacturing, as is the case for a French EV purchase subsidy available to consumers, which is linked to vehicle lifecycle analysis rather than emissions from use.

In parallel to these support schemes to encourage domestic manufacturing, the European Union is also pursuing an investigation to assess potential unfair subsidy practices for EV manufacturers. In October 2023, the European Commission launched an anti-subsidy investigation to determine whether electric vehicle manufacturers in China benefit from unfair subsidisation, and to assess the effects for EU manufacturers. Based on the findings, the European Union will decide whether to impose tariffs above the standard 10% EU rate for cars. A similar investigation was launched in April 2024, targeting two companies which have responded to a public bid for the design, construction and operation of a solar PV park in Romania, and who might have benefited from unfair foreign subsidies.

Other regions

In India, the Production Linked Incentive (PLI) scheme provides financial support to reduce investment costs in new integrated PV module manufacturing plants through payments linked with sales volumes achieved. Following the approval in March 2023 of incentives for solar PV module manufacturing under Tranche II of the PLI scheme, concerns have been raised about the likelihood of manufacturers being able to compete across all key components quickly, and meet efficiency targets. In addition, following the introduction of the Advanced Chemistry Cell PLI scheme in 2021, the government launched a new consultation in July 2023 to re-open bids for 20 GWh of unutilised battery cell manufacturing capacity. More recently, in October 2023 the Minister of Power, New & Renewable Energy announced that the government will launch another PLI scheme for batteries. In June 2023 India also announced the implementation of tenders to support 15 GW of electrolysis manufacturing capacity in the country. A first call (for 1.5 GW), which launched in June 2023, received 21 bids, with a combined capacity twice as high as the call itself.

In Indonesia, the first electric vehicle battery cell manufacturing facility in the country could start operating in April 2024 with a 10 GWh capacity. The plant received support from the Indonesian government as part of an IDR 142 trillion (Indonesian rupiah) (USD 9.8 billion) support package for the battery industry.

In December 2023, Korea announced a KRW 38 trillion (Korean won) (USD 29 billion) envelope in the form of tax incentives, loans, and insurance to support Korean firms in the battery industry, including in the processing of critical minerals. This funding also aims to support Korean firms making investments abroad.

In Türkiye, minimum import prices on solar cells were implemented in January 2023 to protect domestic manufacturers, and since May 2023, solar PV plants using domestic components have benefited from higher feed-in tariffs than ones operating with imported systems.

In its 2023 budget, Canada proposed a series of investment tax credits which could directly and indirectly support domestic clean energy technology manufacturing. These include the Clean Technology Manufacturing investment tax credit, which could support 30% of costs of equipment for the manufacture of clean technologies, as well as investments in critical materials and minerals processing, extraction and refining.

In April 2024, Australia announced plans to introduce a “Future Made in Australia Act” to support domestic clean technology manufacturing. The legislation is expected to be introduced in 2024.

Chapter 4. The role of innovation in advancing clean technology manufacturing

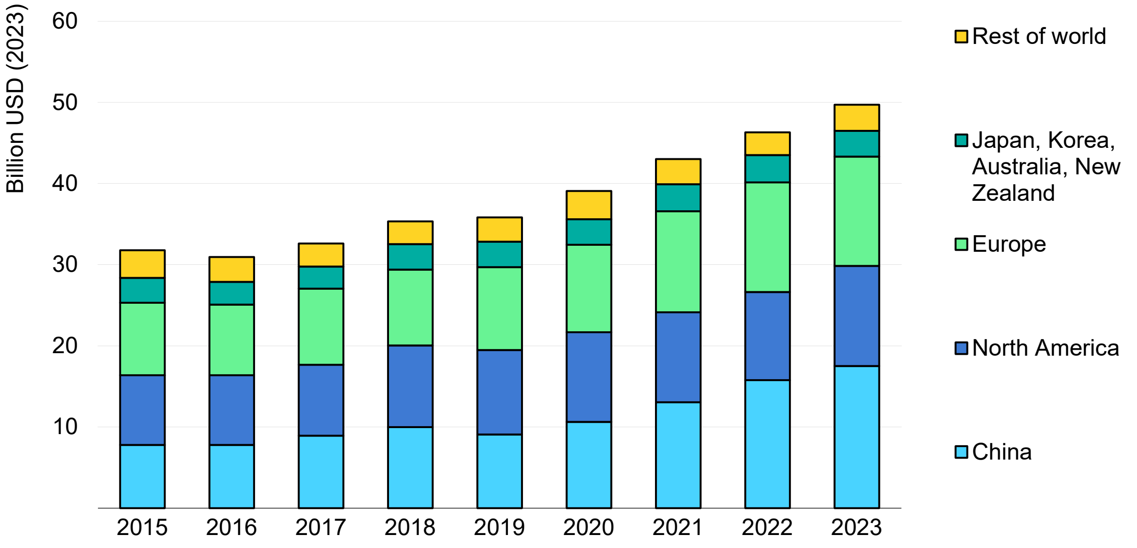
Technology innovation is an engine of economic growth. Investment flows to new technologies that can outcompete incumbents or offer new value to consumers. Throughout the history of energy systems, dramatic shifts in fuel sources and end-uses have been triggered by the emergence of new technology ideas, often led by governments via research funding, national laboratories or the provision of related infrastructure. These dynamics have played a central role in the development of the clean energy technologies featured throughout this report. Innovation – including R&D, demonstration projects and continued optimisation – has opened opportunities for market uptake of these products and helped by government support, has led them to a scale of manufacturing at which heads of state are now concerned with their contributions to national trade balances.

Government spending on energy R&D is on the increase and boosting competitiveness is a key reason. Despite challenging economic conditions, spending rose in all major regions between 2019 and 2023. Globally, four-fifths of the USD 50 billion that governments spent on energy R&D in 2023 was dedicated to clean energy topics. The impact of this funding should be to reduce fossil fuel emissions more quickly than is possible with the current technology portfolio.

From the perspective of an individual government seeking to secure investment in clean technology manufacturing for policy goals including job creation and supply chain security, innovation spending can be a means of minimising the costs of the overall policy package in the medium to long term. For example, if a country is not the lowest-cost producer today, it may need to use subsidies to help a manufacturer bridge the cost gap in relation to imports, or to use regulation to raise the cost of imports. These policy approaches imply a cost for taxpayers or consumers that is likely to persist after the manufacturing base is established. Technology improvements to products or production processes can reduce costs or increase the value to consumers relative to the imported good, thereby narrowing the cost gap to be addressed by subsidy or regulation.

Another major aim of using public funds in this way is to lock in an early comparative advantage in an emerging technology area. Innovation can be nurtured so that recipient firms can be among the first to commercialise new technologies or improvements to them in order to gain market share or enter new markets. Firms that are innovating at the technological frontier increase the likelihood of investment, employment and tax revenues in the country in which they are headquartered.

Figure 24 Government spending on energy R&D and demonstration, 2015-2023



IEA. CC BY 4.0.

Source: IEA (2024), World Energy Investment 2024, forthcoming.

For hardware innovation in particular, the innovator's goal is often for their product to be manufactured and/or used in factories, for domestic markets, or for export. Whether this is "incremental" innovation (an improvement to an existing technology that improves performance or lowers costs) or "radical" innovation (a new type of product that changes the fundamental nature of how a service is delivered), it will contribute to a country's manufacturing competitiveness if successful. There is, of course, a risk that companies will relocate abroad after the technology is commercialised, but experience shows that most innovative companies stay close to where they were established and keep a share of their R&D and manufacturing there: international moves are rare.

There are four main ways in which technology innovation can advance clean technology manufacturing:

- By capturing a larger share of an existing market or increasing the size of the market, typically via lowering costs. For example, by commercialising a cheaper and more efficient heat pump that, in turn, raises demand for heat pumps.
- By raising the value of a certain subset of the overall market. A technical advance can lead to changes in consumer preferences or regulatory requirements if it shows the feasibility of meeting demand with lower emissions, more positive social impact, greater durability or higher safety and security. For example, the

development of a more recyclable battery, or one that eliminates minerals with poorly governed supply chains, could command a price premium or drive regulatory change to increase the value of that market segment.[12]

- By creating intellectual property – whether formalised in patents or not – that generates wealth from the sale of licences, levies and services. For example, a designer of wind turbine components that licenses its design production overseas by a third party and sells its services as an engineering contractor to assemblers and installers of wind turbines, with the revenue returning to the headquarters of the company, where its R&D centre is based.
- By inspiring "spillovers" of knowledge into adjacent technology areas that become more competitive through this "free" innovation resource. For example, electrolysis techniques or components that have value for mineral processing or CO_2 capture as well as hydrogen production.

The link between energy innovation and manufacturing has strengthened

A large share of the technologies that can contribute to reaching net zero emissions have unit sizes that are smaller in scale than those of past energy systems.

Some of these technologies are small because they are electronic or digital. Some are small because they operate best when distributed across many small installations. Some are small because they are end-user technologies that can be tailored to user needs and sold to millions of separate users. Some could have cheaper unit costs if they were bigger, but their developers are adopting a modular approach to control risks related to the budget overruns of past mega projects. Regardless of the underlying reason, these new breeds of small energy technologies can be mass-manufactured and traded more easily across borders.

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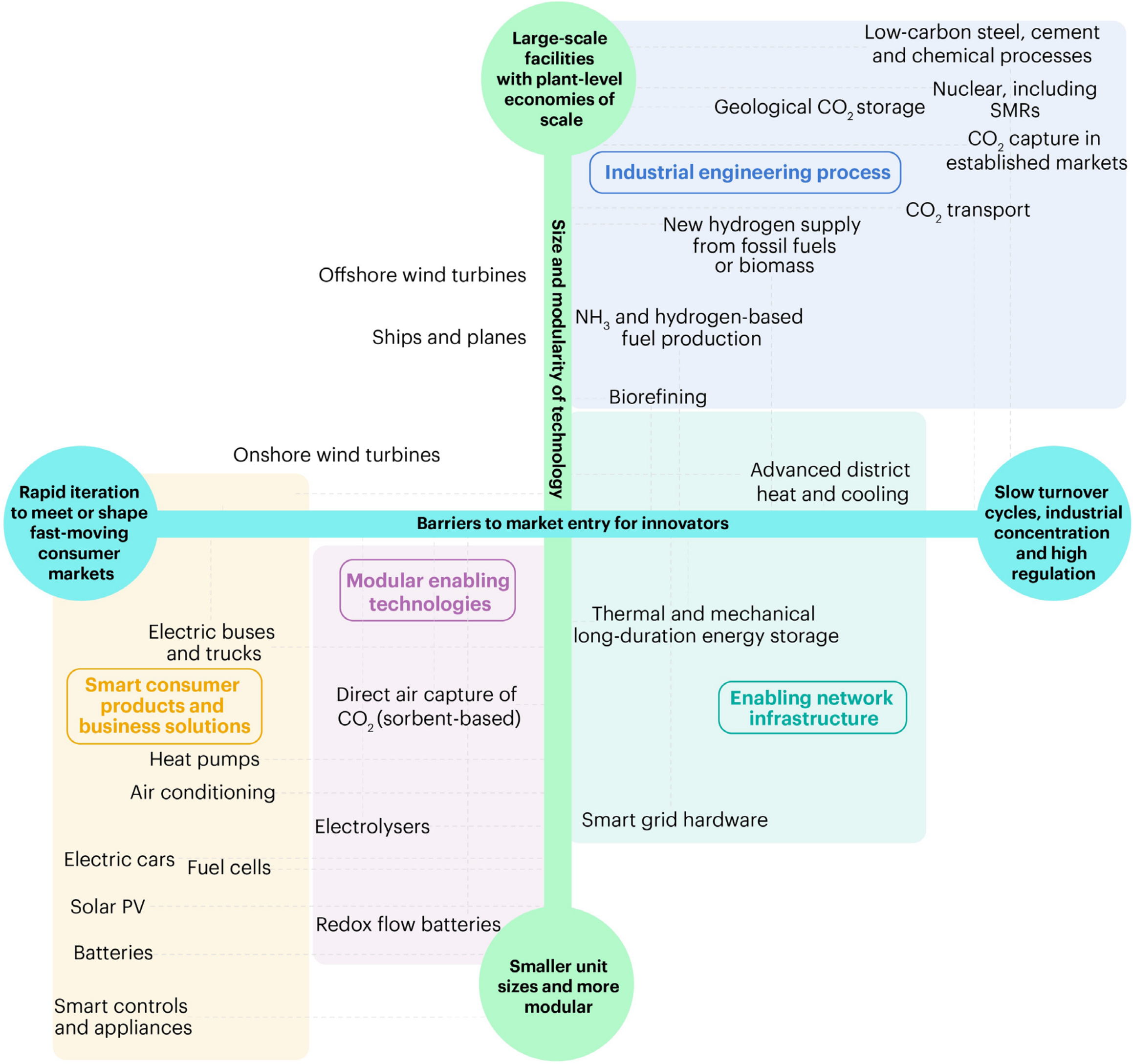
[12] In a small number of cases, such as the direct capture of CO_2 from the air, entirely new markets could be created this way.

Figure 25 Clean energy technology types mapped according to their general attributes of size and modularity versus barriers to market entry



Notes: SMR = small modular reactor; NH_3 = ammonia.
Source: IEA (2022), How Governments Support Clean Energy Start-ups.

This evolution of the scale of energy technologies has implications for the scope of energy innovation. First, it implies a much bigger role in the energy sector for innovation in technologies used in manufacturing that reduce the costs or increase reliability of factory output. Technologies such as multi-wire saws for silicon wafers have played as much of a role in delivering cost reductions for solar PV as innovation in the design of the solar cells and modules themselves. Second, it can reduce the reliance of energy systems on “flows” of fuels that are consumed during use, and increase the importance of “stocks” of materials that go into manufactured hardware, such as batteries. New technologies that can enhance the resilience of highly dispersed supply chains for these inputs, such as those that enable the extraction of critical minerals from diffuse sources or avoid their use in batteries altogether, are now an accepted part of the energy innovation landscape.

A further effect of the changing technology portfolio is the greater ease with which smaller innovators can break into the market for energy products. If the market demands thousands to billions of individual units each year, then there is scope for more suppliers to enter it and to differentiate their products. Barriers to entrepreneurs that relate to working capital, access to regulated infrastructure and economies of scale tend to be lower for technologies with smaller unit sizes. This phenomenon is further embedded by the deregulation of markets for electricity and gas supplies in many countries. As a result, there is now more opportunity for a clean energy technology spin-off from a university to successfully commercialise a new technology and steadily grow its market share from almost anywhere in the world.

Whereas the energy system of the 20th Century was dominated by a limited number of major engineering firms – often state-owned – selling costly and customised installations in the oil, gas, coal, nuclear and power grid sectors, today there is no shortage of smaller players based in China, India, Scandinavia or South Africa with stated ambitions to become leading exporters of EVs, batteries, steel or energy management services.

Innovation can overcome high cost factors to maintain manufacturing competitiveness

The purpose of R&D spending and innovation in the private sector is typically to capture a larger share of the market or increase the size of the market. Corporate R&D on energy technologies is estimated at around USD 130 billion per year, indicating a continuing faith in the ability of technology improvements to keep prices attractive while meeting customers' needs and satisfying regulatory requirements. These large sums spent on innovation each year, in a wide range of countries, show that industrial competitiveness can only be understood as a function of technology, labour costs, energy costs and other input costs. For example, input costs and economies of scale cannot explain all of the cost decline of solar PV. It is estimated that around 60% of solar PV cost reductions between 1980 and 2001 arose from R&D. Indeed, the role of continued R&D in reducing costs was roughly equal to that of economies of scale even after wide commercialisation in 2001.

Improving the technological basis of a company's products and production processes can keep costs competitive even in situations where the input costs are higher than those of competitors. If successful, a manufacturer's investments in developing new technologies will yield benefits relating to lower energy and materials demand via smaller products or higher production efficiency; lower capital requirements through miniaturisation of processes; or an ability to charge higher prices than competitors by more closely matching consumer preferences. In this way, companies can maintain manufacturing at locations where they already have a knowledgeable workforce, established government relations and a proven supply chain, rather than uprooting to relocate to a lower-cost region. Governments often have an interest in helping companies to bolster domestic employment and revenue, and so provide R&D grants, tax incentives and networking opportunities. A significant co-benefit of this strategy is that R&D often generates spillovers of innovation in co-located companies that are in adjacent parts of the supply chain or related sectors.

Innovation is therefore an important reason why countries that are known for relatively high labour and energy costs continue to have factories that manufacture goods in trade-exposed sectors, including automotive parts, engines, heating equipment and robotics. Firms in these sectors that have successfully operated manufacturing facilities in advanced economies over several decades generally produce goods that are at the top end of the markets in which they operate. Their pursuit of quality helps them access higher profits per unit of output. As they have globalised, such companies may have also opened manufacturing plants in other regions – especially where these are close to new markets – but usually keep R&D facilities in the country of their headquarters and founding. The spending at these R&D centres is significant, representing 2% to 10% of the firm's revenue (Table 3). For a company such as Valeo, an automotive parts supplier, annual R&D spending was over USD 2 billion, or 9% of revenue, in 2023.

Table 3 Eleven selected companies in trade-exposed sectors that have maintained competitiveness through innovation

Company	R&D intensity	R&D locations	Manufacturing locations	Notable innovation area
Alfa Laval	2.5%	Sweden*, Denmark	Sweden*, Brazil, China, India, Italy, Poland	Compact heat plate for efficient heat transfer
Bosch Auto Parts	8.2%	Germany*, China, Czechia, India, Italy, Thailand, United States	Germany*, Brazil, China, Czechia, France, Hungary, India, Italy, Poland, Spain, Thailand, Türkiye, United States	Electronic stability control; EV powertrains
Danfoss Climate Solutions	4.6%	Denmark*, China, India, United States	Denmark*, Germany, India, United Arab Emirates, Poland, China, Türkiye, Slovenia, Mexico, United States, Czechia, Brazil, Bulgaria, Romania, Slovakia	Low-pressure refrigerant compressors for heat pumps
First Solar	4.6%	United States*	United States*, Malaysia, Viet Nam	Advanced thin-film solar PV

Company	R&D intensity	R&D locations	Manufacturing locations	Notable innovation area
Hitachi Energy	2.9%	Switzerland*, Canada, China, Germany, Poland, Sweden, United States	Switzerland*, Argentina, Australia, Canada, China, Egypt, Mexico, Colombia, India, Indonesia, Japan, Korea, Saudi Arabia, Thailand, United States, Viet Nam, 13 European countries	High-voltage direct current components and systems
Kia Motors	2.6%	Korea*, China, Germany, United States	Korea*, China, India, Mexico, Pakistan, Slovakia, United States, Uzbekistan, Viet Nam	Modular platform for mass-market EVs; waste heat recovery
Magna International	2.0%	Canada*, Austria, Brazil, China, Czechia, France, Germany, India, Italy, Japan, Korea, Morocco, Romania, Spain, Sweden, Thailand, United Kingdom, United States	Canada*, Argentina, Brazil, China, India, Korea, Mexico, Morocco, Thailand, United States, 17 European countries	Composite materials for lightweight vehicles; EV powertrains
Panasonic Energy	2.6%	Japan*	Japan*, Brazil, China, Costa Rica, India, Indonesia, Mexico, Thailand, United States	Lithium-ion car battery coatings to raise stability and energy density
Rolls Royce Power Systems	4.7%	United Kingdom*, Germany, Hungary, India, Norway, United States	China, Germany, India, Türkiye, United States	High efficiency, flexible engines for marine or back-up applications
Valeo	9.2%	France*, Brazil, China, Czechia, Egypt, Germany, Italy, India, Japan, Korea, Mexico, Poland, United States	France*, Brazil, China, Czechia, Germany, Italy, India, Japan, Korea, Mexico, Poland, Romania, Slovakia, Spain, Tunisia, Türkiye, United States	Integrated EV vehicle powertrain for low- and high-voltage EVs
Wärtsilä	4.3%	Finland*, Italy, Netherlands, Norway, Singapore, United Kingdom	Finland*, Brazil, China, France, India, Italy, Japan, Spain, Sweden	World's most efficient 4-stroke diesel engine; methanol and ammonia engines and systems

* Country of headquarters (domicile).

Note: R&D intensity = research and development expenditure divided by revenue for the latest year for which data is available for the company or its parent company.

As clean energy expands, and healthy competition between equipment suppliers intensifies, it is reasonable to expect that clean energy innovation efforts will increase. This comes with additional benefits as more innovative companies have more capacity to weather macroeconomic storms, or adjust to new competitive landscapes, than those that are reliant on resource rents or cheap factor inputs.

Policy missions for innovation to unlock new manufacturing opportunities

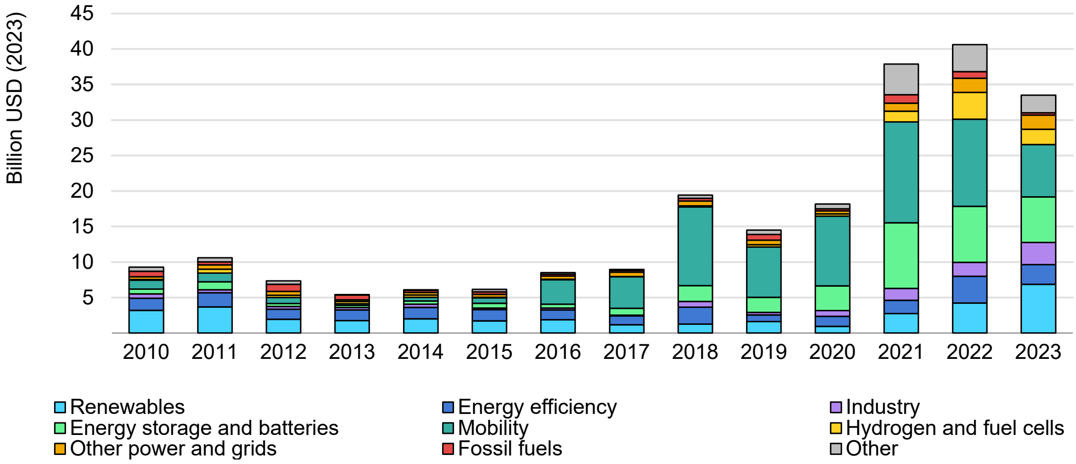
Policy support for clean technology manufacturing is mounting in many countries as governments respond to the energy crisis and seek more resilient clean energy supply chains. Some of these policies provide a boost to the drivers of clean energy innovation by creating demand for manufactured products, or by helping companies to advance their plans to build factories and industrial facilities. To enable more rapid progress towards more competitive manufactured clean energy technologies, more direct innovation policies can be used, and specific technology areas are worthy of consideration.

Significant policy focus has been given recently to investments that could diversify value chains or raise the level of recycled content in manufactured energy equipment. The US Bipartisan Infrastructure Law and IRA, which include grants and production and investment tax credits for a range of manufactured products, are examples of such policies. In Europe, the EU Innovation Fund backs successful applicants for clean tech manufacturing grants, and there is scope for the EU IPCEI mechanism to also provide this type of support, and the European Solar PV Industry Alliance and UK Green Industry Growth Accelerator could facilitate similar measures in future. Climate Transition Bonds could play a comparable role in Japan. India's PLI instrument provides payments to selected manufacturers of solar PV modules and batteries per unit of output.

These types of policies indirectly support innovation by amplifying the incentives for established firms and newcomers to gain a competitive edge, for example by improving the quality of their product or reducing the price. In the case of India's PLI, the subsidy is tied to certain criteria for efficiency or chemical composition, an approach that can send a stronger signal to innovators if set at an ambitious level. Indirect inducement of innovation can be highly effective.

In cases where it is not clear that the private sector can respond to these signals by bringing new technologies online quickly and in line with policy goals, complementary policies are needed. Direct innovation programmes typically include targeted government grants for underfunded but promising R&D or demonstration projects. Most countries have budgets for targeted grants, including China's so-called "bounty system" that covers research challenges for electric vehicles, energy storage and hydrogen. The European Investment Bank's loans to companies for electric vehicle research are an example of the use of debt as a targeted R&D instrument, while the US loan guarantees for demonstration projects illustrate a complementary type of finance tool. Direct support can also include in-kind assistance, as provided by Canada's public laboratories in its Critical Minerals Research, Development and Demonstration Program, and via the research networking elements of the EU IPCEIs for batteries and hydrogen.

Figure 26 Venture capital investment in energy start-ups, by technology area, for early-stage and growth-stage deals, 2010-2023



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Notes: Industry includes start-ups developing alternative routes to materials such as building materials, steel and chemicals; mobility includes technologies specific to alternative powertrains, their infrastructure and vehicles, but not generic shared mobility, logistics or autonomous vehicle technology; "Other" includes CCUS, nuclear, critical minerals and heat generation; fossil fuels cover start-ups whose businesses aim to make fossil fuel use cheaper or otherwise more attractive, including fossil fuel extraction and fuel economy of hydrocarbon combustion vehicles.
Source: IEA analysis based on Cleantech Group (2024).

In recognition of the potential for new, manufactured clean energy technologies to be developed and scaled up into products by smaller companies, government support for start-ups in this area is rising. While they represent relatively risky bets, start-ups can be a conduit for the most disruptive ideas that can accelerate energy transitions. Governments also appreciate their potential to seed new, large manufacturing businesses in regions that may not currently be leaders in a given technology area, or regions that risk losing their competitive edge without innovation. However, establishing the conditions that could foster the next "breakout" clean energy firm – think of Tesla, BYD, Ola Electric, Northvolt, Enphase Energy or EVBox – requires attention to a range of policy issues. These include availability of venture capital (VC) funds, facilities for technology testing, the preferences and behaviours of potential customers, and barriers to market access for new entrants. The rapid global growth in VC funding for clean energy start-ups in the past 5 years in part reflects the improvements to start-up ecosystems due to targeted government efforts in China, Europe, India and North America. The dip in funding in 2023 is a clear reminder that governments must remain alert to the impacts of macroeconomic pressures on clean energy innovation progress, but they can be partly reassured that the 2023 drop in VC funding was greater in sectors other than clean energy.

Several technology innovation challenges present themselves as potential means of advancing clean energy technology manufacturing from the end of this decade. Four are listed in Table 4 to illustrate possible target areas for direct government innovation policy in the near term that could support longer-term goals.

They each build from existing trends that create new market opportunities or could hinder scale-up. For example, energy efficiency efforts and the deployment of renewable electricity and nuclear power underpin different environmental impacts of solar PV production among countries – the emissions intensity of Chinese solar PV has been halved through efficiency and other measures since 2011, for example – creating opportunities for further product differentiation on this basis. However, the reliance on silicon-based PV cells has not changed in recent years, and there is renewed interest in alternative designs that use different raw materials and could reach higher conversion rates. When used in tandem designs that use less silicon, halide perovskites have already been demonstrated to reach higher efficiencies than crystalline silicon alone. Attempts for wider commercialisation of perovskites gain momentum by overcoming innovation challenges related to durability and stability, which are focus areas for companies such as Sekisui Chemical in Japan, and the US Department of Energy Solar Energy Technology Office.

With respect to adaptation of technology to consumer needs in different locations, innovators can be encouraged by the precedent of reduced noise and visual impacts of wind turbines in the past two decades. However, the wind sector has also experienced misalignment of technology and manufacturing in its value chain: As economies of scale and land use pressures drove up the size of the largest wind turbines by nearly 70% in around 10 years, the development cycles for new components became shorter, increasing the risk of failures, which is exacerbated by reliance on a small number of third-party factories for outsourcing production of new designs. Strategies to manage this type of risk will be required if clean technologies continue to expand rapidly.

Table 4 Technology innovation challenges to advance clean technology manufacturing

Type of challenge	Examples	Possible approaches
Design technologies that preserve quality while avoiding inputs of scarce minerals or those at greatest risk of supply chain disruption	Battery chemistries that favour more abundant minerals over cobalt or lithium. Electrolyser catalysts that reduce the need for platinum group metals (see Box 7).	Digital technologies (including machine learning and digital twins) that can radically speed up the hunt for new chemical combinations that could have desirable properties.
	Cut wastage in the solar PV supply chain to minimise requirements for critical minerals and energy-intensive inputs.	Techniques such as 3D-printing to reduce material inputs per unit of power generation. Optimising for durability and recycling to reduce demand for energy-intensive polysilicon. Non-silicon designs, introducing perovskites.
Innovate for consumers that value low emissions intensity	Integrate low-emissions electricity or waste heat into manufacturing facilities.	Digital tools that can schedule and modulate manufacturing process steps according to the availability of renewable electricity. Connection of multiple facilities with a geothermal or waste heat source.
	Reduce emissions from shipping products, such as EVs, internationally.	New fuel and propulsion technologies for ships, including large roll-on-roll-off vessels. Standardised designs for efficiently shipping large offshore wind turbine components.
Tailor product specifications to meet the next waves of consumer demand, which will be required for technologies to reach their full potentials	Overcome obstacles to heat pump deployment associated with certain locations, such as the need to reduce noise and/or improve visual impact.	Scroll compressors are a first step towards very quiet heat pumps and air conditioners. Thermoacoustic devices or responsiveness to background noise may help further.
	Adapt the specifications, cost and durability of clean energy products to the budgets of rapidly-growing consumer segments in EMDEs.	Innovation in open access platforms for designing reliable, affordable, small electric vehicles.
Help align R&D programmes throughout the value chain to ensure that suppliers can provide components for next generation designs	Innovation in component and material supply must lead, not lag, turbine design.	Enhance dialogue among players in the wind energy value chain to guide basic R&D and standardisation of key components, such as fixation dimensions between wind turbine hubs and blades, and share experiences.

Box 7 The value of technology diversity to electrolyser supply chains

For a century, one technology – liquid alkaline – captured the entire market for water electrolysers, largely due to its dominance in the related and, until recently, larger market for producing chlorine. However, the number of competing technologies has proliferated in the past 5 years. Polymer electrolyte membrane (PEM), solid oxide electrolyser cell (SOEC), anion exchange membrane (AEM), microbial electrolysis cell (MEC) and decoupled water electrolysis (DWE) are among the technologies at different stages of maturity for different applications. Depending on the mix of electrolysers ultimately deployed to meet future demand for low-emissions hydrogen, the impact on demand for critical mineral inputs could vary considerably. This has implications for strategic planning of mineral supplies in the public and private sectors, and for expectations for how prices of these manufacturing inputs might evolve. It also points towards the importance of early consideration of recycling infrastructure and requirements.

Unlike for some battery chemistries, electrolysers are not expected to dominate demand for many minerals, with the possible exception of iridium. However, their influence on supplies of nickel and platinum could be felt strongly if there is a "winner-takes-all" outcome to the competition between technologies (see table below). In the case of alkaline electrolysers dominating the market, demand for nickel for electrolysers in 2030 could equal 4% of total nickel demand today, a modest increase in the context of an overall nickel market that would grow 75% by 2030 in the NZE Scenario due to battery requirements. Nevertheless, sourcing nickel for electrolysers affordably and securely could be more challenging if suppliers struggle to keep ahead of battery demand. In the case of PEM dominating the market, there might be a sizeable increase in demand for iridium and platinum, two elements that are co-produced in a small number of locations today. However, this would be moderated by a more balanced mix of electrolyser technologies and further research into new PEM designs that aim to substitute iridium, for example with ruthenium.

Possible mineral demand from electrolysers in 2030 depending on technology choices in the Net Zero Emissions by 2050 Scenario

Electrolyser technology mix	Mineral demand in 2030 as a share of current demand		
	Iridium	Nickel	Platinum
If all installations are alkaline	-	4%	-
If all installations are PEM	420%	-	6%
If all installations are SOEC	-	-	-
60% ALK, 30% PEM, 10% SOEC	125%	2%	2%

The value of technology innovation besides lowering manufacturing costs at home

Countries that host companies and researchers who are innovating at the technology frontier can generate multiple value streams. While the prospect of competitive mass-market manufacturing may be a key reason to support such R&D, not all of the value streams require the country to be a major manufacturer, and they can lead to additional returns to innovation.

As discussed above, the most common goal for technology innovators is to supply a large share of the market. Countries that host manufacturing facilities accrue the advantages of employment, spending of income and tax receipts. They may also come to host the factories of related suppliers due to so-called "network externalities" that encompass the benefits of locally aggregated demand, preferential access to specialised inputs and knowledge exchange. However, not all successful innovation results in a competitive edge that can corner a market through mass manufacturing. There are two other mechanisms that can help create wealth for cutting-edge innovators:

- Production of high-performance products that have the highest value per unit.
- Trade in intellectual property and intangible goods.

In most markets, there are customers that are willing to pay more for a high-quality product that has specific attributes that are unavailable in mass-market offerings. In the area of clean energy, higher "willingness to pay" may be exhibited by:

- First-movers who can afford to buy a product that more closely matches their customer preferences before it is affordable for other consumers. For example, early EV adopters.
- Buyers in a country, company or sector that is required by regulation or shareholders to pay for more expensive products with higher environmental performance. For example, EU carmakers that must buy batteries with CO_2 intensity below a specified level and a minimum level of recycled content.
- Customers that require a higher level of reliability and performance than the market average. For example, military procurement of fuel cells or users of electrolysers to supply processes with very low tolerance for downtime.

These cases can add up to a significant economic opportunity that is only accessible to those operating at the technological frontier and staying there over time. Furthermore, technology developers that seek to supply customers of this kind often generate inventions that subsequently trickle down to the mass market.[13] Therefore, companies producing the highest-performing products are

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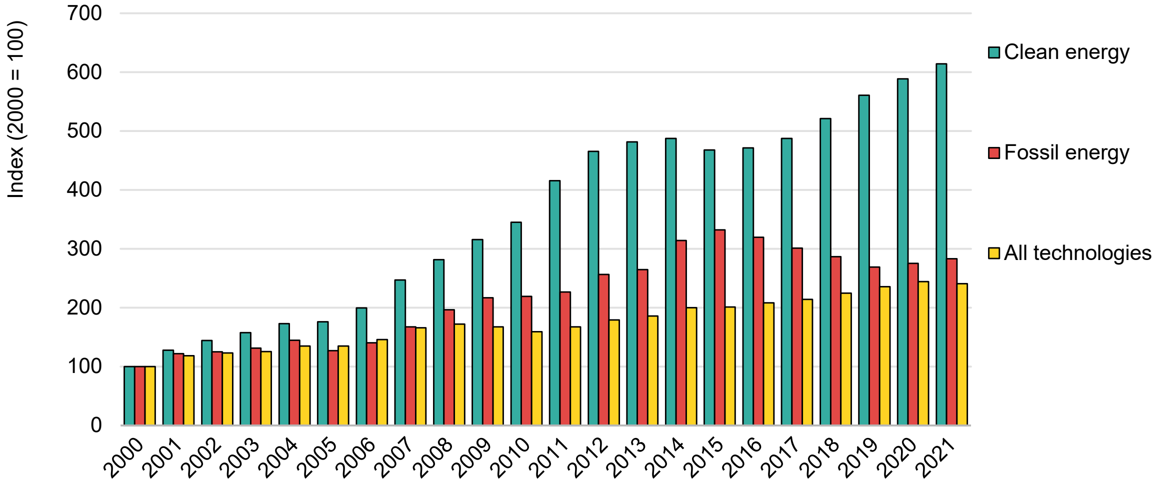
[13] When regulation raises the "willingness to pay" in a given jurisdiction, this is part of a phenomena sometimes referred to as the Porter Hypothesis, for which evidence for its strongest interpretation is mixed. However, the assertion that regulation or other market incentives can create valuable market differentiation for higher-performing products and processes is not contested.

often also the companies that can profit from owning intellectual property that is used around the world. Patents for clean energy technologies, which represent the most formal measure of intellectual property, are growing faster in number than patents for all inventions globally.

Figure 27 Global growth of patents in low-carbon energy technologies versus all technologies, 2000-2021



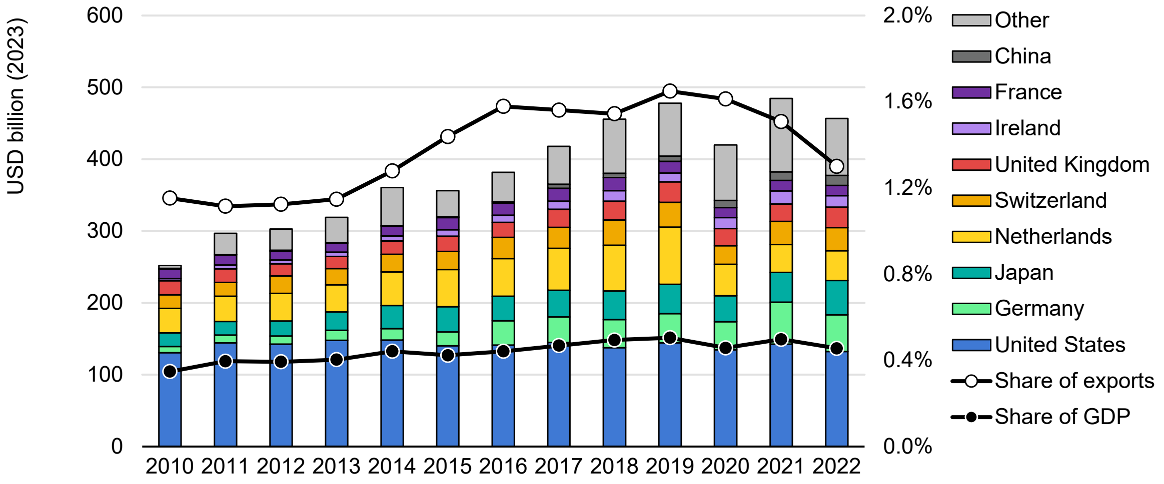
Notes: Shows a count of international patent families, each of which represents a unique invention and includes patent applications targeting at least two countries

Source: IEA analysis based on data from the European Patent Office (EPO), and EPO and OECD/IEA (2021), Patents and the Energy Transition.

While data on trade in intellectual property, including patent licences, are scarce, there is evidence that trade in intangible capital related to manufacturing is significant to economic prosperity. For several G7 countries, the trade balance exceeds 1% of GDP. Across countries, intangible capital has been found to account for around 50% more of the income in global value chains than returns to tangible capital, such as investments in factories, and a share that is half that of labour income. Most intangible capital value relates to R&D, including intellectual property, computer software and databases. A smaller share derives from organisational capital and brand value.

Globally, income from charges to overseas users of intellectual property grew 50% in the 10 years to 2022 to a level that is equivalent to 0.5% of world GDP. Just three countries – the United States, Germany and Japan – were responsible for half the global total in 2022. In the United States, a country for which data is available, half of this income relates to licences for the use of outcomes of R&D, indicating that the trade is not dominated by copyrights, trademarks and noninnovation intellectual property.[14] However, since 2019, international trade in intellectual property has stagnated while revenue from total exports has grown. At present, there are no strong reasons to believe that this phenomenon will persist in the long term if recent inflationary and supply chain obstacles recede.

Figure 28 **Income from charges to overseas customers for the use of intellectual property, and as a share of total exports and GDP, 2010-2022**



Source: IEA analysis based on WTO (2024) Trade in commercial services database.

One trend that supports the increase in national income from intangible capital is the separation of the location of design and production in industries such as smartphones. Digital technologies have made it possible for firms to unbundle the value in ideas from the physical manufacturing of the product in question. It has been calculated that 35-50% of the value of a smartphone accrues to the companies that own the design and the intellectual property, and not to the manufacturers of the handset or the components.

The development of Extreme Ultraviolet Lithography (EUV) for semiconductor manufacture is an example of how R&D can generate outsize value for the developers of the intellectual property. It also echoes the critical link between innovation and the continuation of the "learning curve" trends that show declines in prices for solar PV and batteries over time. Learning curves are not laws of nature and cannot usually be delivered through economies of scale alone. They will grind to a halt without R&D and innovation in both products and processes, and sometimes require step changes in technology approach in order to stay on track in the long term.

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[14] The link between the location of the R&D and the country receiving the income remains somewhat uncertain as variable tax rates between countries and other factors can encourage firms to register intellectual property in ways that relocate ownership to maximise financial returns.

Box 8 Innovation by customers to help semiconductor manufacturers keep Moore's Law on track

The long-standing trend towards miniaturisation of semiconductors and increase of computing power since the 1960s – colloquially known as "Moore's Law" – is widely reported. However, in the 1990s, semiconductor production had largely relocated to cheaper manufacturers in Korea and China Taipei who did not have the in-house capacity for the innovation necessary to follow the miniaturisation trend. At the time, increased computing power was enabling unprecedented changes in economic productivity and entertainment, and it was conceivable for the buyers of silicon chips to be content to limit risk and accept these products - the cheapest and best chips ever available – for their future electronic devices. Had they done so, Moore's Law would not have been maintained. Instead, the major North American, Japanese and European designers of semiconductors and computers worked with governments on a high-risk approach to lithography (the process of engraving functionality in silicon chips) that would allow it to operate at scales closer to 10 nanometres than 100 nanometres.

Following a programme of R&D investment at US national laboratories and testing by firms such as Intel and ASML, EUV technology was commercialised by 2010 – in time to keep the long-term trend on track, and to meet demands from the new smartphone market. It was the product of international collaboration along the value chain. Despite the vast majority of semiconductor chips being produced outside the countries that funded the R&D, the key innovator countries have reaped huge benefits: they are home to the production of the machines and components for EUV-based manufacture. In addition, their companies continue to be the leading designers and creators of cutting-edge products that would not be possible if such advanced EUV-based processors were not available.

It is sometimes tempting to dismiss the opportunities for countries or companies to invest in manufacturing R&D in sectors with mature process technology and high input costs. In these cases, outsourcing or offshoring production may be accepted as the only options for reducing costs. But this oversimplifies the ways in which innovation can generate new sources of value for established players and existing manufacturing regions. One such way is to focus on market segments that will pay the most for quality or environmental attributes. Well-designed industrial policies and public procurement can guide incumbent and start-up companies towards this outcome. Another way is to focus on potential game-changing process technologies that can raise the quality of manufactured components worldwide, with the aim of integrating them into higher value clean energy equipment for end consumers. Hi-tech process technologies are particularly well-suited to these types of strategies because proprietary manufacturing processes are typically harder to reverse-engineer than to work out the details of a product design. A third way is to maximise the comparative advantage of co-location for producing intangible capital in networks of interacting experts and for raising efficiency and reliability through physical integration of processes and suppliers.

The size of the future market for clean technologies is expected to be large enough to accommodate examples of advanced economies stepping back down value chains and also EMDEs moving progressively up them. In advanced economies, where the energy R&D focus has, until recently, been on product and system design, especially to make final goods that add value to intermediate commodities, innovation can help industrial processes and mass manufacturing stay competitive. In particular, investments in innovation today can reduce the costs of meeting employment and other social policy goals related to clean technology manufacturing during energy transitions. In EMDEs, stronger innovation policies can create new sources of value in much the same way, including by enhancing the local capacity to absorb and adapt technologies originating abroad. In addition, EMDEs have the potential to seed entirely new manufacturing bases based on geographic or cost-based comparative advantages that are specific to clean technologies – such as renewable resources, mineral resources, proximity to export markets or skilled labour.

Chapter 5. Policy priorities for advancing clean technology manufacturing

Governments have a variety of tools at their disposal to advance clean technology manufacturing in their jurisdictions; cost competitiveness of domestic output is an important driver for companies to invest, but by no means the only one. As described in the previous chapter, supporting innovation is one possible means of advancing clean technology manufacturing by promoting cutting-edge research to reduce costs and raise product quality. However, as innovation can take time to be translated into project investment, a range of other complementary policies can foster investment in the near term. They include, but are not limited to, overarching climate policies, clear environmental and social standards, accelerated permitting, workforce training and international co-operation.

How attractive a given location is to potential investors in new manufacturing capacity is determined by many more factors than cost alone, such as robust local demand for the technologies being produced. The same is true for the competitiveness of continued output from an existing facility in that location. In both cases, million-dollar decisions are routinely taken by investors or owners in ways that cannot be explained solely by cost, even if cost is always a major factor.

While many of the policies that are currently in place to advance clean technology manufacturing in the near term are cost-based (see Chapter 3), in this chapter we consider policy interventions that can improve the attractiveness of investment or production in a region without subsidising the costs of manufacturing. Cost disadvantages can also be offset in a range of ways that are not covered in this chapter, including the stability of the political and economic outlook, the fiscal regime, the availability of dependable infrastructure, the ease of exchanging knowledge and skills and the absence of corruption, or reputational factors, including a track record for quality output.

Enlarging domestic markets with climate policy

Strong and stable energy and climate policies can help catalyse markets for clean technologies. Proximity to sizeable domestic demand can help manufacturers achieve economies of scale and partially offset cost differences with producers in other regions. In addition, local demand makes domestic manufacturing less dependent on uncertainties in export markets, thereby reducing project risks.

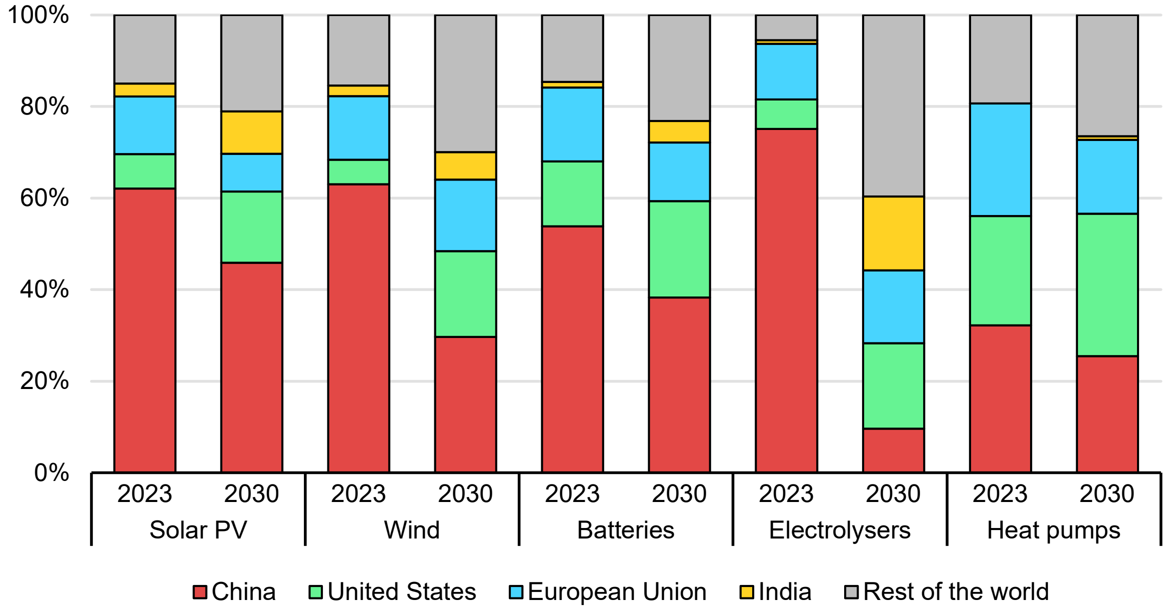
The prominence of China, the United States and the European Union in global investment in clean technology manufacturing has been partly driven by strong domestic demand for technologies, and the sheer size of these markets. China alone currently accounts for 30-75% of global demand for the technologies we focus on in this report.

Looking forward, demand for clean energy technologies will expand rapidly if all countries follow through on their climate pledges. In the APS in 2030, solar PV capacity additions grow from 420 GW today to 640 GW, and wind capacity more than doubles, up from 115 GW to 240 GW. Battery capacity increases more than fivefold, from 865 GWh to 4380 GWh, and electrolyser capacity from 1 GW to 60 GW. Heat pump capacity more than triples, from 110 GW to 355 GW. However, demand remains concentrated in China, the United States and the European Union, reflecting rapid growth in the sizes of their domestic markets for clean technologies. These regions account for 45-75% of global demand for clean energy technologies in 2030 in the APS, with China alone making up 10-45%.

However, a lack of near-term demand in emerging economies could further increase the investment gap between advanced and emerging economies. Emerging economies are projected to account for 0-10% of announced manufacturing capacity for 2030 on the basis of announced projects, and only 5-25% of deployment in 2030 in the APS. Given the low levels of demand in these countries today, it will be challenging – though by no means impossible – for many EMDEs to create sufficient domestic demand on their own in the near term to attract investment in clean energy technology manufacturing.

Two key pillars can contribute to success towards this aim: first, policy support is needed to build up demand in order to spark meaningful investment in manufacturing capacity. Second, co-ordination between countries can play a crucial role in expanding the size of the market for clean energy technologies. In Association of Southeast Asian Nations (ASEAN) countries, for example, in order to achieve each country’s own climate goals as reflected in the APS, the size of the electric light-duty vehicle market across the ASEAN region needs to grow by a factor of eight to 2030, to around 1.1 million vehicles being sold. This is equivalent to the size of the US EV market in 2023. On its own, Indonesia, as one of the largest markets in the region, reaches around half of the size of this market in 2030. In May 2023, ASEAN leaders signed a declaration to close this gap by working together to develop a regional EV ecosystem, from building regional EV production to improving charging infrastructure.

Figure 29 Share of global deployment for selected clean energy technologies by region in 2023 and in the Announced Pledges Scenario in 2030



Compressing lead times

A regulatory environment that helps to accelerate lead times can be a source of competitive advantage. Commissioning new manufacturing plants is not typically considered a bottleneck in clean energy technology deployment, compared to the time it takes to commission new mining projects, power plants or transmission and distribution infrastructure. Commissioning manufacturing facilities can take anything in the range of 3-4 months (e.g. for solar PV module and cell facilities in China) to more than 3 years (e.g. for polysilicon plants in Europe and the United States) from FID to operation. It is also typical for manufacturing plants to operate at a level of output significantly lower than their maximum rated capacity for the first 1-2 years, while operations are honed. Lead times have a significant indirect impact on the cost of manufacturing, as capital costs still need to be met during the period in which facilities are not generating any revenue (see Chapter 3). Regions with shorter lead times to ramp up manufacturing also have the potential to capture a larger share of the global market in the near term.

Policies to shorten lead times, such as streamlined permitting and clear regulatory frameworks, when combined with adequate resourcing for regulatory agencies, can help provide certainty for contractors, suppliers and investors. This should be balanced against the need to ensure that environmental and social safeguards are part of the process. Lead times for the downstream installations like power plants and storage facilities are also relevant, as any project delays can give rise to uncertainty in manufacturers' order books. Wind power projects are rightly an area of focus for policy makers in this regard. In the European Union, the adoption of the revised Renewable Energy Directive aims to shorten permitting times for certain wind energy installations (to 1 year for onshore projects and 2 years for offshore, with an extension of up to 6 months) and limit the grounds of legal objections to new installations. Moreover, the European Wind Power Action Plan was proposed in October 2023 to support European competitiveness in the wind industry. A key pillar of the plan is improved auction design, as well as improved access to finance, monitoring of unfair trade practices, and skills development.

Grid expansion and modernisation projects can also create uncertainty for clean technology manufacturers. In the United States, insufficient grid capacity to integrate new renewable electricity projects is stifling investment. Average queue lead times there rose from 3 years in 2015 to 5 years in 2022. In the United Kingdom, 120 GW of projects awaiting connection have been offered it only in 2030 at the earliest. Meanwhile, France's backlog of projects has led to connection delays of 22 months. In Brazil, increased development of solar PV and onshore wind has increased grid connection queues and project lead times. Where permitting and connection delays create a lack of visibility on future demand, the resulting delays in investment in domestic manufacturing facilities can, in turn, create insecurity in component supply, further delaying installation projects. In India, higher turbine prices due to supply chain challenges have reduced the bankability of projects that had already concluded their auctions, resulting in delays.

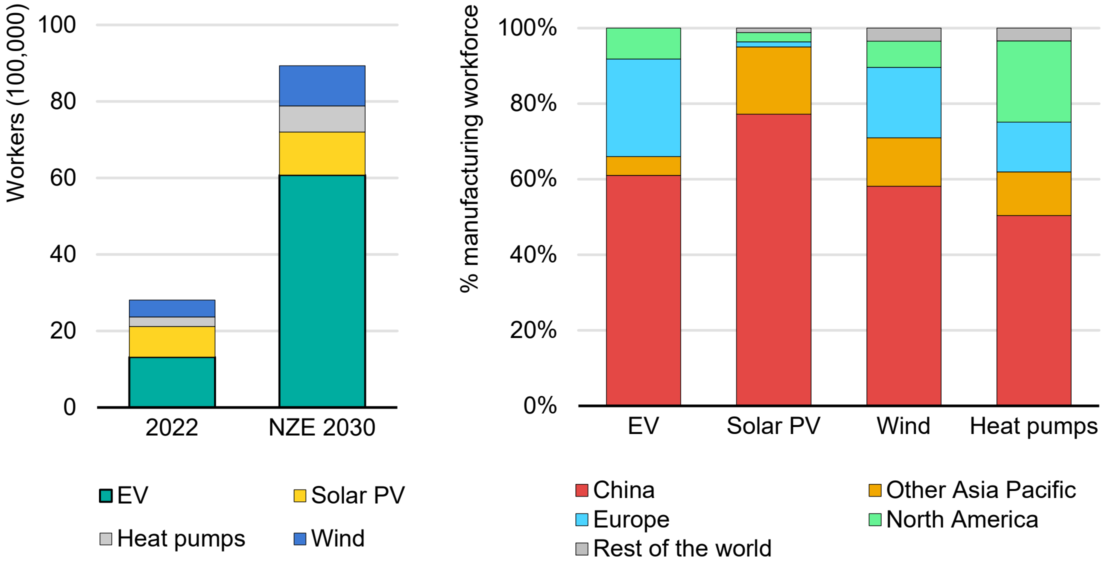
Boosting the availability of skilled workers

The clean energy transition requires a rapid expansion of the energy workforce, with manufacturing clean energy technologies presenting some of the greatest demand for new workers. In the NZE Scenario, manufacturing jobs in electric vehicles, solar PV, heat pumps and wind increase 220% between 2022 and 2030. This is driven primarily by a boom in the workforce for manufacturing electric vehicles and their batteries, with assembly jobs increasing by more than 400% as electric cars come to represent 65% of new car sales by 2030. Wind manufacturing jobs, which accounted for nearly one-third of all jobs in the wind sector in 2022, more than double by the end of the decade. Expansion is slightly more limited for solar PV, where installation represents a greater share of workforce growth, with manufacturing employment increasing by 40% over the same period. Employment in residential heat pump manufacturing grows by approximately 180% to 2030 in the NZE Scenario as deployment accelerates.

Manufacturing facilities in some regions already struggle to attract and maintain adequate staff, and regions with large existing manufacturing workforces have greater potential to retrain workers from other manufacturing sectors in order to more rapidly ramp up clean energy manufacturing to meet future demand. Today, China is home to the majority of manufacturing jobs for all technologies considered in this report, accounting for around 80% of the workforce in solar PV manufacturing, about 60% for wind, electric vehicle and battery manufacturing, and around half for heat pump manufacturing. While Europe boasts a relatively sizeable manufacturing workforce in electric vehicle assembly, and to a lesser extent in wind, workforce numbers in solar PV and battery manufacturing are well behind those of China. Many battery manufacturing companies in Europe already struggle to hire qualified employees locally, often recruiting personnel from Asia to build out their workforces. However, well-established industry players in Asia are also facing difficulties staffing new facilities and hiring sufficient high-skilled specialists such as engineers. To remedy this problem, major firms often rely on transferring existing workers to recently built plants to help with training and upskilling new recruits, resulting in up to 30% of staff in a new plant coming from existing manufacturing facilities.

Availability of skilled workers can constitute a significant bottleneck. In India, only around 3% of the population has undergone formal vocational training (though this figure rises to 17% if informal training is included). This is far from the OECD average of 44% of upper secondary students being in vocational training. As a result, even if the levelised cost of battery production would in theory be lower in India than in China (see Chapter 3), the lack of qualified workers could be a barrier to expansion of manufacturing.

Figure 30 **Number of workers in clean energy manufacturing by technology, 2022, and global employment needs in manufacturing by region and technology in the Net Zero Emissions by 2050 Scenario, 2030**



IEA. CC BY 4.0.

Notes: EV includes both vehicle assembly and battery manufacturing.

Building up a trained workforce to manufacture a new technology takes time, so proactive and strategic labour planning is needed to prevent shortages. Training programmes that target clean energy technologies, such as those proposed as part of the European Commission NZIA, could help build up a skilled workforce. Stakeholders in industry, education and labour relations should collaborate to ensure these training programmes are designed with a view to priority skills and requirements at each supply chain stage, as well as potential synergies across technologies. For example, electrode and polysilicon manufacturing might require more chemical and mechanical engineering skills, while automation and electrochemical engineering skills might be more relevant for battery and PV cell manufacturing. Taking advantage of existing training structures, for example through partnerships between industry and educational institutions, can decrease uncertainties and lead times when building a pipeline of skilled clean energy workers.

Experience with similar technologies already in use can also be leveraged to reduce the time and resources needed to train clean energy manufacturers. For example, a significant portion of the workforce currently manufacturing internal combustion engine (ICE) vehicles may switch to assembling EVs, which are often produced by the same companies. However, these "transfers" are not always straightforward. In EV manufacturing, growth in battery manufacturing jobs has offset declines in other parts of the automotive manufacturing chain. But firms that manufacture components for ICE vehicles are not the same as those that make EV batteries, nor are their production facilities necessarily located in the same regions. For that reason, some regions with large workforces focused on ICE upstream manufacturing are set to lose jobs on a net basis without large-scale investments in EV supply chains.

Even when there is geographic overlap between fossil fuel and clean energy sectors, wage differentials can present another barrier to skills transfer. While wages in the energy sector are generally higher than for comparable occupations in the broader economy, wages in clean energy sectors are often lower than those in fossil fuel sectors. In the United States, for example, ICE powertrain plants may pay as much as USD 10-15 more per hour than vehicle battery plants, despite high labour demand from the latter. To address this obstacle, government funding or incentives for clean energy manufacturing can include contingencies. The Department of Energy's USD 2 billion Domestic Manufacturing Conversion Grants programme is therefore preferencing applications that transfer workers from ICE to EV manufacturing at comparable wages, or that maintain collective bargaining agreements.

Synergies from supply chain integration

Regions that rely on imported components as inputs in their manufacturing processes are more susceptible to shocks and disruptions in component markets and supply than regions with an integrated supply chain. Recent surges in international shipping costs have also led to significant inflation in imported components.

More than in any other region, companies in China have increasingly consolidated manufacturing in each segment of the supply chain over the last decade, particularly in solar PV. China now produces the vast majority of the world's solar PV modules, with large and medium-sized integrated solar PV manufacturers producing three out of every four supply chain products on the market. These firms account for over 90% of global polysilicon, wafer and cell manufacturing capacity, and around 80% of module manufacturing capacity. The cost efficiencies resulting from integration, and the consequent ability to absorb price shocks, allow these firms to produce the lowest-cost solar PV equipment while also introducing labour and manufacturing efficiencies to reduce variable costs. In contrast, PV module manufacturing in the United States, Europe and India depends on imported cells, the cost of which can account for 60-70% of overall module costs.

Similarly, electric vehicle and battery supply chains are highly integrated in China, more so than in the rest of the world, which leads to cost advantages. Chinese manufacturers boast a surplus of electrolyte, anode and cathode manufacturing capacity relative to their domestic production of batteries, opening up potential for exports, while manufacturers in Europe and the United States largely rely on imported components throughout the supply chain (see Chapter 2). These integrated supply chains are part of what enabled Chinese automakers to produce more than half of the electric cars sold worldwide in 2023.

Owing to the significant cost of transporting large components for wind, particularly towers and blades, manufacturing tends to be located closer to demand across the value chain, and supply chains tend to be more integrated at the domestic level.

Reducing supply chain uncertainty with trade agreements

Trade of clean energy technologies is an opportunity to help strengthen emerging markets and create new ones, and to facilitate greater co-operation throughout supply chains. In some cases, relationships that cover the trade of clean technologies may continue under the umbrella of larger, existing agreements. In others, the trade of clean technologies may open the door to new trade partners and create opportunities for a wider group of countries. These existing and new trade relationships must be carefully evaluated in the broader context of a country's industrial strategy.

Recent trade agreements relating to clean technologies have tended to be bilateral, have relied on existing relationships, and have largely focused on critical minerals supply and processing. There has been a concerted effort in different countries worldwide to establish agreements with mineral-rich countries to secure upstream supply chains.

Table 5 Recent agreements on clean energy technology supply chains

Agreement	Description	Type	Signatories	Coverage
Zambia-Democratic Republic of the Congo	Zambia and the Democratic Republic of the Congo signed a co-operation agreement in April 2022 to facilitate development of the **battery supply chain for EVs**. The two countries, both major producers of key critical minerals for EV batteries (cobalt and copper), established a Battery Council to oversee the new agreement. The United States and European Union have also both signed MoUs with each of the two countries.	Bilateral	Zambia, Democratic Republic of the Congo	EV battery supply chain (critical minerals)
Indo-Pacific Economic Framework for Prosperity (IPEF)	Pillar III of the IPEF covers a range of issues critical to transitions to clean economies, including an agreement to **strengthen clean energy supply chains** across markets by building a better understanding of the challenges and vulnerabilities of the region's supply chains and securing more diversified and sustainable sources of critical inputs, including critical minerals or materials for clean energy technologies.	Multilateral	Australia, Brunei Darussalam, Fiji, India, Indonesia, Japan, Korea, Malaysia, New Zealand, Philippines, Singapore, Thailand, United States, Viet Nam	Clean energy supply chains
Australia-Netherlands	Australia and the Netherlands signed an MoU in January 2023 to support the development of a renewable hydrogen supply chain from Australia to Europe.	Bilateral	Australia, the Netherlands	Hydrogen supply chain
ASEAN-Canada Strategic Partnership	In 2023, ASEAN member states and Canada agreed to work together to build new clean energy supply chains under their existing strategic partnership framework established in 2022.	Multilateral	Brunei Darussalam, Myanmar, Cambodia, Canada, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, Viet Nam	Clean energy supply chains

Agreement	Description	Type	Signatories	Coverage
Climate, Critical Minerals and Clean Energy Transformation Compact	In 2023, the United States and Australia signed a compact to accelerate the expansion and diversification of end-to-end clean energy supply chains; promote responsible, sustainable, and stable supply of critical minerals; drive the development of emerging battery technologies; and support the development of emerging markets for clean hydrogen and its derivatives in the respective countries and across the Indo-Pacific.	Bilateral	United States, Australia	Clean energy supply chains; critical minerals

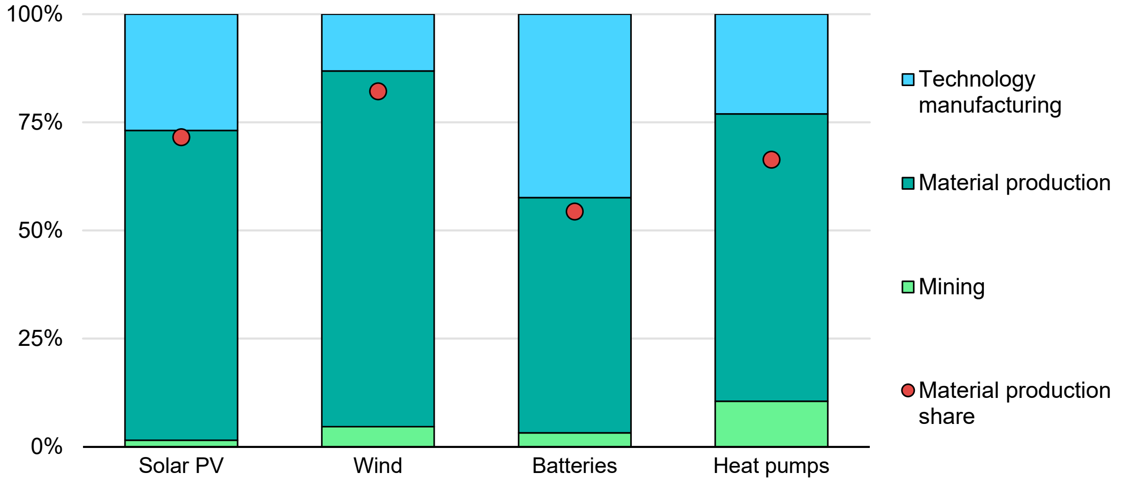
Notes: EV = Electric Vehicle; MoU = Memorandum of Understanding.

Reducing environmental impacts and addressing social considerations

The environmental impacts of clean technology manufacturing and its supply chains could influence the partners that countries and companies choose to work with. Environmental regulation relating to the lifecycle emissions of clean energy technologies, including from mining, material production and transport, can encourage investment in new locations with access to low-cost, low-emissions electricity, or incentivise investment that serves to reduce the emissions intensity of existing operations. Regulation may include caps on lifecycle emissions, emissions intensity-based technical border adjustments, and incentives indexed to lifecycle emissions performance.

Upstream steps of clean technology supply chains today are generally more emissions-intensive than those downstream. The production of materials (e.g. steel, aluminium, copper, nickel) typically generate the largest share of CO_2 emissions across the supply chain for key clean technologies – typically upwards of 60% when including indirect emissions from electricity generation. Technology manufacturing tends not to be as energy- or emissions-intensive as material production, with electricity being the main energy input. For example, the primary factor influencing the carbon intensity of solar PV manufacturing is the share of fossil fuels in a country's electricity generation mix. In addition, water needs for mining and processing the ores and minerals required for clean technologies are often much higher than those required for technology manufacturing.

Figure 31 Share of CO_2 emissions by supply chain segment for key clean technologies



Notes: Includes indirect emissions from electricity generation and the production of chemicals used for mining and material production. Shares derived based on estimates of global average emission and material intensities. An emission factor of 460 g CO_2/kWh (approximately the global average in 2022) is used to calculate emissions from electricity generation. Shares for batteries based on NMC 811 battery chemistry. For batteries, material production refers to material refining, while technology manufacturing refers to cell and pack production, and active material synthesis. Shares for wind based on onshore wind turbine components. Refer to the Technical annex for more details on the analytical boundaries and methodologies used in this analysis.

Regulations that directly target materials production may play a role, as countries aim to source near-zero emissions materials for their clean technology manufacturing base. For instance, regulations that consider emissions intensity improvement can help incentivise material savings all along supply chains. An example is the European Union's Energy Performance of Buildings Directive, which will cap buildings' embodied carbon emissions.

Some countries, including France and Korea, have begun to include the embodied carbon footprint of solar PV panels as a criterion in their competitive tender evaluations for new power plants. Countries with ambitious climate targets are also considering policies for imported renewable energy goods, including solar PV (for example in the European Union and the United Kingdom). In France, since October 2023, EV purchase subsidies available to consumers have been linked to vehicle lifecycle analysis, rather than solely considering the emissions generated during the use-phase of the vehicle. Other countries around the world, including Canada, are considering similar approaches. Such policies favour vehicles manufactured in jurisdictions with access to clean energy – particularly low-emissions electricity – to power their facilities.

As countries look to increase transparency along supply chains, social considerations are also increasingly factored into decision-making on procurement. Public and private sector investors are increasingly demanding greater transparency on critical mineral supply chains, given that mines, processing facilities and refineries carry risks of harm to the environment, workers, communities and societies.

Social and human rights considerations, while generally most widely discussed with reference to critical mineral production, could also play a role in clean technology manufacturing. In March 2024, the European Union reached an agreement on a regulation to ban products from the EU market that are made with forced labour. In June 2021, the US Customs and Border Protection agency issued a Withhold Release Order on shipments containing polysilicon from several producers in Xinjiang, China, due to concerns over human rights and international labour standards.

The use of trade policy to serve non-trade policy objectives, such as with regards to addressing corruption, can also help create a more stable environment for businesses and investors over the longer term.

Part III. Key principles for decision makers

Part I of this report (Chapters 1 and 2) examines the current state of play for clean technology manufacturing. On the one hand, the analysis reveals that encouraging progress is being made, both in monetary terms (with around USD 200 billion invested globally in 2023) and in relation to climate goals, with the global project pipeline of solar PV, battery and electrolyser manufacturing facilities on track to serve NZE Scenario deployment levels in 2030 if all announced projects materialise. On the other hand, the analysis highlights important gaps in the manufacturing project pipeline for wind and heat pump technologies, and persistent levels of geographic concentration that pose risks to security and resilience in clean technology supply chains.

Whichever combination of measures is favoured in countries’ industrial strategies, maintaining competitiveness and improving resilience will be central themes. Part II of this report (Chapters 3 to 5) provides an analytical toolkit for examining trade-offs and complementarities for resilience and competitiveness in three key areas – cost fundamentals, innovation and other non-cost measures. Part III builds on the analysis in each of these areas, providing principles for designing key aspects of industrial strategies. The analysis deliberately stops short of recommending the specific measures these strategies should comprise, as they are highly context and country specific. The principles cover two main areas: The first concerns measures that can be taken domestically, whereas the second pertains to measures that inherently involve collaborating with international partners.

Domestic actions to advance clean technology manufacturing

Prioritise and play to strengths

It is self-evident that governments cannot prioritise everything at once. For most countries, it is simply not realistic to effectively compete in all supply chain steps, or even in parts of all clean technology supply chains. Not only would the costs of the various support measures be prohibitive for countries with higher-cost production or no legacy of leadership in these sectors, but the sizes of many individual economies would be unlikely to accommodate all the requisite investment (see Chapter 1). Understanding relative strengths and weaknesses, and where it might be better to build complementary strategic partnerships with other countries (see below), should be key considerations of industrial strategies for clean technology manufacturing.

Beyond deciding where to focus, it is also important for governments to define what they wish to achieve. Clearly articulating thresholds for success before making any financial commitments gives a government room to cease or redirect support when things do not turn out as hoped. In this domain, more so than in many other energy policy areas, precise outcomes are often highly uncertain, and unintended consequences may arise. Therefore, the ability to experiment and course-correct should be built in from the start. As industrial policy inevitably involves picking winners at a sectoral level, and often at a company level too, governments need to create the political and economic headroom to identify, monitor and manage any “losers” resulting from the policy measures. Many of the oft-cited examples of industrial policy backfire stem from a commitment to a specific measure, firm or project without a clear means of determining or monitoring success. In such cases, precise objectives (e.g. “limit single-supplier dependencies for a given product to less than 50% of annual demand”) are preferable to broadly defined ones (e.g. “improve national security”).

Attract and support innovators

Hosting researchers and other innovators can have multiple benefits for a country. Chief among these is the strong link between innovation and domestic manufacturing that is at the cutting edge of technical advances, able to withstand competition from regions with low-cost inputs and able to command a premium price. Other benefits include the ability to attract highly educated workers and the spillovers that accrue from co-location of innovative firms, raising the combined and individual productivity of clustered firms more quickly. Governments can use a combination of direct and indirect measures to support clean technology manufacturing innovation. Indirect measures, which can be very effective, involve making the market for successful clean technologies larger, more differentiated or more dependable.

Direct support for innovation – including R&D grants, tax incentives, start-up incubation, knowledge sharing and demonstration project finance – enables support to be allocated to important challenges or high-potential domestic capabilities. In Chapter 4 we identify several potential “missions” for direct innovation policy to advance clean technology manufacturing: high-quality designs that avoid scarce or unreliable mineral supplies; products with low emissions intensity; products with attributes that target the next waves of consumer demand; and alignment of R&D advances across value chains.

Plug cost gaps strategically and for the long term

Governments may deem it appropriate to subsidise or otherwise provide direct financial support to manufacturing operations or investments. The intention is typically to lower the costs faced by manufacturers and thereby raise their competitiveness, usually by redistributing costs from private to public balance sheets. This may well be warranted in certain circumstances, but governments have limited balance sheets just as private sector actors do, and every subsidy comes with opportunity costs.

Aside from innovation, which is not usually a short-term option, there are some measures that can help fundamentally reduce the total cost for all stakeholders. Chapter 5 explores several such “low regret” options that come without significant production or investment subsidies. Reducing lead times through enhanced permitting procedures reduces transaction costs, project risks and consequently the interest paid on monies committed during the early stages of a project. While some aspects of upskilling or reskilling workforces are costly outlays, targeted training programmes and certification schemes can increase productivity and alleviate costly skilled labour shortages.

International co-operation to support domestic investment and global progress

Collect data and track progress

It is difficult to manage what is not measured, and the current state of data availability on clean technology manufacturing makes accurate measurement challenging. Much of the data used in Chapters 1-3 of this report are from proprietary sources, which can have gaps in their coverage and require significant post-processing and analysis. Policy makers may often be left with two or more conflicting data points or trends. Efforts to improve data collection can be advanced to a certain extent by national statistical offices and agencies. But to obtain effective, granular comparisons between technologies and along supply chains, governments could benefit from co-operating on data collection efforts internationally.

One specific area that deserves prompt attention are the international systems for collecting production and trade data for clean technologies and their components. As described in Chapter 1, internationally adopted frameworks for collecting statistics on industrial activity currently lack the detail to be able to isolate individual clean technologies and their components. Individual countries’ customs authorities and other national bodies already collect data at higher levels of granularity, but often not in a harmonised manner. Tried and tested frameworks like the ISIC and HS already exist and should be adapted to incorporate sufficient detail on production activity and products, but further data on clean technology manufacturing (e.g. energy use, physical production quantities, emissions foot-printing, investments, costs, employment) should also be sought and harmonised by governments internationally.

Co-ordinate efforts across supply chains

Much attention is now paid – quite rightly – to the security of supply of critical minerals, but any supply chain is only as strong as its weakest link. Governments should co-ordinate the work they are doing at each stage in the supply chain to increase overall resilience and avoid unwanted duplication, examining remaining gaps that may lead to bottlenecks. Wherever possible, governments should co-ordinate efforts to enhance the resilience of supply chains.

This collaboration can cover many specific areas and take many forms. Sharing best practice in the appropriate fora and at an appropriate level of detail is an important vehicle for collaboration. This could include domestic experience with creating favourable investment conditions at home or abroad, accelerating permitting, designing effective and efficient environmental regulation and stockpiling of input materials and components. “How-to-guides” for developing industrial strategies could be a method of disseminating such efforts and experiences among countries. Beyond sharing experience, governments can also collaborate on the ground. Efforts to reduce the costs of financing for capital-intensive components of supply chains in developing economies, by, for example, pooling investments, is an area where many hands can make for lighter work.

Identify and build strategic partnerships

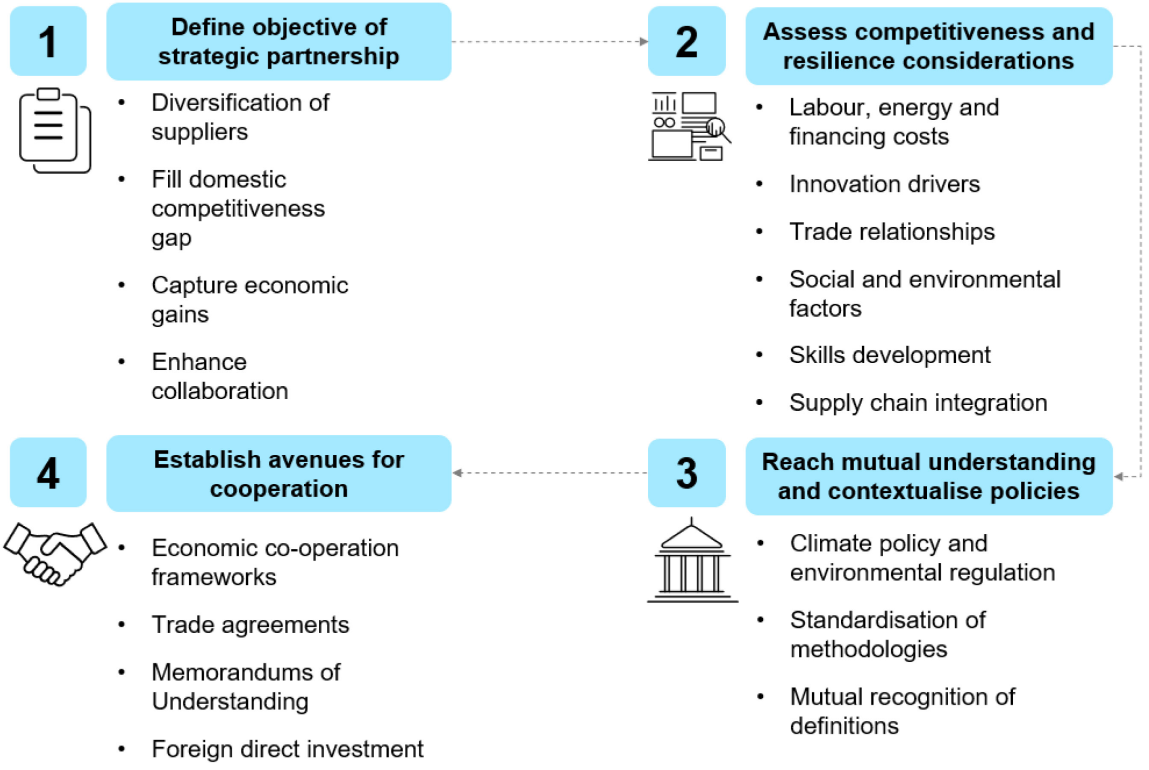
Strategic partnerships are a way for countries to increase resilience in areas of manufacturing supply chains where domestic production may otherwise be uncompetitive. At the same time, such partnerships can facilitate investment in EMDEs. An appropriate balance should be sought between export opportunities and support for in-country clean energy transitions and socioeconomic development. Risks can be mitigated by developing a systematic framework for identifying and evaluating potential partnerships, rather than proceeding ad-hoc.

Establish a framework for co-operation

It is not always easy for countries to co-operate on interventions that need to balance the domestic interests of two or more parties with the larger goal of accelerating the clean energy transition. Having a general framework for co-operation that takes into account competitiveness factors, trade relationships, and social, environmental and developmental considerations can help countries identify the right strategic partner. At a minimum, this framework could include:

- **Definition of objective**: Identifying strategic partners starts with defining the objective of the partnership. For some countries the objective may be to increase the number of suppliers at a certain step in the supply chain; for others it may be to fill a domestic competitiveness gap, or to find new export markets.
- **Competitiveness and resilience considerations**: The next step is to gauge factors that will have a bearing on domestic competitiveness and resilience. Part II of this report provides an analytical toolkit for examining some cost and non-cost factors.
- **Mutual understanding**: It is important that countries come to an agreement on the definitions and methodologies that underpin the deployment of clean energy technologies, particularly their upstream inputs like low-emission fuels and materials.
- **Avenues for co-operation**: Existing investment and economic co-operation frameworks, as well as trade agreements, are good "off the shelf" starting points for strategic partnership discussions. Memoranda of Understanding (MoUs) and Foreign Direct Investment (FDI) are potentially more expedient routes to collaboration, where no existing trade agreements are in place.

Figure 32 Framework for establishing strategic partnerships



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Potential processes and outcomes

There are several types of outcomes and processes that countries may choose to pursue; each one determined by the objective that a country is hoping to achieve in the context of its larger industrial strategy. Different outcomes could occur depending on the stage of the above framework. For instance, as countries assess competitiveness and resilience considerations, they may choose to partner with other countries through offtake agreements or co-investment in a project. As countries work to establish a mutual understanding, pursuing discussion through multilateral dialogues could be an option. Below is a sample of the types of outcomes and processes.

Offtake agreements across the supply chain

In general, this type of partnership is based on where individual countries may sit along clean technology supply chains. It involves finding a partner country that is at another step in the chain to purchase or offtake a product. This type of partnership can provide investment security for the exporting partner to develop capital-intensive clean energy projects, and provide supply security for the importing partner that may not be able to produce that product competitively.

Such trade agreements are common between companies, but in some cases can also involve government institutions that are looking beyond their borders to fill in supply chain gaps. For hydrogen, one of the most developed support mechanisms of this kind is the H2Global double-auction programme initiated by Germany. A market intermediary conducts an auction to purchase hydrogen from suppliers outside of the European Union through fixed price contracts, then a separate auction is conducted to sell the hydrogen to interested buyers. Using public funds, the market intermediary covers the price differential. The programme is not limited to Germany – in fact the Netherlands announced it will dedicate EUR 300 million in subsidies to use H2Global.

For EVs, this could mean that a country that manufactures EVs enters into a strategic partnership with another country that can provide anode and cathode materials needed for EV batteries. For example, Zambia and the Democratic Republic of Congo signed a co-operation agreement in April 2022 to facilitate development of the battery supply chain for EVs. The agreement is expected to provide a framework for bilateral co-operation between these two countries, who are major producers of cobalt and copper, key critical minerals used in EV batteries. The United States and European Union have each signed MoUs with these countries in an effort to secure EV battery supply chains.

On a more detailed level, taking into consideration social and environmental factors, that same EV manufacturing country may place additional demands on its suppliers to provide increased transparency on the mineral and material inputs.

For instance, requiring certain labour standards are met for critical mineral extraction, or opting for near-zero emission steel.

Co-investment and development of a project

This type of partnership involves a shared financial commitment between the two countries in order to reach a certain level of scale. In this case, a country may choose to invest in a facility or project located in another country, typically through direct foreign investment mechanisms, allowing risk to be shared across the countries. In some cases, this type of partnership could be driven by industry, where a company identifies its specific needs along the supply chain; in other cases this could be expanded under a larger government-led strategy to include a set of projects or targeting a specific sector.

This type of partnership in the energy sector is not new; the initial scale-up of the liquified natural gas (LNG) market showed that importers seeking access to new supplies shared much of the risk with the operators of export infrastructure. Japan was a frontrunner in the development of the LNG market, and it held a 75% share of global LNG trade through to the late 1980s due to its active development of contracting and co-investment.

Partnerships based on co-investment and development could help more nascent supply chains scale up, and simultaneously aid the development of supporting infrastructure that underpin those supply chains. One example of this type of partnership is the direct investment in a project in exchange for part of that project's output. At the country level this is typically done through state-controlled enterprises. For example, over the years China has directly invested in cobalt mines and supporting infrastructure in the Democratic Republic of the Congo (DRC) to feed its metal refining capabilities. Consequently, the DRC supplies China with nearly all of its mined cobalt needs and it is estimated that one-third of China's imported intermediate products are from mines or smelters in which it has a stake.

Another example is to leverage development funding as a means to support a nascent industry in a partner country. This is the case with the proposed HYPHEN Hydrogen Energy project in Namibia, a massive complex that will use solar and wind power to produce electrolytic hydrogen. The proposed project, which aims to export the hydrogen in the form of liquid ammonia, has received, or is in the process of receiving, funding from a variety of international sources, including the European Commission, the Netherlands and the United States.

Multilateral dialogues

Establishing a multilateral dialogue on certain clean technology manufacturing topics may be a potential option to ensure consistency and standardisation across supply chains. International organisations and fora are natural avenues for countries to discuss supply chain questions, share best practices and experiences, and co-ordinate assessments.

Multilateral dialogues can be used as a way to remove barriers to the trade of clean energy technologies. For example, a lack of clarity surrounding what constitutes low-emissions materials, such as steel and cement, can prevent countries from procuring these materials if there is commonly agreed standard. The IEA's Working Party on Industrial Decarbonisation, established in 2023, is working to address this barrier by providing a platform for policy officials to discuss common measurement methodologies. Multilateral dialogues can also provide alignment on standards for other technologies and fuels, such as the production of low-emissions hydrogen, or monitoring, reporting and verification requirements for carbon removal technologies. Without internationally agreed-upon definitions and approaches, there is a risk that fragmentation in the global market may hinder global trade. Equally important is the *recognition* of such standards and definitions in domestic procurement decisions.

In addition, as some countries and regions finalise subsidies for domestic clean technology industries, discussions at the multilateral level can provide a platform to discuss trade concerns and enhance regulatory co-operation. For example, the WTO Technical Barriers to Trade (TBT) Committee works to clarify proposed trade measures and enhance alignment with international standards, and could act as a valuable forum for technical discussions on trade-related aspects of carbon measurement methodologies and verification procedures.

Technical annex

Manufacturing capacity, output and demand

Unless otherwise specified, manufacturing capacity and output figures are stated on an annual (i.e. GW or GWh per year) basis, and in direct current (DC) terms where relevant. Capacity refers to the maximum rated capacity of the facility. Default utilisation rates of 85% are used to derive output from capacity, or vice versa, for 2022-2023, where data for one of these quantities are lacking.

Utilisation rates of 85% are also used to derive forward-looking quantities of output from existing and announced projects such that a comparison can be made with deployment levels in IEA scenarios (see Box 4 and Box 5 in Chapter 2 for a description of the scenarios and manufacturing data categories used in this report). This level of utilisation is to be interpreted as a practical maximum, and not as a level that is reflective of all current operations.

In instances where no specific component in a multi-step supply chain is specified, manufacturing capacity and output figures are stated for the final step. For example, “solar PV manufacturing capacity”, stated without reference to cells, wafers or polysilicon, refers to the module assembly (final) step. For batteries, the final step considered in this analysis is cells. For wind, where the components are in parallel, nacelles are used as the default capacity/output figure.

Demand numbers for all technologies are approximated using deployment figures from IEA scenarios in the same year, unless otherwise specified. This is a simplification for comparative purposes, as not all manufactured units are installed the same year they are produced.

Beyond these cross-cutting factors, there are a number of technology-specific considerations for the analytical boundaries used in the analysis.

Solar PV

- Capacity and output figures are stated for each step in the supply chain in series – polysilicon, wafers, cells and modules.
- Ingot production is included within the wafer production step, with all capacity and output figures stated for wafers.
- A polysilicon material intensity of 2.9 g/W is used for stating polysilicon in power units.
- Metallurgical grade silicon production is not considered within the boundary of our analysis.

- Demand for solar PV corresponds to total module installations (rooftop and utility scale) in the same year.
- In this report there has been an update to the method for splitting the committed and preliminary announced capacity since the last iteration of this analysis. Specifically, the announced capacity that is due to come online within the next 1-2 years (i.e. up to end 2025) for modules, cells and wafers, and 2-3 years for polysilicon (i.e. up to end 2026) is considered "committed" and the rest as "preliminary".
- All PV-related capacity numbers are expressed in DC.

Wind

- Capacity and output figures correspond to the final manufacturing step for the three components considered in parallel: nacelles, blades and towers, including both onshore and offshore units.
- Upstream sub-components such as generators and gearboxes are not included within the scope of the analysis, and the figures therefore do not reflect the capacity or output at these points in the supply chain. Foundations are not included within the scope.
- Only dedicated facilities for manufacturing towers are included, with the exception of China, where we assume that an apparent capacity shortfall is being addressed using generic steel fabrication facilities, which are included within the capacity figures.
- Demand for wind corresponds to total wind power installations (onshore and offshore) in the same year.

Batteries

- The supply chain steps considered in the analysis are cells, anodes and cathodes.
- Other components like electrolytes, foils, separators and casings are not included in the analysis of capacity, output and demand.
- The capacity stated for anodes and cathodes corresponds to the facilities for making the active material in these components.
- All tiers of battery manufacturing facilities (I-III), indicating both battery manufacturers certified to serve the EV and stationary market, and manufacturers currently certified to serve the stationary storage market only, are included in the capacity and output figures.
- Only lithium-ion batteries are included within the scope of this analysis.
- Demand for batteries includes both electric vehicle and stationary storage applications, but excludes other segments like consumer electronics, which in 2023 accounted for less than 10% of demand, and which is projected to represent a minor (<5%) share of battery demand in 2030 and beyond.

Electrolysers

- Only the final assembly step is considered for capacity and output figures.

- Capacity figures for 2022-23 include facilities used to produce brine electrolyser units for the chlor-alkali industry.
- The capacity and output figures do not speak to the capacity of the upstream components such as electrodes.
- All major electrolyser technologies (including alkaline, proton exchange membrane, solid oxide electrolysis and others) are included in the capacity and output figures.
- Demand for electrolysers corresponds to electrolysis plant installations in the same year.

Heat pumps

- Only the final assembly step is considered for capacity and output figures.
- These figures do not speak to the capacity of the upstream components such as compressors.
- Only heat pumps for residential and commercial buildings for space heating and/or hot water provision are included in the analysis.
- Reversible air conditioners are included where they are used as primary heating equipment, i.e. they are not complementary to other equipment such as a boiler.
- Industrial heat pumps are excluded.

Levelised costs of manufacturing

The analytical boundaries used to assess levelised costs of manufacturing (see Figure 33) are broadly similar to those used in the assessments of capacity, output and demand (see above). There are some important exceptions. Only the manufacturing facility for an electrolyser stack assembly is included. All costs associated with manufacturing the other components that form the balance of plant for an electrolysis system (e.g. rectifiers, inverters etc.) are excluded. For batteries, the focus remains on cells, but foils, separators, electrolytes, binders and casings are also included in the “Other components” cost category for cells.

In instances where the technology category (e.g. wind) comprises multiple designs or characteristics (e.g. onshore and offshore), the general approach to reflecting this in our indicative manufacturing cost estimates is to use a deployment-weighted average. This also applies to battery chemistries, which are summarised in the latest edition of the Global Electric Vehicle Outlook. For electrolysers, the levelised cost calculations are based on a plant producing alkaline units.

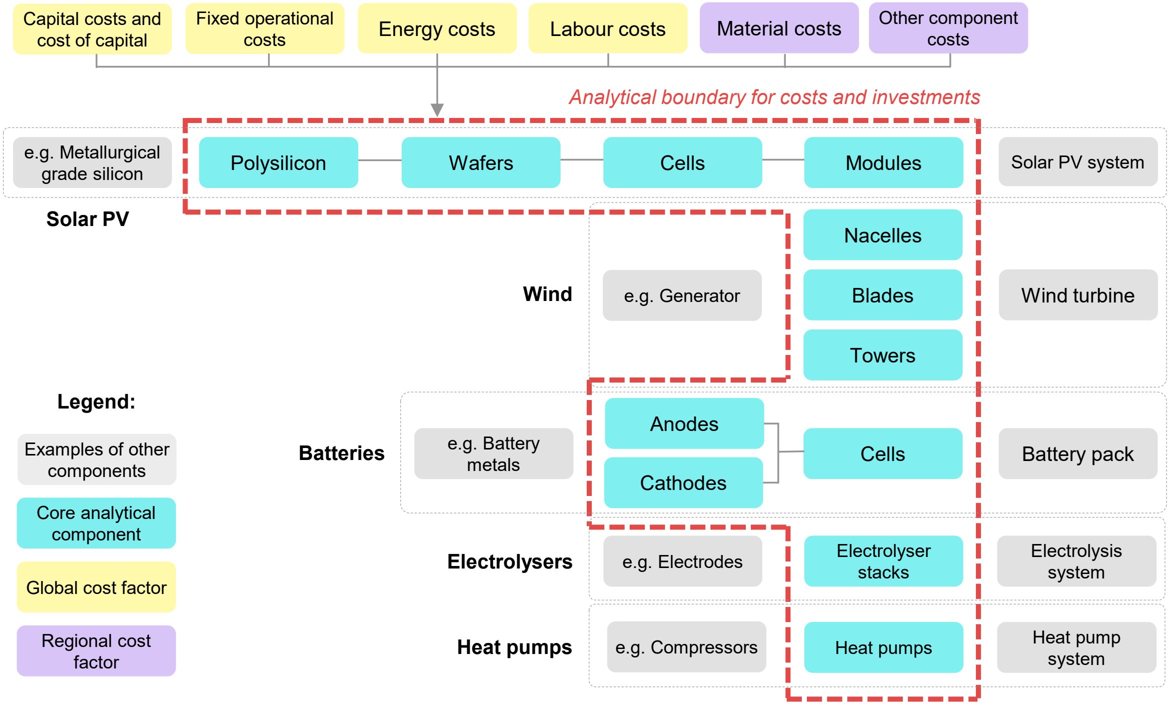
Beyond these specific considerations for individual technologies, the common elements of the levelised cost calculations are as follows:

- Unit capital expenditure is derived on an overnight basis using a sample of outturn costs and capacities for more than 750 plants (see Box 6 in Chapter 3 for a description of the analysis of capital costs) and is differentiated regionally.

- Annual fixed operational expenditure is assumed to be 5% of the overnight capital expenditure.
- Material intensities and global average material prices in 2023 are used to calculate material costs.
- Energy intensities and regionally differentiated end-user prices in 2023 for electricity and natural gas are used to calculate energy costs.
- Labour intensities and regionally differentiated manufacturing wages for the most recent year available are used to calculate labour costs.
- Other components are accounted for as a subset of material costs, and global average prices are used where relevant, except where a component directly upstream falls within the boundary of our analysis (e.g. polysilicon for wafer production).
- To aid comparability, an 85% utilisation rate, a 25-year depreciation period and an 8% weighted adjusted cost of capital are used to compute all levelised costs.

Levelised costs exclude profit margins, expenses associated with company R&D, and other overheads, and do not reflect supply and demand dynamics. Levelised manufacturing cost estimates are therefore not intended to align with market prices for finished units.

Figure 33 Scope of analytical assessment for manufacturing cost and investment calculations



Notes: PV = Photovoltaic.

Manufacturing investment spending

Manufacturing investment spending is calculated using the same analytical boundary for overnight unit capital expenditure (USD/kW or USD/kWh of annual capacity) as that for calculating levelised costs of manufacturing (see above). Overnight capital costs are multiplied by capacity additions (GW or GWh of annual capacity) for each technology to obtain overnight investments (USD). Investment spending (USD) is derived from overnight investments using the assumption of an even distribution of expenditure over the period between final investment decision (FID) and the start of operations. This period is assumed to be 2 years for all technologies and components considered in the analysis, apart from solar PV modules and cell facilities, for which we assume a period of 1 year.

Data sources

The table below summarises the main external data sources used in this report, which are supplemented by desk research and personal communications with manufacturers and other technology experts. IEA scenario and modelling data from the Global Energy and Climate Model are used in conjunction with the data below.

Table 6 Description of the main data sources used in this report

Technology	Data sources	Description
Solar PV	InfoLink, BNEF, IEA PVPS, SPV Marker Research, RTS Corporation	InfoLink data is the primary source for capacity and output data, supplemented by BNEF for cross-checking.
Wind	S&P Global Commodity Insights, BNEF, GWEC, WindEurope, Wood Mackenzie and NREL	S&P Global Commodity Insights is the primary data source for capacity and output data, which are supplement with data from WindEurope, BNEF and GWEC. The Wind Supply Chain series from Wood Mackenzie and NREL studies were used to inform the assessment of levelised costs.
Batteries	BMI, EV-Volumes, BNEF	BMI is the primary data source for current and projected battery cell manufacturing capacity and for classifying announcements as committed or preliminary. BNEF is used as a supplementary source. EV-Volumes is the primary data source used to assess demand for EV batteries.
Electrolysers	Primary research	Manufacturing capacity data are based on announcements by manufacturers and personal communications, gathered by the IEA.
Heat pumps	UN Comtrade, Oxford Economics Trade Prism	Manufacturing capacities are derived combining heat pump sales in different regions and trade flows based on Oxford Economics and UN Comtrade. Manufacturing capacity additions and expansion plans are based on public announcements by manufacturers.

Technology	Data sources	Description
Other	Bloomberg, IEA World Energy Prices, ILOSTAT	Bloomberg is the primary source for information on material prices; IEA data are used for end-user prices for energy and ILOSTAT data are used to calculate labour costs. Academic literature is consulted to derive material, labour and energy intensities and to benchmark results for levelised cost.

Note: Many of the data sources are only accessible via subscription – in these instances a link to the data provider's website is provided.

Abbreviations and acronyms

AEM	anion exchange membrane
ALK	alkaline electrolyser
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
CBAM	Carbon Border Adjustment Mechanism
CCUS	carbon capture, utilisation and storage
COP	Conference of the Parties
CO_2	carbon dioxide
CTM	clean technology manufacturing
DRC	Democratic Republic of Congo
DWE	decoupled water electrolysis
EMDE	emerging markets and developing economies
EPO	European Patent Office
ESG	environmental, social and governance
EUR	Euro
EUV	extreme ultraviolet lithography
EV	electric vehicle
FDI	Foreign Direct Investment
FEOC	Foreign Entities of Concern
FID	final investment decision
GDP	gross domestic product
GEC	Global Energy and Climate
HS	Harmonized System
ICE	internal combustion engine
IDR	Indonesian rupiah
ILOSTAT	International Labour Organization Department of Statistics
IPCEI	Important Projects of Common Interest
IPEF	Indo-Pacific Economic Framework for Prosperity
IRA	Inflation Reduction Act
ISCO	International Standard Classification of Occupations
ISIC	International Standard Industrial Classification of All Economic Activities
ITC	Investment Tax Credit
KRW	Korean won
LFP	lithium-iron phosphate
LNG	Liquified Natural Gas
MEC	microbial electrolysis cell
MoU	Memorandum of Understanding
NH_3	ammonia
NMC	lithium nickel manganese cobalt oxide
NZE	Net Zero Emissions by 2050 Scenario

NZIA	Net-Zero Industry Act
OECD	Organisation for Economic Co-operation and Development
PEM	proton exchange membrane
PLI	Production Linked Incentives
R&D	Research & Development
SMR	small modular reactor
SOEC	solid oxide electrolyser cell
TBT	Technical Barriers to Trade
TOPCon	Tunnel Oxide Passivated Contact
UN	United Nations
USD	United States dollar
VA	value added
VAT	Value Added Tax
VC	venture capital
WACC	Weighted Average Cost of Capital
WTO	World Trade Organization

Units

g CO_2/kWh	grammes of carbon dioxide per kilowatt-hour
GW	gigawatt
GWh	gigawatt hour
kg/MW	kilogramme per megawatt
kW	kilowatt
kWh	kilowatt-hour
m	metre
m^2	square metre
MW	megawatt
MWh	megawatt-hour
t	tonne
TWh	terawatt-hour
W	watt
Wh/kg	Watt-hour per kilogramme

International Energy Agency (IEA)

Unless otherwise indicated, all material presented in figures and tables is derived from IEA data and analysis.

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