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Strengthening India's Clean Energy Supply Chains

Building Manufacturing Competitiveness in a Globally Fragmented Market

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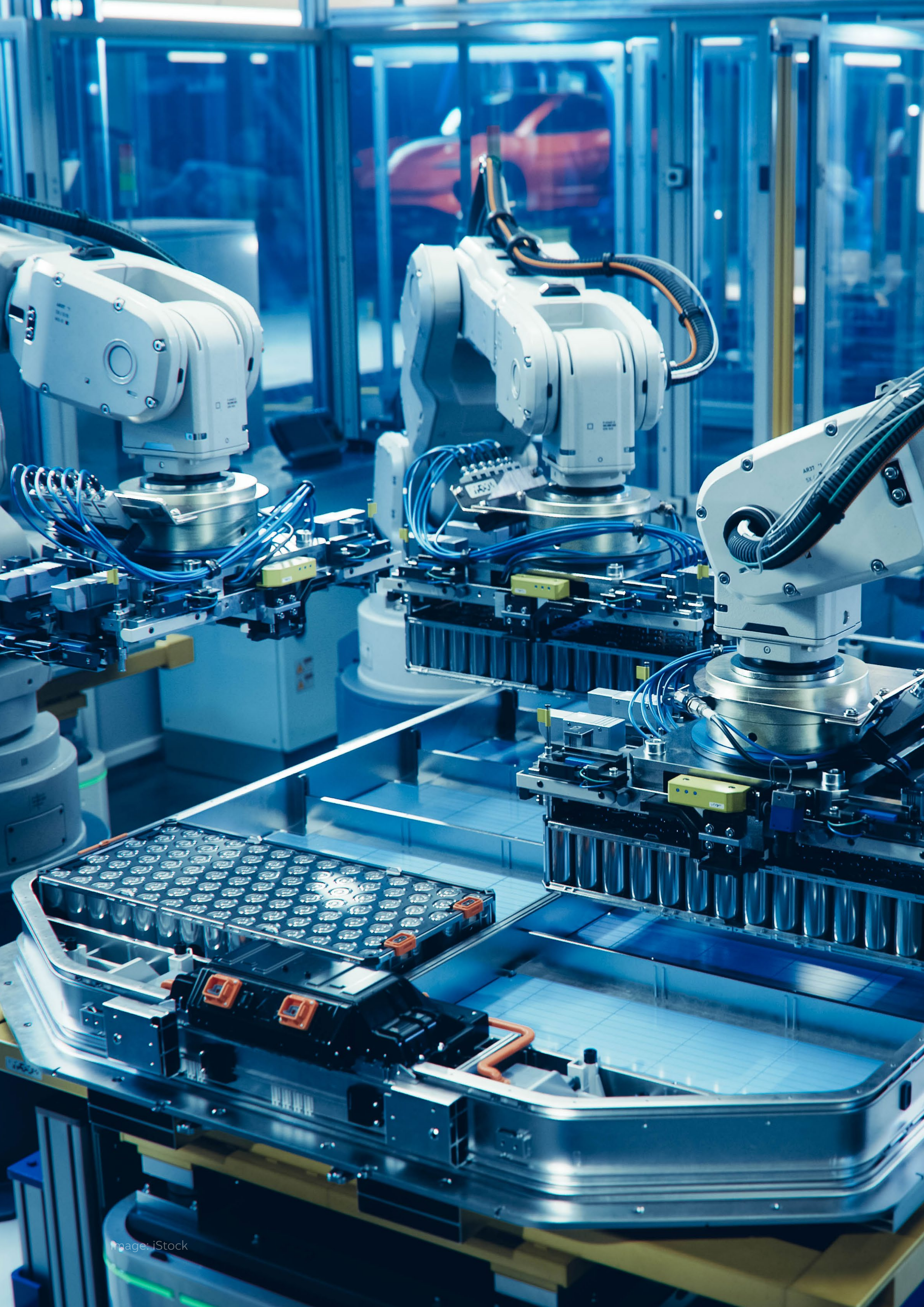

भारत सरकार
नवीन और नवीकरणीय ऊर्जा मंत्रालय
GOVERNMENT OF INDIA
MINISTRY OF NEW AND RENEWABLE ENERGY

सत्यमेव जयते

Dinesh Dayanand Jagdale
Joint Secretary

Date: 06th September 2024

FOREWORD

The world is dealing with the dual challenge of mitigating climate change and fostering economic growth, making the strategic importance of clean energy more pronounced than ever. India is on a rapid development trajectory and is expected to be the third-largest economy by 2030. For India, the challenge extends beyond mere growth; it is about securing an economically viable, strategically secure, and environmentally sustainable future.

This report, prepared by the Council on Energy, Environment, and Water (CEEW), and supported by the Asian Development Bank and Bloomberg Philanthropies, critically examines the strategic value of deepening clean energy manufacturing in India, emphasising that India's current approach may need to be amplified in a fiercely competitive global market. In the post COVID-19 scenario and further global economy marked by geopolitical tensions, large, developed economies with substantial fiscal resources are increasingly influencing global clean energy markets through a renewed focus on industrial policy. To counter balance this global race India would need a continued strategic focus to develop a strong clean energy value chain.

The key question to address is: which segments of the supply chains should India prioritise? On what criteria should these decisions be based? What should India's indigenisation strategy for the clean energy sector look like? Addressing these questions is essential for developing a focused agenda that identifies key supply chain segments for Indian policymakers to support, thereby maximising strategic value to the Indian economy. As India stands at the intersection of decision-making for development and sustainability, a nuanced and strategic approach to clean energy manufacturing is imperative—one that aligns with the nation's long-term economic goals and global environmental commitments.

I commend the Council on Energy, Environment, and Water (CEEW) for building on the MNRE-CEEW G20 report - *Developing Resilient Renewable Energy Supply Chains for Global Clean Energy Transition* which was published under India's G20 presidency. This timely in-depth analysis of the clean energy manufacturing landscape, distilling complex dynamics into actionable findings and recommendations can be a vital resource for policymakers, industry leaders, and stakeholders as India seeks to leverage its inherent strengths while addressing its strategic vulnerabilities in the clean energy sector. The insights and recommendations offered here are not only relevant to India but also provide valuable guidance for other countries aiming to build globally competitive clean energy value chains.

We hope this report will stimulate informed decision-making and collective action to rapidly scale up clean energy manufacturing, delivering significant benefits to the economy, the environment, and, most importantly, to our citizens.

Jagdale
06/09/2024

(Dinesh Dayanand Jagdale)

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About CEEW

The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses **data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources**. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW is a strategic/ knowledge partner to 11 ministries for India's G20 presidency.

The Council's illustrious Board comprises Mr Jamshyd Godrej (Chairperson), Mr S. Ramadorai, Mr Montek Singh Ahluwalia, Dr Naushad Forbes, and Dr Janmejaya Sinha. The 330+-strong executive team is led by Dr Arunabha Ghosh. CEEW has repeatedly featured among the world's best managed and independent think tanks.

In over 14 years of operations, The Council has engaged in over 450 research projects, published 440+ peer-reviewed books, policy reports and papers, created 190+ databases or improved access to data, advised governments around the world 1400+ times, promoted bilateral and multilateral initiatives on 130+ occasions, and organised 590+ seminars and conferences. In July 2019, Minister Dharmendra Pradhan and Dr Fatih Birol (IEA) launched the CEEW Centre for Energy Finance. In August 2020, Powering Livelihoods — a CEEW and Villgro initiative for rural start-ups — was launched by Minister Piyush Goyal, Dr Rajiv Kumar (then NITI Aayog), and H.E. Ms Damilola Ogunbiyi (SEforAll).

The Council's major contributions include: Informing India's net-zero goals; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, *Swachh Bharat*; pathbreaking work for India's G20 presidency, the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the first independent evaluation of the *National Solar Mission*; India's first report on global governance, submitted to the National Security Advisor; support to the National Green Hydrogen and Green Steel Missions; the 584-page *National Water Resources Framework Study* for India's 12th Five Year Plan; irrigation reform for Bihar; the birth of the Clean Energy Access Network; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); India's largest multidimensional energy access survey (ACCESS); critical minerals for *Make in India*; India's climate geoengineering governance; analysing energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka, and Viet Nam. CEEW published *Jobs, Growth and Sustainability: A New Social Contract for India's Recovery*, the first economic recovery report by a think tank during the COVID-19 pandemic.

The Council's current initiatives include: State-level modelling for energy and climate policies; consumer-centric smart metering transition and wholesale power market reforms; modelling carbon markets; piloting business models for solar rooftop adoption; fleet electrification and developing low-emission zones across cities; assessing green jobs potential at the state-level, circular economy of solar supply chains and wastewater; assessing carbon pricing mechanisms and India's carbon capture, usage and storage (CCUS) potential; developing a first-of-its-kind Climate Risk Atlas for India; sustainable cooling solutions; developing state-specific dairy sector roadmaps; supporting India's electric vehicle and battery ambitions; and enhancing global action for clean air via a global commission 'Our Common Air'.

The Council has a footprint in over 20 Indian states, working extensively with 15 state governments and grassroots NGOs. Some of these engagements include supporting power sector reforms in Uttar Pradesh, Rajasthan, and Haryana; energy policy in Rajasthan, Jharkhand, and Uttarakhand; driving low-carbon transitions in Bihar, Maharashtra, and Tamil Nadu; promoting sustainable livelihoods in Odisha, Bihar, and Uttar Pradesh; advancing industrial sustainability in Tamil Nadu, Uttar Pradesh, and Gujarat; evaluating community-based natural farming in Andhra Pradesh; and supporting groundwater management, e-auto adoption and examining crop residue burning in Punjab.

Contents

Clean energy manufacturing provides opportunities for decarbonisation, while also boosting energy independence, enhancing value addition, and generating positive externalities on growth and innovation.

Image: Lohum

Executive summary

The pace of deployment of clean energy is increasing at an unprecedented rate every year. Presented with the opportunity to produce for both domestic and international markets, clean energy manufacturing in India is poised at a critical juncture. In a fragmenting global market, India possesses the potential to become a globally competitive manufacturing hub. However, this opportunity is also accompanied by several risks arising from global manufacturing overcapacities, razor-thin profit margins in the post-COVID economy, and uncertainties associated with domestic demand. These risks threaten the investments of USD 4.56 billion (INR 36,492 crore) committed by governments to catalyse this nascent sector through *Production-linked incentive* (PLI) schemes.[1] Strategic policy choices made now will determine whether Indian manufacturers of clean energy technologies emerge as world leaders or remain reliant on continuous government support in the short to medium term.

Targeted policymaking is essential to align economic prospects of indigenisation with India's energy security and energy transition goals

Precisely targeted policymaking is essential to align the wide-ranging economic prospects of indigenisation with India's energy security and energy transition goals. Therefore, we critically evaluate the strategic value of deepening clean energy manufacturing in this report, and assess the efficacy of central government policies at realising this value. We argue that the conventional industrial and trade policy tools instituted so far can prove inadequate in securing the myriad strategic advantages of this sector, given the intense competition across various segments of the supply chain, and the larger fiscal capacities of other developed economies. We aim to fill these gaps by providing a nuanced rationale and a methodological approach for advancing the indigenisation of this sector in India.

Recognising that industrial development is a gradual process contingent on a country's existing production capabilities, we utilise product space mapping analysis to identify segments of the supply chain that India should prioritise in its indigenisation strategy. We complement this with a bottom-up analysis based on stakeholder engagements, discussions with industrial players, and literature reviews to complete the identification exercise. Identification of the relevant supply chain segments is hence based on a comprehensive and methodological approach, taking into account their complexity, competitiveness, impact on the total cost of the final technology/product, and potential to open up pathways into more complex sectors.

To ensure a focused analysis, we deep-dive into three key clean energy technologies –solar photovoltaics, onshore and offshore wind turbines, and lithium-ion batteries. Each has a mature manufacturing sector globally as well as an existing demand base in India, offering

1. Solar PLI 1: INR 4,455 crore; solar PLI 2: INR 13,937 crore; ACC PLI: INR 18,100 crore, as published by Ministry of New and Renewable Energy (MNRE), and Ministry of Heavy Industries (MHI).

relevant insights to scale these sectors rapidly. We also touch upon certain alternate solar, wind, and battery technologies where relevant to the discussion. However, we have not assessed the supply chains for clean energy technologies such as green hydrogen or biofuels in this study. By addressing the strategic imperatives and identifying key areas for policy intervention for select technologies, we aim to provide targeted recommendations for India – and possibly other developing countries – to build sustainable, future-oriented, globally competitive clean energy value-chain segments.

A. Why should India prioritise clean energy manufacturing?

Clean energy manufacturing not only offers pathways for decarbonisation, but can also enhance energy independence, foster value-addition in manufacturing, and create positive externalities on growth and innovation (more details in Table ES1). Indigenising this sector thus supports distinct yet interconnected avenues of strategic value to the Indian economy – resilience and security; domestic value capture; export opportunities; and structural transformation. We take the view that Indian manufacturing policies have yet to make significant progress towards maximising value across all four avenues. In its policy development, it is crucial for India to balance the important, albeit uncertain, benefits of export-oriented growth, value addition, and techno-economic transformations against the important, but limited, benefits of energy security.

Table ES1 There are four avenues of strategic value from deepening clean energy manufacturing in India

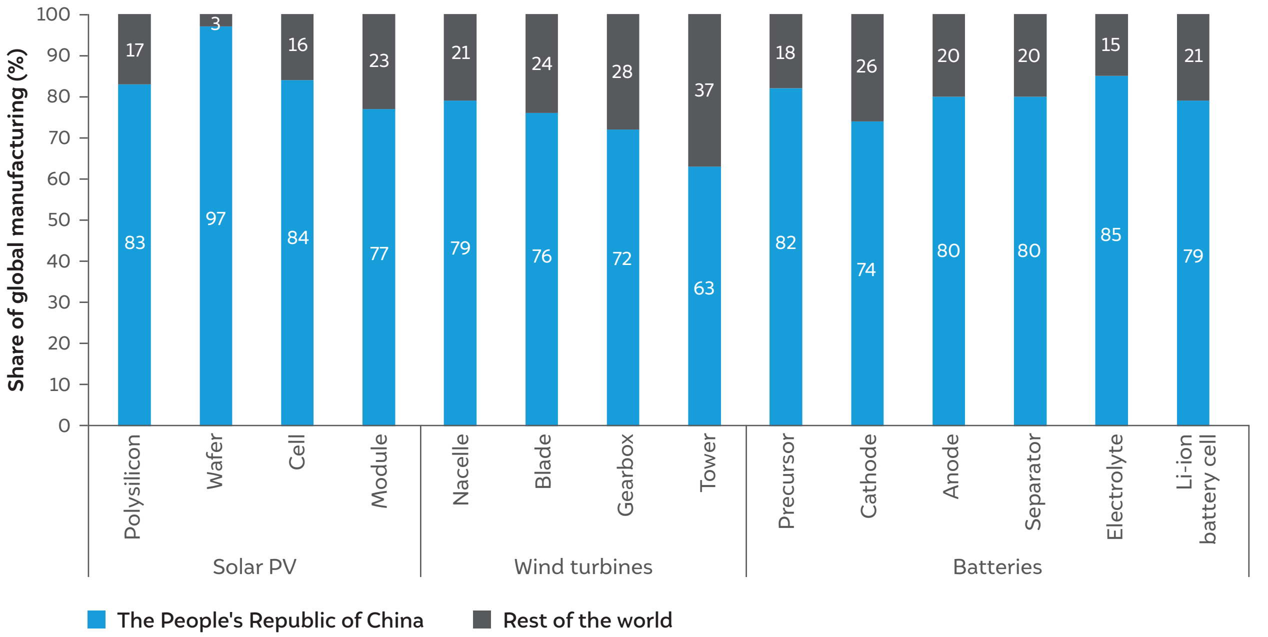
Benefit	Description
Resilience and security	Reduces reliance on foreign imports, enhances energy security through domestic production
Domestic value capture	Improves the balance of payments, potentially enhances energy price stability, and creates additional jobs
Export opportunities	Opens up substantial export opportunities by aligning domestic industries with global demand, drives economic growth
Structural transformation	Knowledge synergies and spillover effects on various other important manufacturing sectors

Source: Authors' analysis

The manufacturing sector in the People's Republic of China has been the front-runner in clean energy technology, dominating the global market for nearly a decade (Figure ES1). While this concentration is alarming, India needs a well-informed response to Chinese market dominance as various manufacturing policies could lead to very different types of economic impact. For instance, policies aiming for complete control over clean energy manufacturing through very high tariff barriers and domestic content requirements (DCRs) could rapidly increase domestic value capture. However, these measures could also negatively impact innovation, reducing export competitiveness and limiting technological spillovers into the broader economy, as well as slowing deployment due to higher technology prices.

From a security standpoint, policymakers will need to consider two important points: first, clean energy technologies and their embodied materials last for decades within the energy system and secondly, the cartel-like behaviour seen amongst producers within the petroleum sector will not be as significant in the clean energy sector (World Economic Forum 2024). We therefore recommend a balance between policies that support increased domestic control and those that encourage innovation and global competitiveness.

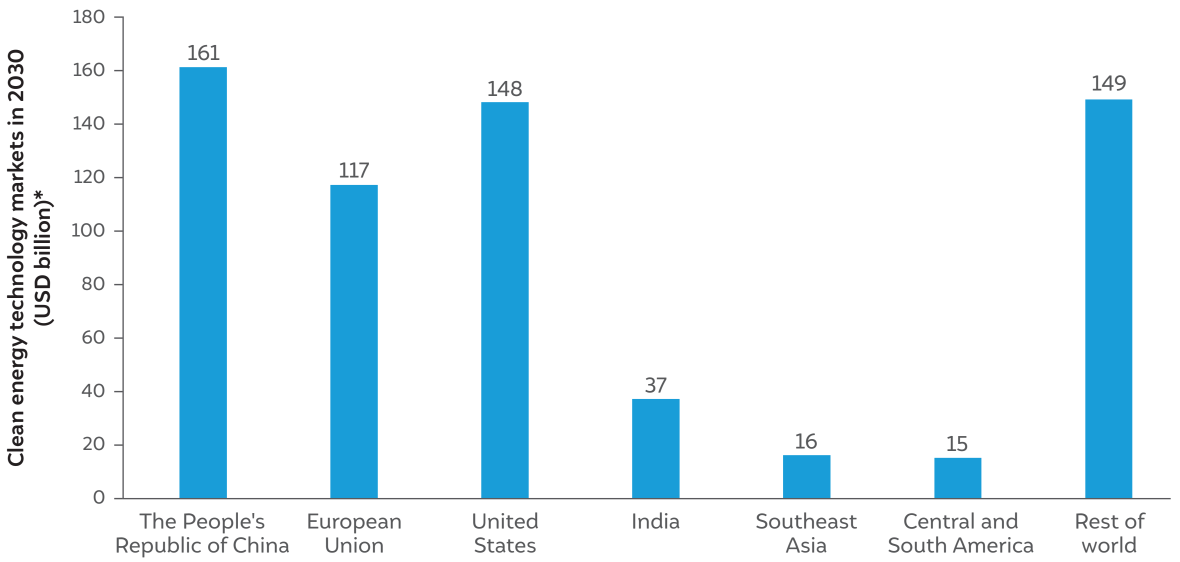
Figure ES1 The People's Republic of China dominates the global clean technology manufacturing capacities



Source: Authors' compilation based on Mccarthy, Rory. 2024. "Not Made in China: The US$6 Trillion Cost of Shifting the World's Clean-Tech Manufacturing Hub." Wood Mackenzie, February 12, 2024. https://www.woodmac.com/news/opinion/not-made-in-china-the-us$6-trillion-cost-of-shifting-the-worlds-clean-tech-manufacturing-hub/#:~:text=The costs reflected in an,not made in China' scenario.

Approaching this sector strategically could also open up huge export opportunities for India. In Figure ES2, we showcase the International Energy Agency's (IEA) more conservative estimate of the clean energy market in 2030, representing an annual demand of around USD 640 billion. We expect this demand will be evenly spread across the PRC, Europe, and the United States, each with markets sized at around USD 140 billion. In contrast, the Indian market is likely to be much smaller at around USD 40 billion, or about 6 per cent of the global market. However, orienting India's clean energy industries to be competitive globally could potentially unlock a much larger market even in a conservative deployment scenario.

Figure ES2 India's market size for clean energy technologies is expected to remain smaller than other key nations in 2030



Source: Authors' analysis based on IEA. 2023a. Critical Minerals Market Review. Paris: International Energy Agency. https://iea.blob.core.windows.net/assets/afc35261-41b2-47d4-86d6-d5d77fc259be/CriticalMineralsMarketReview2023.pdf.

Note: *As per IEA Announced Pledges Scenario

However, the challenge of a changing global reality is particularly significant. Since 2020, clean energy technologies have gone from a severe global supply crunch, both of components and final products, to significant oversupply, with crashing product prices – primarily due to rapid growth of supply from the PRC. This situation of oversupply is expected to continue into 2030 (IEA 2023a). The United States and Europe have responded to the economic and energy security threat they perceive from this concentration and its potential to reindustrialise their economies by implementing strong industrial and trade policies such as the Inflation Reduction Act (IRA) in the United States and the Net Zero Industry Act (NZIA) in Europe (EurpoeanCommission 2023.; IEA 2023f). These initiatives are expected to attract significant investment in the years ahead, potentially drawing investment away from Global South economies such as India (IEEFA-JMK 2023). Unless it collaborates with like-minded countries and opens up free trade access, India may jeopardise its own access to essential global markets.

B. What specific segments/components of the clean energy supply chain must India focus on?

In this report, we have identified those segments which can contribute at least one of the following to the Indian economy:

1. Manufacturing competitiveness
2. Solutions to supply or technology risks in Indian manufacturing
3. Enable a high-tech manufacturing and innovation ecosystem.

This identification is guided by a dual approach: bottom-up research that utilises stakeholder consultations and roundtable discussions with manufacturers, along with a quantitative, top-down analysis that utilises the product space mapping methodology (elaborated in Section 4.2).

Focus areas based on market analysis and stakeholder consultation: Based on our assessment of global market developments and India's domestic requirements and existing capabilities within product segments, we have shortlisted nine components that Indian policymakers should focus on to enhance policy support (Figure ES3). We have prioritised supply-chain segments with a high market concentration, high technological complexity, or high impact on final product cost.

Figure ES3 Technology-specific focus areas for policymakers

Wafer manufacturing (next generation technologies, wafer-cutting equipment): Leverage early adopter advantage in highly concentrated sector; increase strategic control of equipment supply (for e.g. diamond wires)

Cell additives (metallisation paste): Increase domestic value capture in high valve-share products

Nacelle components (bearings, hub castings etc.): Support capability of MSMEs to secure supply; enhance economic co-benefits

Generator components (rare earth magnets): Increase control of highly concentrated sector for offshore market; leverage domestic R&D capabilities

Anode material (synthetic): Leverage domestic pitch and coke feedstocks to secure concentrated supplies

Cathode material (lithium metal phosphate (LMP)): Increase control of concentrated and domestically required sectors

Aluminium components (foil, casing): Leverage existing domestic scale for export market

Next generation battery manufacturing (dry coating, sodium ion): Support pilot lines for first-mover advantage

Source: Authors' analysis

Focus areas based on the product space map method: Further, the product space approach can help policymakers in India assess the broader ecosystem effects and opportunities from scaling various clean energy components (Harvard University 2024b). Findings from the economic complexity concept inherent to the product space approach can be generalised; however, these findings can only be a preliminary guidance for policymakers and must be complemented by technology-specific market research and stakeholder consultations. Table ES2 highlights clean energy–relevant product families (details in Section 5.2) that India may prioritise, either to achieve global competitiveness or to enhance spillover effects in the economy.

Table ES2 Top clean energy-relevant product families relevant for India

8464	4-digit harmonised systems (HS) code by product family
Diamond wire saw	Application in clean energy value chain

Clean energy relevant product families that…

…may enable structural transformation within the manufacturing industry		…India can achieve export competitiveness in		…India already has a comparative advantage in	
8464	Diamond wire saw	3801	Synthetic graphite (anode)	8535	Junction box
3801	Synthetic graphite (anode)	3818	Solar wafer	7106	Silver paste
2804	Polysilicon	2804	Polysilicon	8483	Wind turbine gearbox
7607	Aluminium foil	3920	EVA	8503	Hub castings
3920	EVA	7607	Aluminium foil	8412	Wind turbine
8507	Lithium-ion batteries	8464	Diamond wire saw		

Solar Wind Batteries

Source: Authors' analysis

Note: EVA stands for ethylene vinyl acetate

C. Recommendations: Future-ready clean energy policy framework for India

We recommend that the Indian government respond to this new global paradigm and maximise strategic value for the Indian economy with a two-pronged approach. First, India should complement its PLI schemes and broad technology-level trade policies by identifying specific clean energy supply-chain segments/components for scaling through tailored support and market protection. Secondly, India must re-evaluate and reconfigure its policies to address domestic policy uncertainties, respond to global demand variability, and ensure the availability of sufficient input materials, technological expertise, finance, and other manufacturing enablers in the domestic ecosystem. Collating insights from both these approaches, we recommend policy priorities for India in the clean energy manufacturing sector (Figure ES4) that can advance the identified supply-chain segments and maximise strategic value for the Indian economy.

Figure ES4 A comprehensive strategy to drive India towards a competitive clean energy supply chain

Recommendations		
Building competitiveness	**Increasing demand**	**Strengthening ecosystem**
Tapping markets with stringent manufacturing emission norms	Raising domestic deployment ambitions	Securing the supply of critical minerals – primary and secondary
Mobilising finance for CapEx	Using import tarrifs judiciously	Improving testing infrastructure
Developing upskilling programmes to meet industry requirement	Leveraging International partnerships to access new markets	Adopting a whole-of-government approach
		Facilitating coherent, consistent, and aligned policymaking

Source: Authors' analysis

- **Building competitiveness**: Given the export potential, India must capitalise on markets with stringent emission norms by establishing robust environmental, social, and governance (ESG) standards, while negotiating favourable terms of trade on bilateral and plurilateral forums. Additionally, mobilising finance for capital expenditures is vital, necessitating the collaboration of the Ministry of New and Renewable Energy (MNRE), the Ministry of Finance, and international banks to secure competitive debt capital for scaling up manufacturing. Furthermore, it is essential to introduce upskilling programmes in partnership with the Ministry of Education, the Department of Science & Technology, and the National Skills Development Corporation to cultivate a skilled workforce capable of supporting the clean energy value chain.

- **Increasing demand**: Raising domestic deployment ambitions is vital to aligning supply and demand and enabling economies of scale. The judicious application of import tariffs on key components and raw materials, accompanied by a transparent, long-term tariff plan, will further protect and encourage nascent industries. Leveraging international partnerships to access new and bigger markets is essential, as global diversification of clean energy procurement offers India opportunities to negotiate trade agreements, eliminate barriers, and enhance the competitiveness of domestic clean energy products.

- **Strengthening the ecosystem**: Securing the supply of critical minerals, both primary and secondary, is paramount. Strengthening entities such as Khanij Bidesh India Limited (KABIL) financially and enhancing coordination with institutions such as Coal India Limited and IREL (formerly Indian Rare Earths Limited) will be essential. Long-term strategies should include establishing critical mineral stockpiles through international collaboration. Improving testing infrastructure will further support the innovation cycle and product validation. Adopting a whole-of-government approach, characterised by enhanced inter-ministerial coordination and the formation of a high-level committee on resilient supply chains for energy transition, will ensure coherent, consistent, and aligned policymaking, thereby stabilising market confidence and fostering long-term investments.

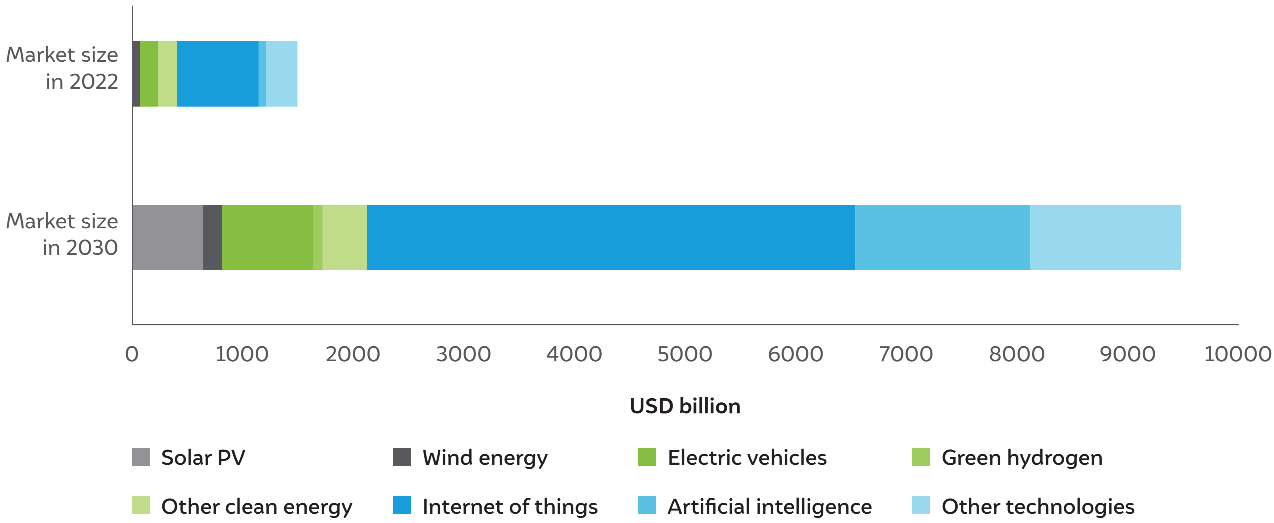
India's rapidly growing population, combined with its substantial economic potential, suggests that the country's energy demand will soar in the coming decades.

Image [illegible]sol Solar Private Limited.

1. What India stands to gain from deepening its clean energy manufacturing landscape

Research suggests that we are entering a new techno-economic paradigm – the Fourth Industrial Revolution – marked by 'frontier' technologies such as artificial intelligence, blockchain, gene editing, and clean, renewable energy technologies (UNCTAD 2021). Together, these sectors will constitute a USD 9 trillion market by 2030 (UNCTAD 2023b). Amongst these, clean energy technologies that will help mitigate carbon emissions, including solar photovoltaic (PV), wind, and electric vehicles, will alone constitute a market of nearly USD 2 trillion by 2030 as showcased in Figure 1.

Figure 1 Clean energy technologies have a huge potential market size in 2030



Source: UNCTAD. 2023a. "Global Trade Slows, but 'Green Goods' Grow." United Nations Trade and Development, March 23, 2023. https://unctad.org/news/global-trade-slows-green-goods-grow.

In light of global developments in technology, economics, climate change mitigation, and the new geopolitical context since COVID-19, indigenising the manufacturing of clean energy technologies presents numerous advantages. For India, one primary benefit is import substitution and resilience, i.e., reducing the nation's reliance on foreign imports and enhancing energy security through energy independence. Another benefit is that it will boost the economy in a couple of ways: through potentially creating new jobs and by driving technological innovation and leadership, ensuring that India remains competitive in a rapidly evolving global market. This technological edge is also crucial for establishing a futuristic, sustainable, and green economy. Finally, there is an opportunity to capitalise on a fragmented global market, attract international investments, and diversify the global supply chains that are currently concentrated in the People's Republic of China.

Given these factors, it is essential to delve into the specific benefits that India can obtain from deepening the manufacturing of clean energy technologies. This allows us to pinpoint the areas with the greatest potential. In doing so, we will recognise the strategic importance of investing in the manufacturing capacity for clean energy technologies and the long-term advantages it can bring to the Indian economy.

At least 60% of global production of clean energy technologies is concentrated in the top three countries, with the PRC playing a dominant role

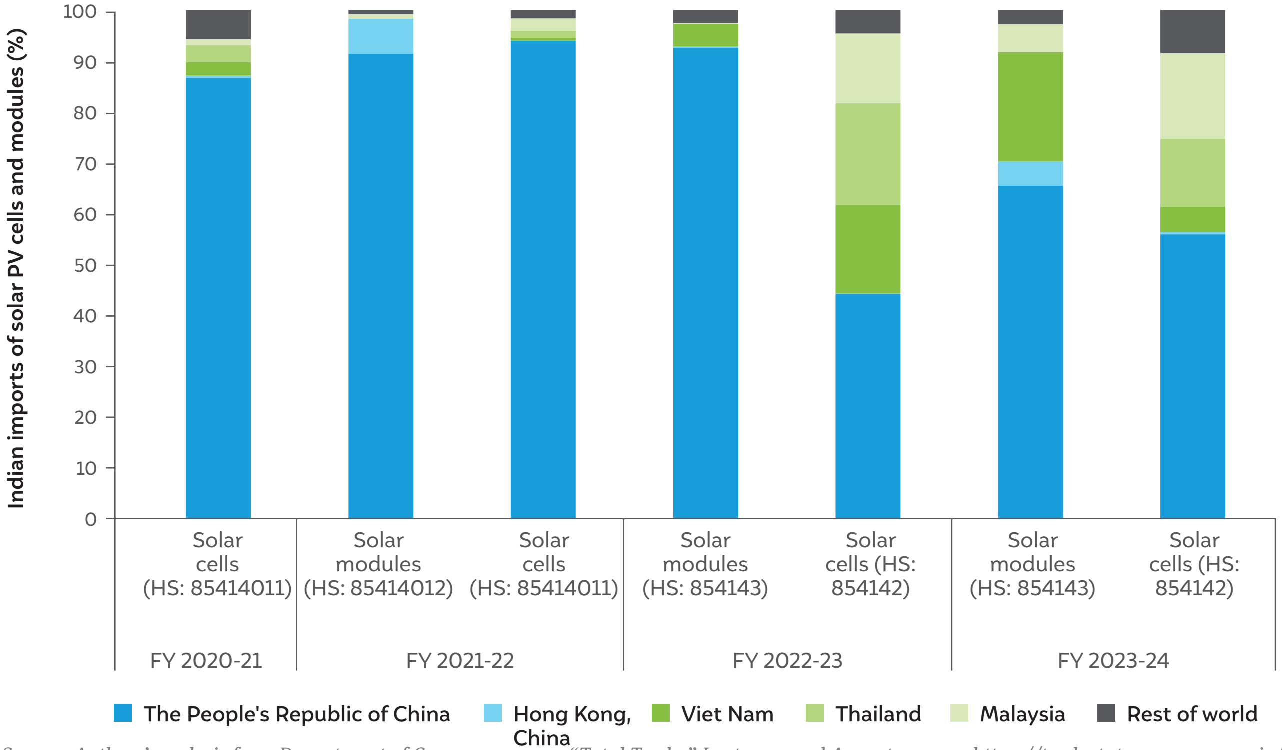
1.1 Limited but important gains from manufacturing for energy security

For developing countries, policy decisions concerned with energy must sufficiently prioritise energy security, as energy supply underpins economic activity, thus directly affecting development (Benoit 2019). Unlike traditional fossil fuels, which are finite and susceptible to depletion, renewables offer resource abundance and utilise technologies that can be distributed globally and evenly (IRENA 2024). The demand for renewable technologies is also more flexible than that for fossil fuels such as petroleum and diesel oil, wherein even small shifts in supply can impact prices. Moreover, materials embodied in clean energy technologies are generally required just once in a project's lifetime – when the equipment is built or installed – and often last decades, with potential for recycling. The benefits of clean energy as a more secure substitute then hinge on deployment, but the supply chains that are vital for their deployment can exhibit vulnerabilities.

The global supply chains for batteries, solar panels, and wind turbines have significant geographical concentration across various stages of production. Overall, from resource extraction and raw material processing to component production, assembly, and recycling, at least 60 per cent of global production is concentrated in the top three countries, with the People's Republic of China playing a dominant role (IEA 2023b). The PRC dominates the midstream of the electric vehicles (EV) battery supply chain – specifically raw material processing and component production – and competes with Japan and Republic of Korea in the downstream stages. In the solar industry, Chinese dominance is even more pronounced, with over 90 per cent of global polysilicon processing occurring there. Unlike with solar panels and batteries, the wind turbine supply chain is slightly more diversified and spread across the world, with 30–70 per cent of global production of wind turbine components situated across a few countries (GWEC 2023).

Unsurprisingly, India's imports of clean energy technology have been concentrated as well thus far. For instance, Figure 2 shows the concentration in the sourcing of solar PV cells and modules, which come mostly from the People's Republic of China.

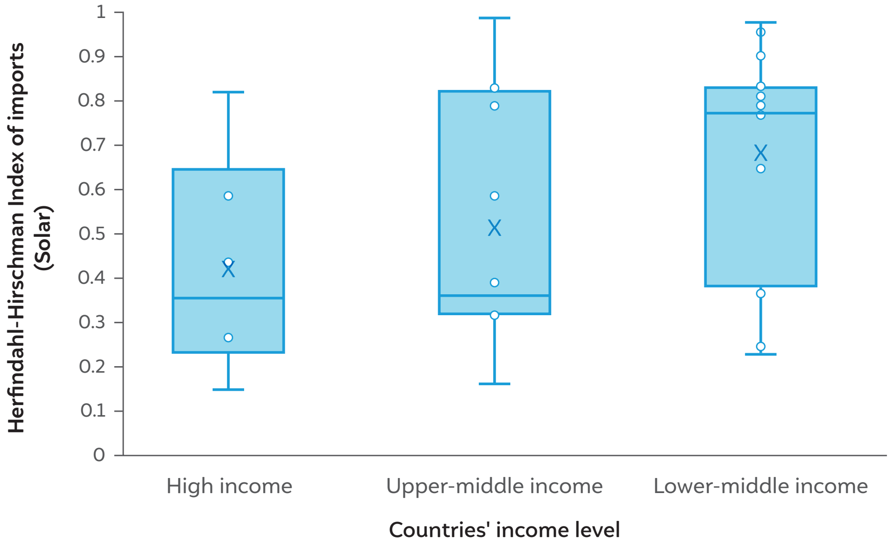
Figure 2 India has been significantly reliant on Chinese imports for solar PV cells and modules



Source: Authors' analysis from Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp.

Globally, sourcing concerns have focused on the PRC, not only due to actual concentrations and dependence but also due to recent tensions between multiple Western nations and the PRC (World Economic Forum 2024). Import concentration levels also differ based on the economic status of the countries participating in international trade, as shown for solar imports in Figure 3. In 2021, about 90 per cent of lower-middle income countries and 65 per cent of high-income countries had concentrated imports in solar PV technology (CEEW 2023). These developments may point to brewing geopolitical concerns in the clean energy supplies sector.

Figure 3 Solar import concentration for lower-middle-income and upper-middle-income countries were significantly higher than high-income countries in 2021



Source: Authors' analysis based on UN Comtrade. 2023. https://comtradeplus.un.org/

Manufacturing concentrations and the resultant import concentrations are concerning for several countries. However, we need a detailed understanding of the actual threat arising from such a market before any policy action can be designed to mitigate the risks. Vulnerability, which can be defined as exposure to risks, is distinct from risk, which is defined as the chance of a shock actually occurring. These concepts require a more nuanced understanding (Finley 2019). For instance, the top three countries dominating the supply of critical minerals essential for clean energy technology manufacturing – such as graphite, nickel, and cobalt – account for 50–90 per cent of global mining and processing. This concentration is notably higher than the nearly 40 per cent share of world oil production held by the Organization of the Petroleum Exporting Countries (OPEC), making it a more significant concern (World Economic Forum 2024). However, unlike with the OPEC, there has hardly been any cartel-like behaviour in the critical minerals market. This is because the capacity to exert pricing power through supply control is much higher in the oil markets due to their lower short-run demand elasticities. This characteristic is not shared by critical mineral or clean energy technologies. As a result, governments and buyers have not had a strong incentive to diversify their supplies, and have instead optimised for cost and ease of access to source materials, such as copper in Chile and lithium in Australia (WEF 2024). Therefore, we need further research to determine the definite necessity of and possible outcomes from indigenisation as a supply chain risk mitigation technique.

Any potential security gains from an indigenisation strategy must be weighed against potential increases in costs

Indigenisation of supply can indeed enhance security to the extent of shifting energy dependencies and reducing exposure to any possible risks. However, as discussed, these risks only pose a limited threat to energy security. From a security standpoint, then, disruptions in the supply of clean energy technologies pose fewer immediate problems. Potential challenges can include difficulty in replacing retiring technologies and barriers to expanding clean energy capacity to meet growing demand.

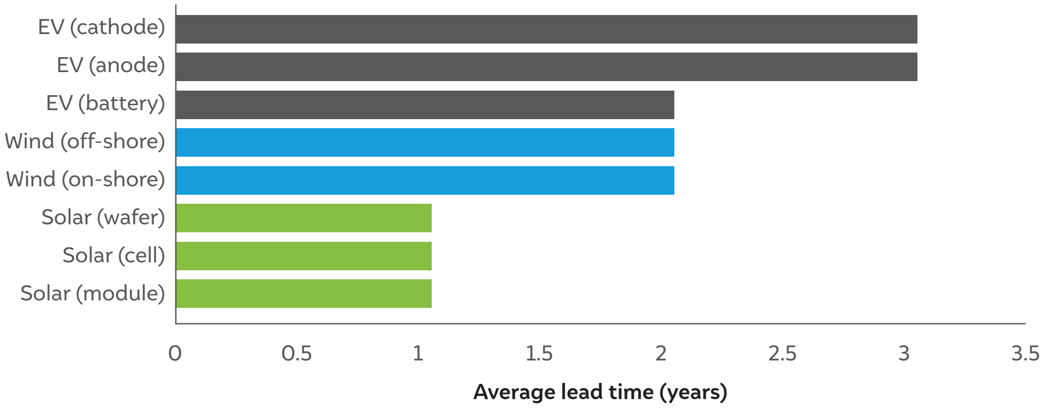
Further, any potential security gains from an indigenisation strategy must be weighed against potential increases in costs, considering the price difference between domestically produced components and cheaper imported options (Mccarthy 2024). Hence, while energy security is a vital consideration, domestic manufacturing may offer limited benefits in this regard.

Supply disruptions, if any, can arise from geopolitical conflicts as well, which have been a recurring theme in global discussions this decade. Accordingly, enhancing resilience, defined as the ability to recover from possible shocks, can benefit from indigenisation.

For energy-importing countries, indigenising supply is also an opportunity to avoid transitioning from import dependence in fossil fuels to import dependence in renewable technologies, affecting long-term geopolitical and economic concerns (Krane and Idel 2021; IRENA 2019). The ability to produce energy, as enabled by renewables, can play a key role in shifting dependencies and elevating a country's geopolitical positioning as well. Some segments of supply chains also face high lead times (Figure 4) and building manufacturing capabilities in these areas can boost resilience against any potential disruption.

Therefore, the rationale for deepening clean energy manufacturing can be driven as much by economic goals and geopolitical leadership ambitions as by security concerns. Indeed, these goals are bound to be intertwined. A more comprehensive approach, one that is inclusive of economic and geopolitical factors, can enhance the indigenisation strategy and potentially offer better outcomes as we will discuss in the following sections of this chapter.

Figure 4 Setting up EV components manufacturing needs higher average lead time than for solar and wind technologies



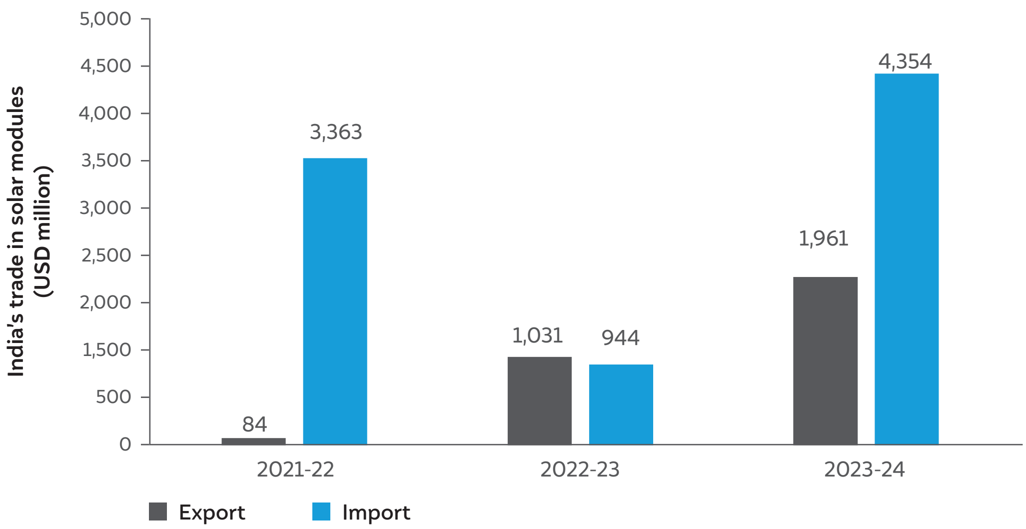
Source: Authors' analysis from IEA. 2023b. "Energy Technology Perspectives Executive Summary." In Energy Technology Perspectives 2023. Paris: International Energy Agency. https://www.iea.org/reports/energy-technology-perspectives-2023/executive-summary

1.2 Resilience and value addition are important benefits of strategic indigenisation

India's vast and growing population coupled with substantial growth potential mean that its energy demand will increase by leaps and bounds in the decades ahead. Our peak electricity demand was 203 GW in 2021–22 and is predicted to increase to 366 GW by 2031–32 (CEA 2022). Currently, meeting this demand through clean energy translates into high import dependence (Figures 5 and 7). Further, Indian solar PV manufacturing also relies heavily on imported machinery, mainly sourced from the PRC and Europe. This leads to significant dependence on spare parts and technical support from international suppliers.

While India has ample capabilities in wind components manufacturing, and is a net exporter of wind generators, its Chinese imports are still increasing (Figure 6). Import volumes have also increased substantially in recent times, rising from USD 3.31 million in FY 2022–23 to USD 11.11 million in FY 2023–24 (Department of Commerce 2024).

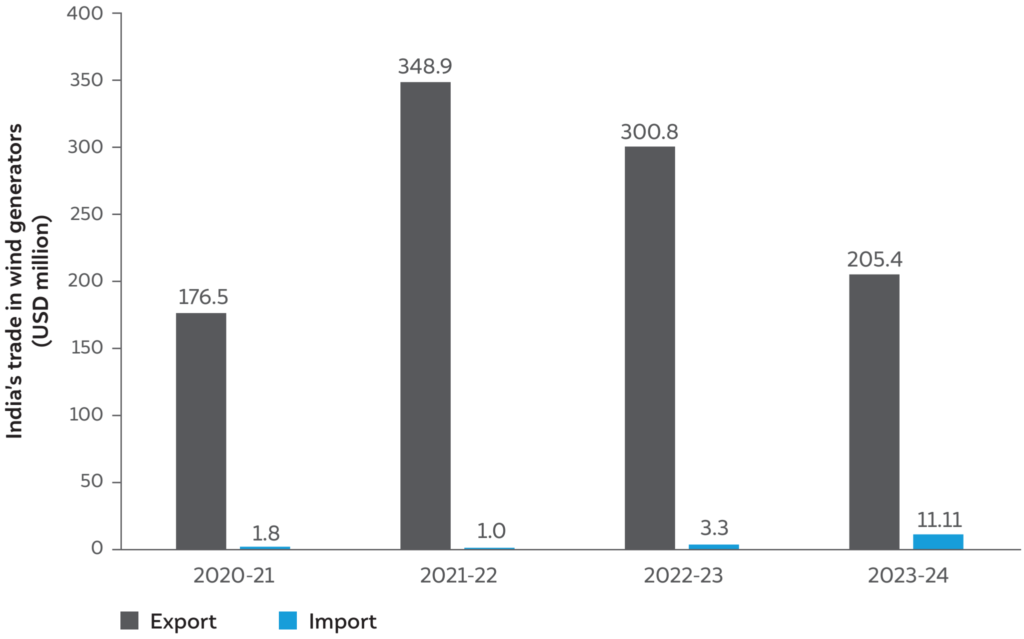
Figure 5 India is a major net importer of solar modules



Source: Authors' analysis from Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp.

Note: HS code 854143

Figure 6 India is a net exporter of wind generators, with imports rising in FY 2023–24

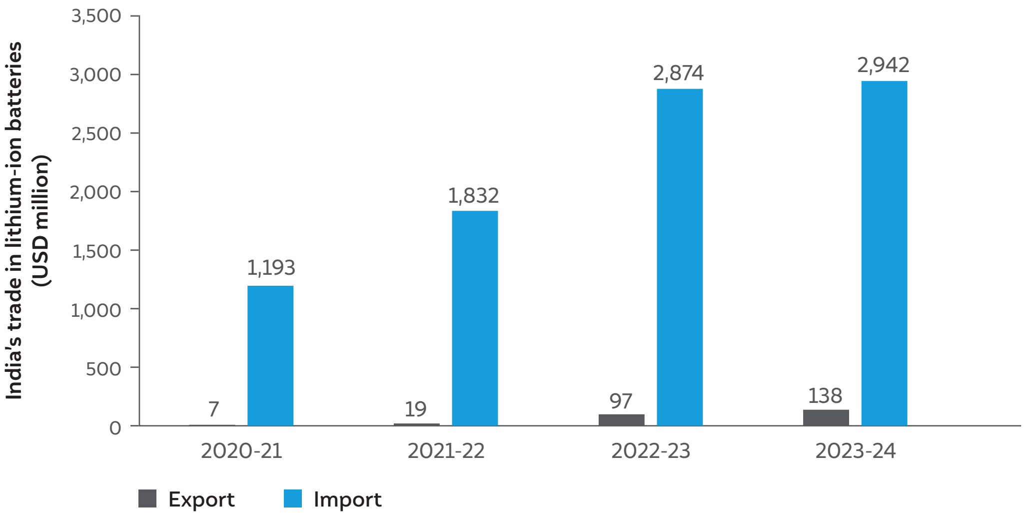


Source: Authors' analysis from Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp.

Note: HS code 850231

Like solar components, India has historically imported lithium-ion batteries and cells as well. The trade data shows that imports of lithium-ion batteries and cells are on an upward trend and reached nearly USD 3 billion in FY 2022–23. It should be noted that India has also begun exporting battery in recent years (Department of Commerce 2024). As the volume of trade has increased (Figure 7), the PRC's share in it has also ticked upwards and reached nearly 80 per cent of total imports in 2023 (Department of Commerce 2024).

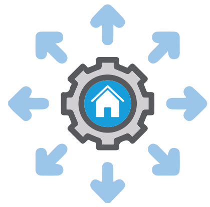
Figure 7 India remains a large net importer of lithium-ion batteries



Source: Authors' analysis based on Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp.

Note: HS code 850760

Not only is India highly dependent on imports for these products, they can also account for a large share of the total battery cost. For example, cathode and anode production is quite concentrated, with 55 per cent of global cathode capacity produced by only seven companies (IEA 2022a). As of 2024, almost 80 per cent of the global battery supply chain is geographically based in the People's Republic of China (Flowers, Mccarthy, and Thompson 2024). Such concentrations heighten the risk of price instability, since the cathode segment also accounts for a substantial share of the battery cost (see Figure 15). Across lithium ferro-phosphate (LFP) battery chemistries, cathodes can account for about 30–40 per cent of LFP battery costs, and in nickel manganese cobalt (NMC) battery chemistries, this share can be as high as 45–55 per cent (IISD 2023; Warrior, Tyagi, and Jain 2023).



Choosing to indigenise manufacturing in selected strategic supply segments can open doors to new opportunities

Hence, choosing to indigenise manufacturing in selected strategic supply segments can open doors to a twin opportunity: reducing import dependence while simultaneously capturing some high value-addition segments. Developing capabilities in these complex and concentrated products will be a challenge, but it will ensure a stable supply of essential components for India's clean energy sector, supporting progress towards its renewable energy targets.

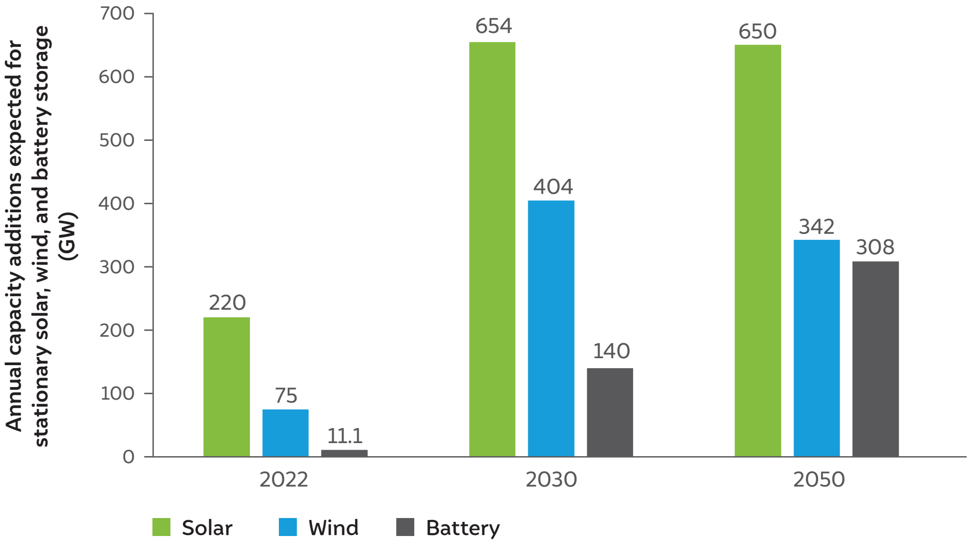
In particular, investing in the development of manufacturing capabilities for these sophisticated, and often costly, parts can help capture markets in high value-addition components. However, an export-oriented outlook will be essential for these products, as exports would unlock access to larger markets, enabling domestic manufacturers to benefit from economies of scale and, consequently, create higher-quality output due to the increased competition. In Section 1.3, we discuss strategies to optimise manufacturing for the export market.

1.3 A large and uncertain export opportunity will drive economic growth

The global shift towards decarbonisation and renewable energy deployment targets has created a substantial market for clean energy technologies. According to the International Energy Agency (IEA), the proportion of renewable energy in the electricity mix must increase from 28.7 per cent in 2021 to 90 per cent by 2050 to achieve global net-zero goals (IEA 2022c). To align with the IEA's 2050 net-zero scenario, cumulative solar and wind energy installations must rise from 1,449 GW in 2020 to 22,723 GW by 2050.

Battery storage will play a crucial role in decarbonising the mobility sector and integrating intermittent clean energy into the grid. Therefore, its demand is expected to grow annually until 2030 and then stabilise until 2050, offering a substantial market opportunity for manufacturing (Figure 8). Similarly, meeting the IEA's 2050 net-zero goal requires the production of solar components to more than double by 2030 (IEA 2022b). This market appetite presents India with an economic opportunity to indigenise manufacturing and export to the vast global markets while capturing high-value segments of these supply chains and reducing its own import dependence.

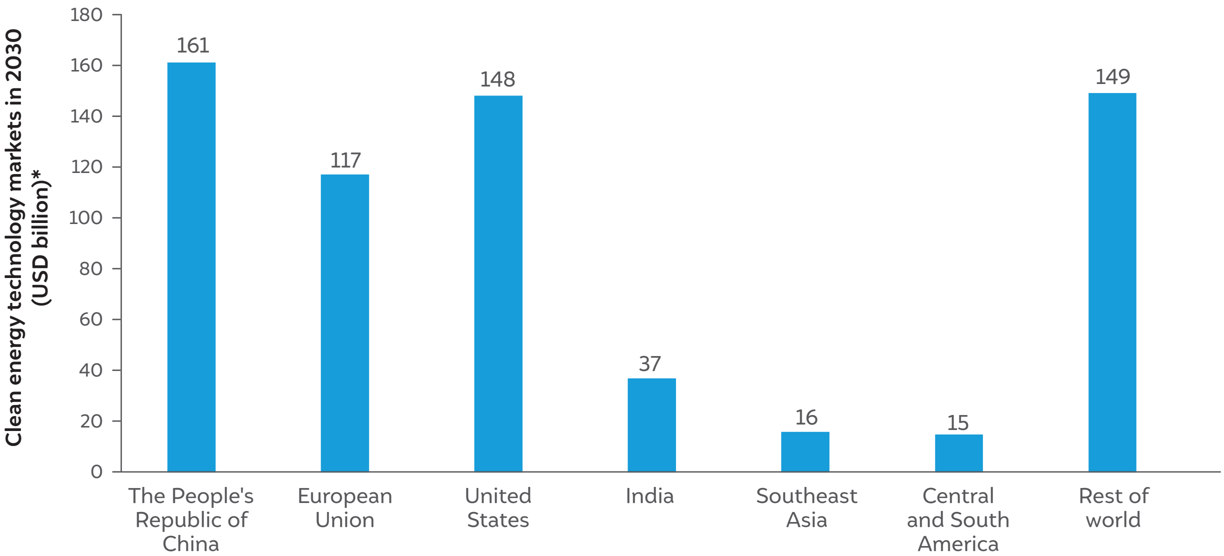
Figure 8 **Massive increase in solar, wind, and battery stationary storage deployment is required to achieve global net-zero goals by 2050**



Source: IEA. 2023d. Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach. Paris: International Energy Agency. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach

The annual market size for clean energy is expected to be USD 640 billion by 2030 (Figure 9). The geographic spread of this demand is expected to be largely and evenly distributed between the People's Republic of China, Europe, and the United States, with markets sized at around USD 140 billion each. The Indian market, by contrast, is likely to be much smaller at around USD 40 billion or around 6 per cent of the global market (Figure 9). Orienting India's clean energy industries to be globally competitive could open up a much larger market, even in a conservative deployment scenario. Similarly, India could capture a larger share of the 14 million clean energy manufacturing jobs expected to be created worldwide by 2030 (IEA 2023b).

Figure 9 **India's market size for clean energy technologies is expected to remain smaller than other key nations in 2030**



Source:IEA. 2023b. Energy Technology Perspectives. https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf.

Note: *As per IEA Announced Pledges Scenario

Capturing a portion of the global export market has the potential to provide export-driven economic growth and to generate highly skilled jobs. This, however, is predicated on India achieving price competitiveness. Due to supply concentration and geopolitical conflicts, many nations are seeking to diversify their supply chains. This shift creates a significant near-term export opportunity for India in a constantly evolving landscape marked by technological breakthroughs and geopolitical changes. Accordingly, India must act strategically and avoid relying heavily on export markets, given their inherent uncertainties such as fluctuating demand, conservative trade policies, and geopolitical tensions. In the short term, India can leverage the 'China Plus One' sentiment and seek to capture exports to countries with aggressive deployment targets, low domestic manufacturing capacity, and a desire to diversify imports away from the PRC. Countries with import duties on China-produced solar PV cells and modules present further opportunities for Indian exports.

A long-term export strategy would require non-cost competitive edges such as ESG standards, low-carbon production, or specific performance parameters

A significant advantage for India, compared to other emerging markets, is its substantial domestic demand for energy and related products. Investments are more likely to flow into manufacturing projects within India because of this anchor demand. This strong internal market support enhances the attractiveness of India's clean energy manufacturing sector and its potential for export growth (ORF 2024). However, Indian products remain significantly costlier than those made in the PRC (Mccarthy 2024), thus necessitating greater efforts to enhance competitiveness across cost and technology parameters.

A longer-term export strategy would require finding new types of competitive edge besides cost, such as environmental, social, and governance (ESG) standards, low-carbon production, or specific performance parameters. Recently, many countries have focused on reducing the emission intensity of imported products by introducing 'green' industrial policies. Compliance with emission and ESG standards could become a crucial determinant of gaining access to export licenses and private finance in the medium to long term.

Despite the slowdown caused by the COVID-19 pandemic, the strong performance of trade in 'green goods' provided a silver lining. Green goods, which are designed to use fewer resources or emit less pollution, grew by about 4 per cent in the second half of 2022, reaching a record value of USD 1.9 trillion in 2022 – an increase of over USD 100 billion compared with 2021. Notable performers included electric and hybrid vehicles (growing by 25 per cent), non-plastic packaging (growing by 20 per cent), and wind turbines (growing by 10 per cent) (UNCTAD 2023b). This robust growth in green goods underscores the potential for India to capitalise on increasing global demand for ESG compliance and environmentally sustainable products, which is likely to be a longer-term trend in the global market (UNCTAD 2023a).

Emerging green industrial policies across the globe represent a starting point, and the decisions policymakers make now will determine future trajectories. Navigating these complexities will be crucial for India to effectively increase its attractiveness as a supplier while aligning with global sustainability trends and enhancing its reputation in the international market. In addition to competitive edge, India must recognise the critical role of technological innovation in maintaining and advancing its position in the global economy. Regardless of how the market evolves, technological innovation will be a key enabler, positioning countries at the forefront of geopolitical, economical, and environmental issues. The ability of countries to enhance their production capabilities and diversify into complex products can become a determiner of their economic success (McMillan and Rodrik 2011).

1.4 High-tech manufacturing can enable structural transformation of the economy

One of the most significant benefits of clean energy manufacturing is its potential to foment an economy-wide structural transformation. Innovation, which is at the heart of energy transition, is also the main source of modern economic growth. This growth occurs when innovation transforms and output from low-productivity into high-productivity sectors, often due to the advent of advanced technology. Research indicates that nations specialising in more advanced and sophisticated goods experience faster growth (Hausmann, Hwang, and Rodrik 2007; Rodrik 2006). Hence, manufacturing high-tech products offers numerous economic benefits. Apart from this structural transformation of the economy, higher technological levels of products also attract higher wages and face less competition in export markets since fewer countries can produce and market them.

Innovation is at the heart of energy transition, and is the main source of modern economic growth

The extent of knowledge spillovers from clean technologies, including renewables, is seemingly equivalent to that from the information technology (IT) industry (Dechezleprêtre, Martin, and Mohnen 2014). These spillovers occur due to shared scientific principles, component designs, materials, and manufacturing techniques. Consequently, advancements in one type of device often directly or indirectly foster progress in others. Such knowledge spillovers are a hallmark of high-tech sectors and have even played a crucial role in the creation of many existing clean energy technologies. For example, the development of the carbon anode used in lithium-ion batteries was made possible by the knowledge and techniques initially developed in the petrochemicals sector, with the first functional carbon anode created by a petrochemical company (IEA 2020).

The three main technological fields in renewable energy – solar, wind, and storage – exhibit intra-technology spillovers, meaning that knowledge primarily flows within the same specific technological field. Innovations in solar and storage rarely contribute to the knowledge base of other power-generation technologies – known as inter-technology spillovers – but do generate substantial spillovers to fields outside power generation – known as external spillovers. External technology spillovers are particularly high in storage, solar, and hydropower fields, accounting for about 40 per cent of their spillovers (Noailly and Shestalova 2017) and indicating that scaling up of clean energy technologies will expand opportunities for India in other high-tech sectors. In addition to knowledge spillovers, there are also application synergies. For example, applications that use a common material and share a common manufacturing base can experience accelerated use and innovation, similar to the use of carbon fibre in road vehicles and aircraft spilling over to light weight turbines.

Moreover, clean energy provides indirect economic benefits, such as enhancing labour productivity through improved air quality and increased energy access (Alam et al. 2018; Sovacool and Monyei 2021). These improvements result in positive socio-economic externalities that are very relevant for India. Technological innovation that has economy-wide transformational impacts is also path-dependent, i.e., it is the result of a combination of existing productive capacities in an economy. India is among the handful of middle-income Asian economies reshaping the innovation landscape, along with the People's Republic of China, Türkiye, the Socialist Republic of Viet Nam, and the Philippines. India excels in developing sophisticated, technologically dynamic services that can be traded internationally, leading the world in information and communications technology (ICT) service exports and ranking highly in domestic industry diversification and the number of graduates in science and engineering. Leveraging this existing foundation, India can deepen its clean energy supply chains and further strengthen its position in the global innovation landscape (WIPO 2021).

Despite India's strides in overall technological innovation, there is scope to catch up with other countries in clean energy innovation. Fewer countries dominate this landscape and reap the associated economic benefits. From 1975 to 2017, only 0.2 per cent of green patents were attributed to India, compared with 18.6 per cent to Japan, 17.7 per cent to the People's Republic of China, and 17.1 per cent to the United States (UNCTAD 2023b). This presents an opportunity for India to compete with technologically advanced nations. Beyond structural transformation and export opportunities, leadership in technology and innovation can enhance geopolitical standing, thus potentially providing some security against the prominent risks plaguing clean energy supply chains.

Prompt, ambitious action to establish green production capabilities can secure India's position in the global green economy of the future

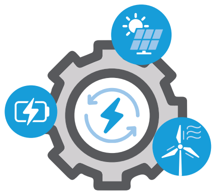
However, it is crucial that India acts swiftly, as innovation depends on the set of technologies that the economy has accumulated. Prompt, ambitious action to establish green production capabilities can enable India's success in the future green economy. India's strategic approach should include identifying sectors that are close to the country's current production capabilities and that are more complex than the country's average production. These new segments have the potential to increase the technological level of the economy. International trade data analysis utilising the product space methodology, as discussed in more detail in Section 4, can facilitate this identification.

While India's emerging manufacturers may struggle to compete immediately with Chinese giants, the industry has strong fundamentals to be cost-competitive with non-Chinese players in the midstream segment of clean energy value chains.

Image: Suzlon

2. India's limited but steady progress in clean energy manufacturing

Manufacturing of clean energy encompasses the production of renewable energy technologies, such as solar panels, batteries, and wind turbines, which are characterised by various parameters such as energy, cost, technology, and skills. In this section, we delve into the components of each clean energy value chain and explore how India, with its existing manufacturing ecosystem and growing expertise, is progressing in this critical sector. We will also analyse the nation's advancements in manufacturing efficiency, workforce development, and cost-reduction strategies. We also highlight the segments India can focus on to become a pivotal link in the global clean energy supply chains including enhancing technological innovation, fostering international collaborations, and implementing supportive policies.



Clean energy sector is characterised by intricate manufacturing processes for producing crystalline silicon solar PVs, wind turbines, and lithium-ion batteries

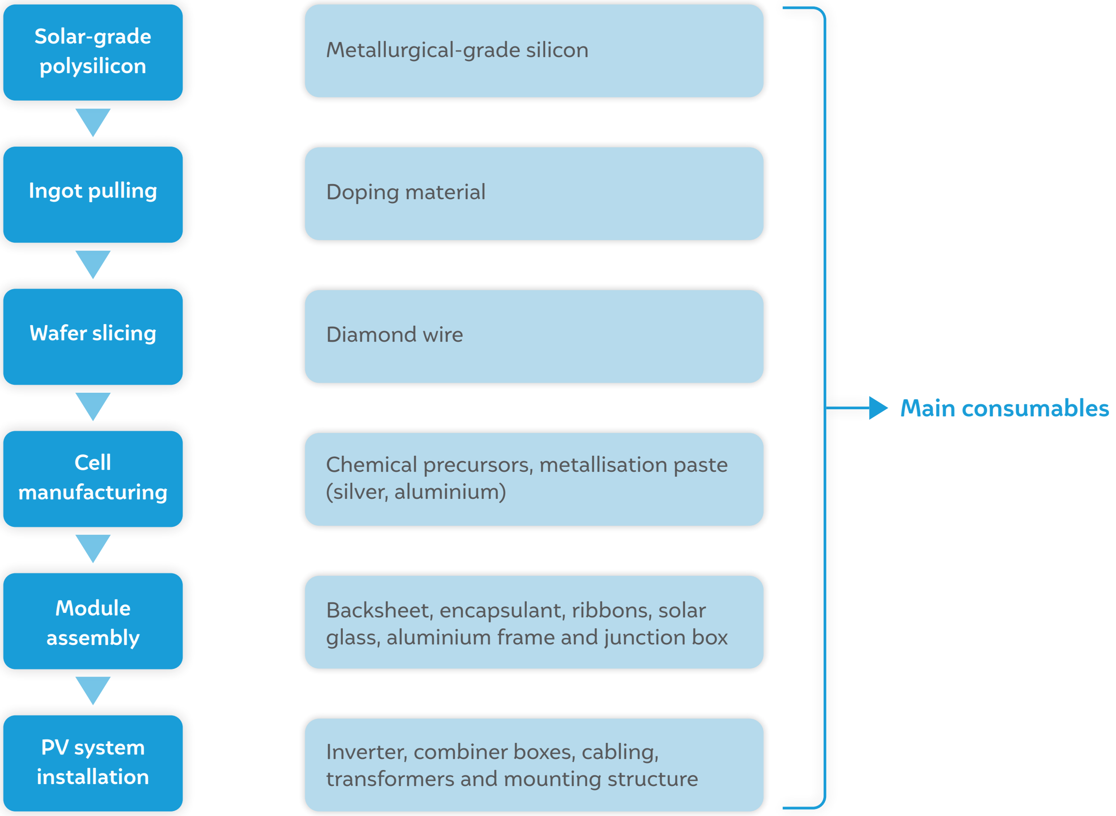
2.1 The clean energy manufacturing supply chain

The clean energy sector is characterised by intricate manufacturing processes that are essential for producing key technologies such as crystalline silicon solar photovoltaics (c-Si), wind turbines, and lithium-ion batteries. Each of these technologies requires a series of complex steps, from the synthesis of raw materials to the assembly of final products, involving both capital and energy-intensive operations. Understanding the production stages, cost factors, and material requirements is crucial for optimizing efficiency and enhancing competitiveness in the global market. This analysis delves into the manufacturing processes, highlighting critical components, cost distributions, and potential areas for strategic advantages, particularly in the context of India's clean energy ambitions.

Crystalline solar photovoltaics

The production of crystalline silicon (c-Si) solar PV modules broadly consists of four stages as illustrated in Figure 10: (i) synthesising a highly pure form of elemental silicon called polysilicon, (ii) converting polysilicon into silicon wafers, (iii) processing wafers into solar cells, and (iv) assembling these solar cells into modules (Vasi et al. 2023; Chen2012; Su 2013).

Figure 10 Solar manufacturing process for wafer-based crystalline silicon solar PV

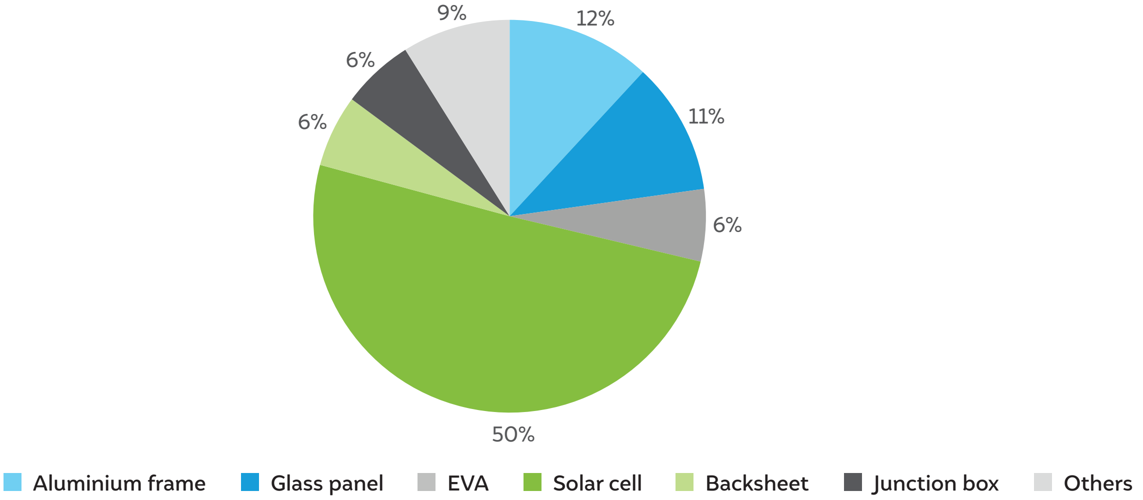


Source: Authors' analysis

The module manufacturing process is the least capital-intensive segment of the solar supply chain (ISA 2023a; Powell et al. 2015). It involves assembling solar cells from components such as copper ribbons, backsheets, aluminium frames, glass, polymer encapsulant (ethylene vinyl acetate or EVA), and junction boxes. Silver busbars on one cell are connected to the rear surface of another cell using copper ribbons. The interconnected cells are then arranged on a glass sheet, covered with a polymer encapsulant, and laminated with a backsheet. This stack is then oven-laminated to make it waterproof. An aluminium frame, edge sealant, and a junction box are added, with the junction box cables conveying current to an adjacent module or the system's power electronics (US DOE 2024). The cost share of the components that make up each module is given in Figure 11. Solar cells, EVA, and glass contribute the maximum share of the cost of a crystalline solar module.

The first step of solar module manufacturing is the production of polysilicon, which is done through the Siemens process. The Siemens process is the most prevalent method for producing polysilicon. This process requires extremely high temperatures and is energy-intensive, which makes low-cost electricity essential for its commercialisation (ORF 2024). The polysilicon is then transformed into an ingot, which is subsequently cut and sliced into wafers. Wafer manufacturing is the most capital-intensive and energy-intensive step in solar manufacturing (ISA 2023b). Thereafter, the manufacturing of solar cells involves chemical texturing of the polysilicon wafers, which are then doped with either boron or phosphorus and coated with a metal paste made out of silver to improve the cells' current collection (US DOE 2024). In the solar manufacturing sector, India already has a comparative advantage in junction boxes and has opportunities to explore ethylene vinyl acetate (EVA) and silver paste manufacturing.

Figure 11 EVA, glass panels, and solar cells are among the costliest components in a solar PV module[2]



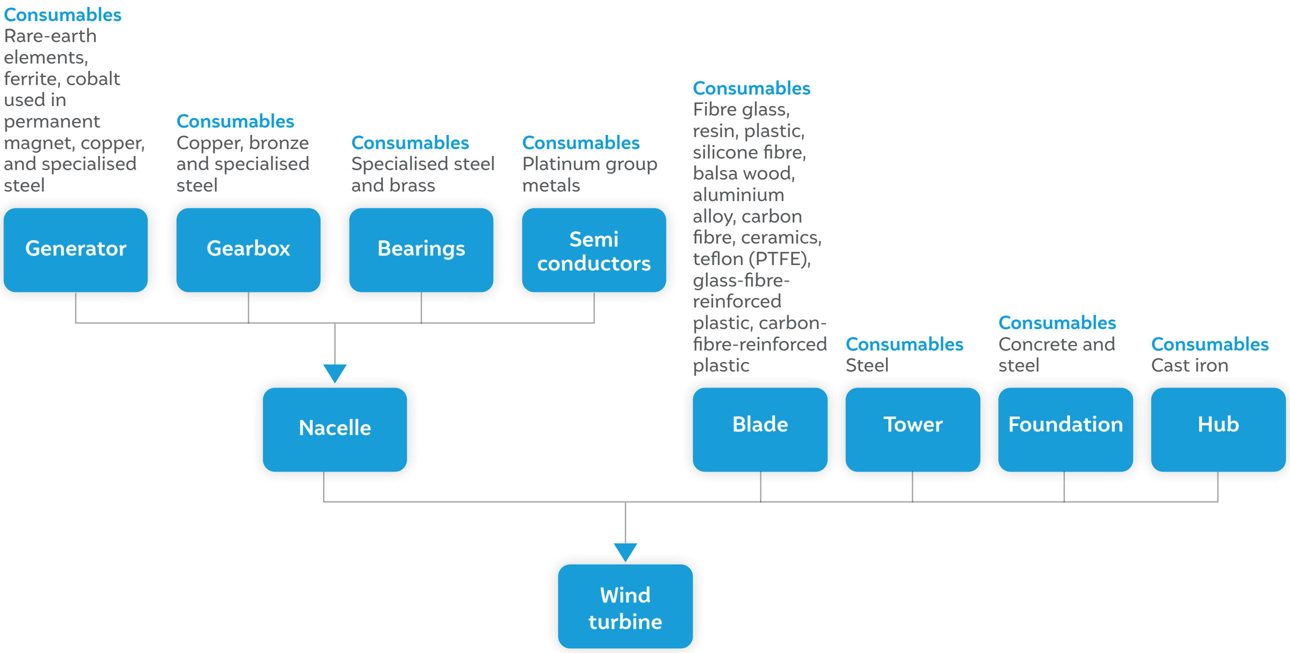
Source: Authors' analysis based on Dehghanimadvar, Mohammad, Renate Egan, and Nathan L. Chang. 2022. "Economic Assessment of Local Solar Module Assembly in a Global Market." Cell Reports Physical Science 3 (2): 100747. https://doi.org/10.1016/j.xcrp.2022.100747.

Note: Pie chart shows cost share of components in total cost of solar PV module manufacturing.

Wind turbines

The manufacturing of wind turbines involves transforming raw materials first into subcomponents and then into components as shown in Figure 12.

Figure 12 Manufacturing a wind turbine involves the assembly of several components, some of which are highly specialised in nature



Source: Authors' analysis from CEEW. 2023. Developing Resilient Renewable Energy Supply Chains for Global Clean Energy Transition. New Delhi: Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/developing-resilient-renewable-energy-supply-chains-for-global-clean-energy-transition.pdf.

2. Pie-chart shows cost share as a percentage of the cost of solar PV module manufacturing

The competitiveness of a wind turbine hinges on the quality and overall cost of manufacturing its key subcomponents, including towers, blades, nacelles, foundations, and grid interconnection equipment.

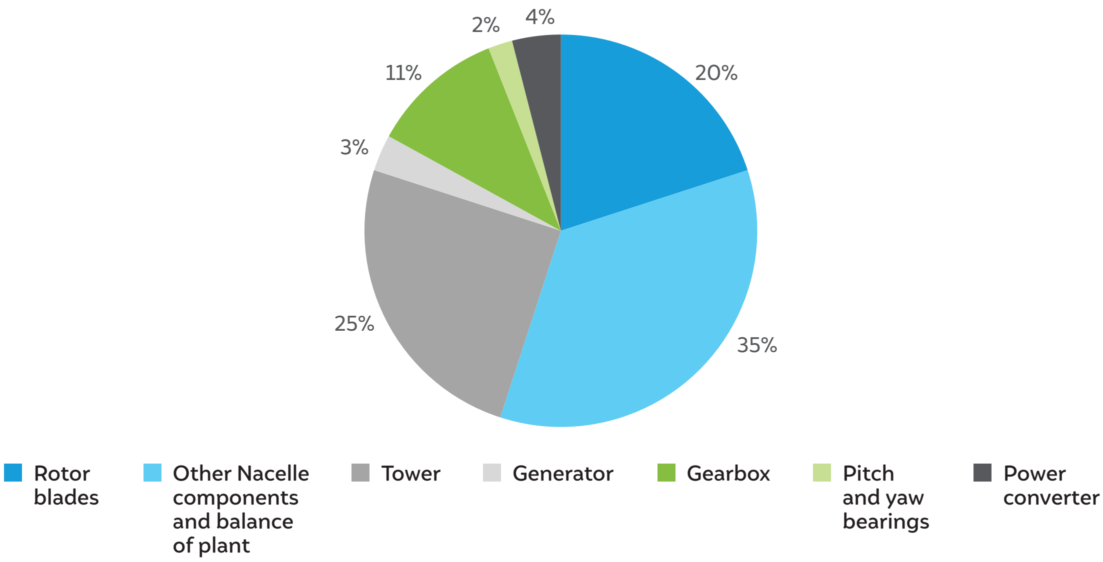
- **Towers**: The towers are predominantly made from steel but can also be constructed from concrete or a hybrid of concrete and steel.
- **Blades**: Typically, three blades are used in a rotor, connected by a hub. Rotor diameters have increased significantly, from 30 m in 1998 to nearly 125 m in 2020 (GWEC 2023).
- **Nacelles**: A nacelle encloses the drivetrain, including the generator, gearbox (for geared drivetrains), yaw system, and power electronics. In this report, we will be focusing on onshore wind turbines, whose foundations are generally made of concrete reinforced with steel or iron. The nacelle comprises over 1,500 components and subsystems, converting wind kinetic energy into mechanical energy to rotate a generator for electricity generation. Key nacelle components include:

  a) **Generators**: Wind turbines use two main types of generators: a doubly fed induction generator (DFIG) for geared operations and a permanent magnet synchronous generator (PMSG) for gearless operations. While DFIGs are favoured for grid coupling and lower material costs, PMSGs offer higher efficiency and can generate power at any speed but require a cooling system due to their temperature sensitivity. The global annual demand for wind turbine generators (WTGs) is expected to grow from 109 GW in 2023 to 189 GW in 2030. India has a generator manufacturing capacity of up to 8.25 GW (GWEC and MEC+ 2023). In India, most wind turbines use DFIGs due to their ease of grid coupling and lower material costs. However, it should be noted that the efficiency of the PMSG is greater than that of the DFIG, and they do not require a gearbox.

  b) **Gearbox**: These convert the torque from the wind turbine's blades into electrical power. There are three drivetrain technologies in use: high-speed gear, medium-speed gear, and direct drives. High-speed systems dominate the market with a 68 per cent share, followed by the direct drive (22 per cent) and hybrid drive (10 per cent) types.

The cost share of these components in the manufacture of a wind turbine is given in Figure 13.

Figure 13 Rotor blades and tower add the most to the cost of a wind turbine



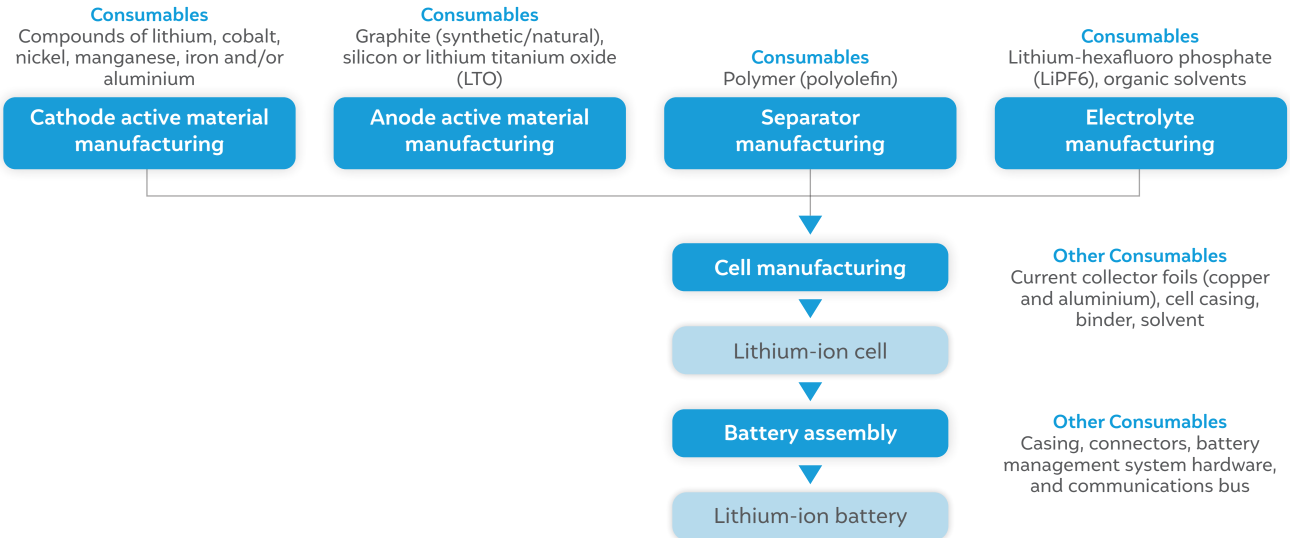
Source: Authors' analysis based on YedaCenter. 2020. "Wind Turbine Operational Cost Parameters." December 27, 2020. https://www.youtube.com/watch?v=Tp26k300_z8.

Blades, gearbox, towers, and foundation have the highest share in the overall cost of an onshore wind turbine. In the wind value chain, India holds a comparative advantage in turbines, gearbox, and hub castings and has a strong potential to gain a comparative advantage in wind generators.

Lithium-ion batteries

The manufacturing of lithium-ion battery involves the production of various cell components – such as the cathode materials, anode materials, separator, electrolyte, as well as the battery cell and battery management system – which are then assembled into a battery module. The value chain for lithium-ion batteries has been highlighted in Figure 14.

Figure 14 Manufacturing of lithium-ion batteries involves multiple steps, some of which are highly specialised in nature



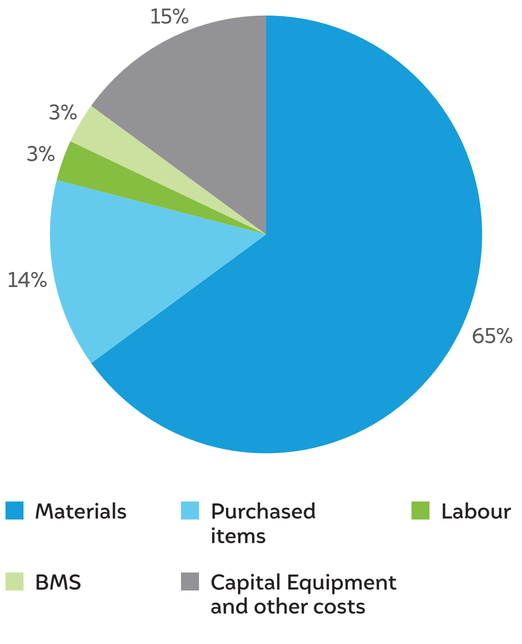
Source: Authors' analysis from CEEW. 2023. Developing Resilient Renewable Energy Supply Chains for Global Clean Energy Transition. New Delhi: Council on Energy, Environment and Water. https://www.ceew.in/sites/default/files/developing-resilient-renewable-energy-supply-chains-for-global-clean-energy-transition.pdf.

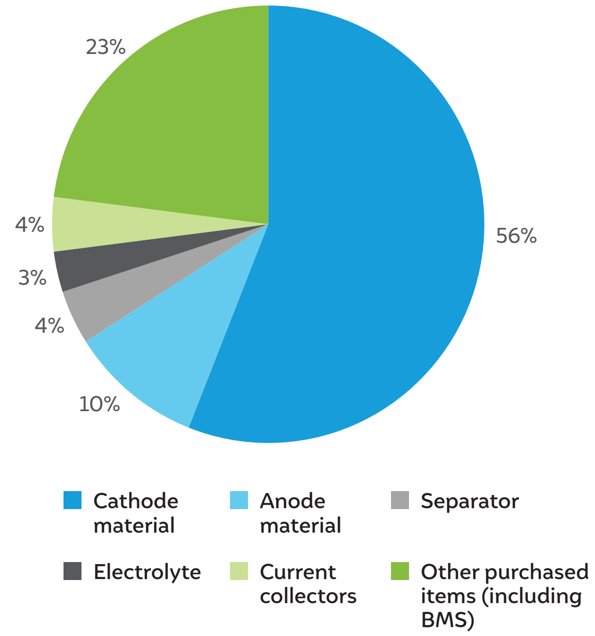
The manufacturing of the lithium-ion battery cathode material begins with the precursor materials, which include electrochemically active metals (NMC; iron and phosphorus) besides lithium. Lithium is then calcined in a kiln to chemically combine it with the precursor materials. Temperature control plays an important role in the final quality of the product (Heimes and Kampker 2019). Carbon coatings can then be added to the material to improve its conductivity.

Anodes can be made from natural graphite, created from high-purity flake (crystalline) graphite ore, or synthetic graphite, produced from petroleum-based needle coke or coal-based pitch coke (NITI Aayog 2023). Synthetic graphite is expected to make up nearly two-thirds of the global market share by 2025, likely due to its higher quality as well as difficulty in accessing flake graphite globally (Benchmark 2023). Production of synthetic graphite, however, is limited by access to high-quality, low-sulphur coke feedstock, of which crude oil refining residues and coal tar produced through coking of coal are the important components.

Most of the value of the battery is added in the component production process, wherein the cell, the battery management system, and structural components are manufactured. In 2022, battery and cell components made up over three-quarters of the final battery cost in the battery value chain as depicted in Figure 15.

Figure 15 Materials costs made up the largest cost share in Nickel, Manganese and Cobalt (NMC811) battery manufacturing in 2022





Source: Authors' compilation based on Argonne National Laboratory. 2023. "BatPaC 5.1." Lemont.

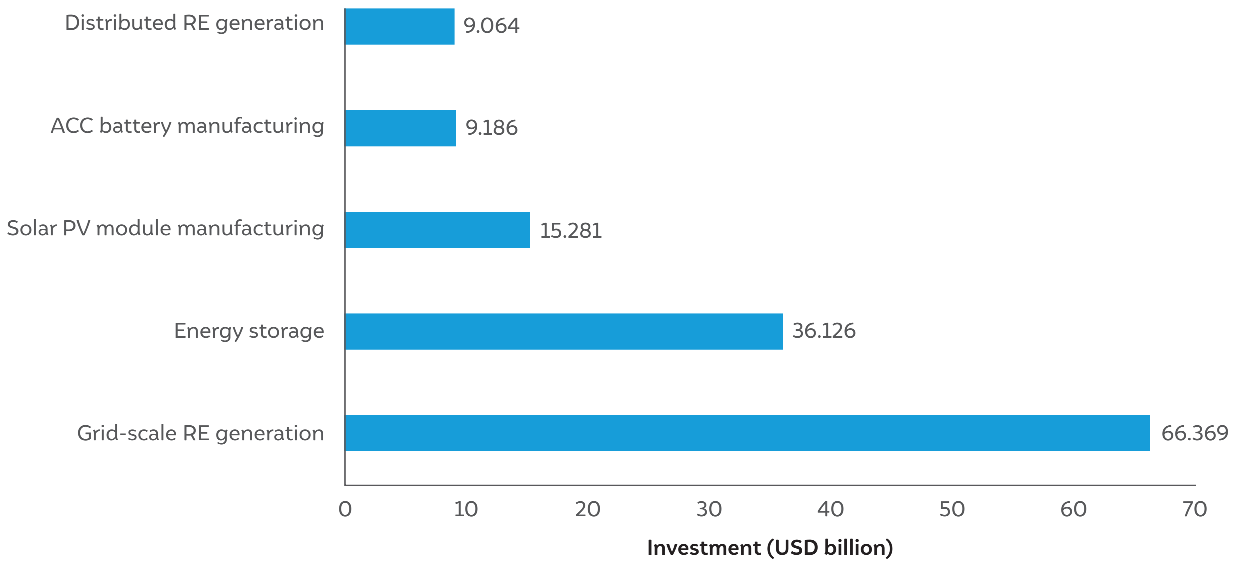
Note:
Graph A represents cost share of various steps involved in battery manufacturing process.
Graph B represents cost share of materials and structural components required to manufacture batteries.

2.2 India's clean energy manufacturing sector has immense potential

The prices of clean energy technologies – especially solar PV and batteries – are falling constantly and, in some cases, they have fallen below production costs. While it may be difficult for India's emerging manufacturers to compete immediately with Chinese hegemons, the industry has the right fundamentals to be cost-competitive against non-Chinese players in the midstream manufacturing portion of clean energy value chains. In the solar sector, for example, Indian manufacturers are on par with their peers in Southeast Asia and produce at a lower cost than European and American manufacturers (Sun 2023). In the battery sector as well, India is likely to be amongst the cheapest producers of cells when manufacturing at scale (IEEFA-JMK 2022). In the wind sector, where it is already amongst the largest global manufacturers of wind turbine components, India can become the key alternate supplier to clean energy markets looking to diversify their imports.

Clean energy supply chains in India are still under development. At present, the focus is on components and product manufacturing, distribution, and deployment to cater to domestic and overseas demand. Solar and wind manufacturing capacities in India have steadily increased with demand from international markets. For battery assembly, the domestic EV industry is expected to be the primary market, while several stationary storage solution manufacturers are looking to exploit a future market for battery-based storage technologies. Significant investments in solar cells and batteries are expected as of 2023, with grid-scale renewable energy generation attracting the largest share of USD 66.36 billion as shown in Figure 16.

Figure 16 Total pipeline of investment for clean energy innovation and manufacturing in India as of 2023



Source: Authors' compilation based on EY. 2023. Global Champions for Advancing Renewable Energy Innovation and Manufacturing. Ernst & Young. https://assets.ey.com/content/dam/ey-sites/ey-com/en_in/topics/energy-resources/2023/ey-global-champions-for-advancing-renewable-energy-innovation-and-manufacturing.pdf.

2.3 Solar photovoltaic manufacturing is beginning to vertically integrate

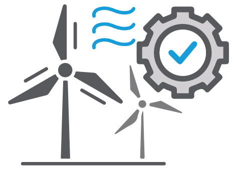
Due to a favourable policy ecosystem, domestic solar module manufacturing is now well-developed in India. Manufacturing capacities are expected to continue to grow in the years ahead. Estimates suggest that India may have more than 100 GW of solar module manufacturing capacity by 2026 (IEEFA-JMK 2023).

In 2023, India's cumulative module manufacturing capacity was around 64.5 GW (Mercom 2024b; Gupta 2024). The Indian solar manufacturing industry now has an established module manufacturing capacity. There are also plans to add significant polysilicon, wafer, and cell manufacturing capacities in future(PIB 2023c). As of June 2024, India's current installed capacity for solar power is 85.4 GW (MNRE 2024a). To achieve its installation target of 339–65 GW by 2031–32 (PIB 2023a), India needs to install more than 33.3 GW of solar annually, compared to 12.8 GW that were installed in FY 2022–23. However, despite such ambitious targets, Indian module manufacturing will need to rely on export markets unless the domestic targets are revised upwards.

Lack of economies of scale for individual factories and limited backward integration is leading to high costs of solar module manufacturing. For instance, it is estimated that solar module companies that have vertically integrated solar cells had profit margins of INR 3.2/watt-peak (Wp) (USD 0.04/Wp) in 2023, whereas the ones that only produce solar modules were unable to book margins and struggled to compete against larger players in the global market when prices fell to an all-time low (Wood Mackenzie 2023).

In 2023, India's cumulative capacity for cell manufacturing was about 6.6 GW. Four cell manufacturers represent 94 per cent of this capacity. Traditionally, Indian manufacturing lines are configured for smaller wafer sizes (156-158 mm) than their Chinese counterparts (166-210 mm) (Garg and Jain 2022). However, this is expected to change with the advent of new online manufacturing facilities in India (Gupta 2024). Larger wafer sizes enhance power generation per module, consequently lowering the product cost. Consequent, more efficient modules will make Indian manufacturers globally competitive.

Overall, failure to keep pace with the latest technological advancements has significantly contributed to the reduced competitiveness of Indian cell manufacturing, leading to heavy import reliance on cells amongst domestic module manufacturers. However, as per the revised Approved List Of Models And Manufacturers (ALMM) list, new manufacturing facilities are increasingly utilising passivated emitter and rear contact (PERC) technologies with high conversion efficiencies (> 500 Wp) (MNRE 2024e; Gupta 2022).



It is estimated that India has already achieved 70–80 per cent indigenisation in wind turbine manufacturing

2.4 India is a global leader in wind turbine manufacturing but more can be done

India has an annual wind turbine manufacturing capacity of 15–16 GW (IWTMA 2023b). However, in the last five years (FY 2019–24), India only installed an average capacity of 1.7 GW per year, which is very low compared to the peak installation rate of 5.5 GW in FY 2016–17 (MNRE 2024d). Such low annual installations have made it difficult for original equipment manufacturers (OEMs) of WTGs to continue operating due to the lack of a sizeable domestic market.

It is estimated that India has already achieved 70–80 per cent indigenisation in wind turbine manufacturing (MNRE 2022). To promote local manufacturing of wind energy turbine and its components, a customs duty exemption is provided through the Concessional Custom Duty Exemption Certificate (CCDC), which was issued along with the Revised List of Models & Manufacturers (RLMM)[3] (MNRE 2024c). As of January 2024, India has 31 approved models across 14 Indian and global companies. The approved models range in capacity from 225 kW to 5.2 GW, but most of the models are in the 2–3.6 GW range (MNRE 2024b). Currently, the manufacture of turbines takes place through (i) licensed production through joint ventures, (ii) manufacturers solely using domestic technology, and (iii) foreign company subsidiaries.

Wind turbines manufactured in the PRC are of the lowest cost globally. Chinese manufacturers can produce turbines within the range of INR 3.4–3.8 crore per MW, marking a nearly 30 per cent reduction compared to the costs of locally assembled Indian turbines, which fall in the range of INR 4.6–4.8 crore per MW. In contrast, turbines predominantly produced in India are the most expensive, in the range of INR 5.6–6.3 crore per MW (GWEC and MEC+ 2023). This discrepancy of around 30 per cent can be attributed to the high costs of commodities and raw materials, such as iron and steel, used in the production of wind turbines in India. Nearly 60 per cent of a wind turbine is made of steel (IWTMA 2023b). As of 2022, the disparity in the cost of steel between India and the People's Republic of China was approximately INR 16,000 per tonne. This difference increased to INR 16,400–20,500 per tonne for specific grades of steel essential for wind turbines, resulting in a roughly 9–12 per cent cost differential (GWEC and MEC+ 2023).

India is the largest manufacturer of wind turbine components after the PRC as shown in Table 1. The PRC typically holds 65–80 per cent of the global manufacturing capacity.

3. The RLMM is a list of type- and quality-certified wind turbine models eligible for installation in the country.

Table 1 India's holds a significant share in global manufacturing capacity of key wind turbine components

Component	Global capacity in 2023 (GW)	India's capacity (& share in the global market) in 2023 (GW)
Gearbox	166.5	15.5 (9%)
Generators	155.6	8.25 (5%)
Blades	156.8	12.92 (8%)
Power converters	222.7	10.6 (5%)
Towers	38	2.8 (7%)

Sources: 1. GWEC. 2023. Global Wind Report. Brussels: Global Wind and Energy Council. 2 GWEC and BCG. 2023. Mission Critical: Building the global wind energy supply chain for a 1.5°C world. https://gwec.net/wp-content/uploads/2023/12/MISSION-CRITICAL-BUILDING-THE-GLOBAL-WIND-ENERGY-SUPPLY-CHAIN-FOR-A-1.5%C2%B0C-WORLD.pdf.

Currently, India produces WTGs of up to 5.2 MW (MNRE 2024b). India has the potential to become a net exporter to countries such as France, Sweden and the United States, which use WTGs in ranges similar to those produced by India given that these domestically produced WTGs are cost competitive. To tap into the approximately 31 GW market for WTGs by 2027 in countries such as Australia, Brazil and the United Kingdom, which use up to 6.2 MW WTGs, India needs to upscale from 5.2 MW WTGs to those closer to 6.2 MW (GWEC and MEC+ 2023).

In terms of rotor diameter, the majority of Indian manufacturers have the capacity to manufacture up to 132 m. However, they must upscale to manufacture rotors larger than 160 m in diameter to meet the global requirements. Currently, in the RLMM list, Adani Wind (in a joint venture with W2E GmbH, Germany) and the Indian arm of Brazil-based WEG are the only manufacturers in India producing 5.2 MW and 4.2MW of WTGs with rotor diameters of 160 m and 142 m, respectively (IWTMA 2023a; MNRE 2024b).

In gearbox manufacturing, the PRC and India are the world's two largest wind gearbox manufacturing countries, so both markets have sufficient capacity to accommodate demand in 2023–30 (GWEC and MEC+ 2023). India has seven major gearbox manufacturers, out of which at least two are exporters of gearboxes globally (All about Renewables 2024; IWTMA 2022). However, the companies in India exporting gearboxes are mostly in joint ventures with companies from Europe and the PRC (ZF 2024).

In blades manufacturing, the PRC and India stand as the world's two primary manufacturing centres for wind turbine blades. Both markets have ample production capacity, adequately meeting the anticipated demand for the decade 2023–33.

In 2022, India was the second-largest casting manufacturer globally, yet commands only a 10 per cent share of the global market. This is attributed to uncertain domestic demand for wind power and intense competition from the People's Republic of China. Although India holds the second position in casting manufacturing, approximately 42 per cent of the total casting needed for turbine export production and 50 per cent for domestic wind installations are sourced from the PRC (GWEC and MEC+ 2023). Additionally, nearly 90 per cent of the total castings required for domestic gearbox manufacturing originate from the PRC (GWEC and MEC+ 2023).

Wind towers are another import component being manufactured in India. It should be noted that Indian wind towers being exported to the United States are subject to countervailing duties of 51 per cent.

2.5 The lithium-ion battery sector is still nascent, but has massive potential

India has a mature but small lithium-ion battery assembly sector, with over 6.5 GWh of manufacturing capacity as of 2022 (IEEFA-JMK 2022). This industry caters to India's battery storage market as well as the growing two-wheeler and three-wheeler EV segments. However, battery assembly is a low-value-addition operation as well as labour intensive.

Most of the value of the battery is added in the battery component production process

Most of the value of the battery is added in the battery component production process, wherein the cell, the battery management system, and structural components are manufactured. While several announcements have been made regarding pilot production of several of these components, India lacks any at-scale production of these technologically complex and high-value-added products. In the wake of the advanced chemistry cell (ACC) production-linked incentives (PLI) scheme, 30 GWh of capacity has been sanctioned with support from the Indian government (PIB 2024a). As much as 115 GWh of manufacturing capacity overall has been committed as of 2023, with or without PLI support (VDMA 2023). However, this is only 2 per cent of the global commitments of 7 terawatt hours (VDMA 2023).[4]

A recent analysis by CEEW suggests that cumulatively, battery cathode materials of 716–902 kt may be required for the domestic cell manufacturing sector between 2022 and 2030 (Warrior, Tyagi, and Jain 2023). Indian companies have announced investments into the cathode material manufacturing sector, including start-ups such as Altmin – targeting 3 GWh production by 2025 – or established chemical players such as Himadri Chemicals, which is looking to manufacture cathode material, required for 100 GWh of Lithium-ion battery production.y. (Altmin 2024; Dutt 2023).

The focus of several of these companies has been on scaling production of LFP materials in India. In the past few years, LFP has gained traction in the global battery market as well. This could be attributed to (a) its lower cost – 32 per cent cheaper than NMC, (b) its independence from 'critical' minerals such as nickel and cobalt, and (c) its beneficial performance characteristics such as a longer cycle life and improved thermal stability (Benchmark 2020; BloombergNEF 2023a).

India has a history in graphite production. Several Indian companies, such as Graphite India (government-owned) and Epsilon Advanced Materials (private), have shown an interest in scaling production of active anode materials. However, for Indian companies with experience primarily in anode manufacturing for steel blast furnaces, significant capacity building will be required to produce 99.95 per cent pure, spherical, battery-grade graphite for anodes. While still a nascent space in India, some preliminary development has already taken place in electrolyte production. As an example, international company Noco-noco and Indian player Neogen have forged a strategic partnership to manufacture battery separators in India, with Neogen already being an important player in the electrolyte space (GlobalNewswire 2024).

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4. It should be noted that not all commitments lead to actual factory commissioning. Further, investors may cancel or delay depending on business conditions. For instance, many battery manufacturing facilities planned in Western countries may face commissioning challenges due to the record low product prices emerging from the People's Republic of China.

3. Challenges to India's manufacturing policies in a new global paradigm

India has reprioritised the indigenisation of the clean energy manufacturing through policies like the PLI schemes for solar modules and batteries.

In recent years, India has reprioritised the indigenisation of the clean energy manufacturing value chains through policies such as the PLI schemes for solar modules and batteries. Through non-tariff measures – such as the ALMM for solar photovoltaic modules and the RLMM for wind turbines – the government also aims to create a market for domestic manufacturers. However, to avail maximum strategic benefit in terms of achieving our objective of (i) energy security, (ii) increased domestic value capture, (iii) export competitiveness, and (iv) structural transformation of the economy, we need to recognise the changing order of the global political economy and identify and solve the challenges faced by India's manufacturing sector. The gaps in policy consistency, market competitiveness, and the absence of critical manufacturing enablers must be addressed to optimise India's policy landscape for scaling a globally competent clean energy manufacturing industry. This section highlights the challenges that the sector has faced, the current status of the sector in the global paradigm, and the missing enablers that have limited the growth of the sector.

3.1 Need for consistency in India's clean energy policies

India has tried to support clean energy deployment and manufacturing through policies of indigenisation, increasing domestic production capabilities in the process. Clean energy equipment related to solar, wind and batteries has been successfully produced in the country. However, to deeply integrate the value chains and establish a globally competitive industry, consistent policy support is required to enable industries and investors in India.

While the ALMM has been described as a quality order, it is often categorised as a non-tariff barrier

Solar

India has tried to support domestic manufacturing through instruments such as trade and non-trade barriers, financial incentives, and preferential procurement. However, there has been a lack of long-term visibility of policy support that has impacted the indigenisation levels. The support for domestic solar manufacturing started with a mandate for the preferential procurement of domestically produced solar modules through the domestic content requirement (DCR) for utility scale solar projects in India (IEEFA-JMK 2021). This continued in other broader programmes – such as the CPSU Scheme, which was launched to help central public sector undertakings (CPSU) set up 1,000 MW of grid-connected solar PV power projects (MNRE 2015), the *Rooftop Solar Scheme,* and the *Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan Yojana* (PM-KUSUM) scheme (MNRE 2019) – all of which mandate the use of domestically produced solar cells and modules.[5] Furthermore, in 2019, the MNRE issued the guidelines for implementing the ALMM wherein only enlisted solar cell and module manufacturers with a specified minimum module efficiency could participate in government projects (MNRE 2021a). Initially the order was supposed to be implemented from 31 March 2020, but it was delayed due to COVID-19, which limited domestic manufacturing capacity. It should be noted that the ALMM for solar modules has been in force since April 2024, but the date for implementing the ALMM for solar cells has not been decided yet due to the limited number of cell manufacturing facilities in India. While the ALMM has been described as a quality order, it is often categorised as a non-tariff barrier since only those companies with manufacturing facilities in India are included in the ALMM as of July 2024 (MNRE 2024c).

Over the years, the government has also experimented with different forms of import tariff duties to reduce the cost disparity between domestically produced and imported products (Table 2, 3). A safeguard duty (SGD) with varying rates was imposed from 2018 to 2021 to protect domestic manufacturers. An anti-dumping duty (ADD) is also levied on solar glass and EVA sheets in India. In 2022, the government also imposed basic customs duty (BCD) of 40 per cent and 25 per cent on imported modules and cells, respectively. However, exemptions for developing countries from SGDs and for Free Trade Agreement (FTA) partners from BCD have reduced the impact of such interventions since imports have been routed through these countries or products manufactured in these regions experienced a significant rise in imports. For these reasons, domestic manufacturing capacities did not increase significantly.

However, with the help of financial support in the form of PLI (Tranche I, which had an outlay of INR 4,455 crore/USD 0.56 billion, and Tranche II, which had an outlay of INR 1,3937.57 crore/USD 1.75 billion (MNRE 2021b; SECI 2022)) – coupled with the ALMM and BCD, India's integrated solar PV manufacturing capacity has reached 48,337 GW . This combined allocated capacity will strengthen India's solar supply chain. The key policy initiatives that have helped realise this capacity have been compiled in Table 2.

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5. Although various programmes and schemes exist, the government has often relaxed implementation efforts due to limited manufacturing capacities and delayed enforcement deadlines.

Table 2 Checkboard for policy levers deployed to facilitate solar manufacturing in India

Policy levers	Financial incentive	Eligibility for public projects	Tariff measure	Non-tariff measure
Domestic Content Requirement (DCR), 2010		✓		✓
Modified – Special Incentives Package Scheme (M-SIPS), 2012	✓			
Central Public Sector Undertaking (CPSU) *Scheme*, 2015		✓		
Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan (PM-KUSUM) *Scheme*, 2019	✓			
Safeguard duty (SGD), 2018–21			✓	
Approved List of Models and Manufacturers (ALMM), 2021		✓		✓
Production-Linked Incentive (PLI) *Scheme – Tranche I and II*, 2021 and 2022	✓			
Basic customs duty (BCD), 2022			✓	

Source: Authors' analysis

Table 3 Varied tariff measures in the solar sector in India

Type of tariff measure	Applicability in the solar sector
Safeguard duty (SGD)	✓
Anti-dumping duty (ADD)	✓
Basic customs duty (BCD)	✓

Source: Authors' analysis

Wind

In the wind sector, the policies have been largely consistent: the period between 1994 and 1996 was referred to as the 'wind rush' due to the increased growth of the sector led by private investments and fiscal incentives introduced by the central government (Sharma and Sinha 2019). Later, the attractiveness of the sector was reduced due to an alternative tax levied on investors. However, the de-licensing of electricity generation through the Electricity Act, 2003, and incentives through the accelerated depreciation (AD) mechanism attracted many players to the market (Ganesan et al. 2014). Additionally, the introduction of the generation-based incentives (GBI) in 2009 accelerated capacity additions and increased the participation of independent power producers (IPPs).

Policy levers such as AD and GBI were discontinued in 2012, resulting in low annual capacity additions in 2013. In 2016, the government implemented reverse bidding for wind projects, leading to lower tariffs for the developers in subsequent years. These developers negotiated with OEMs for lower costs of wind turbines and other components (Saji, Kuldeep, and Tyagi 2019). To promote the local manufacture of wind energy turbine and its components, a CCDC is issued along with the RLMM. Therefore, in the wind sector, there has been a demonstration of trials and learnings – a key tenet for industrial policies. A summary of the policy levers used to spur growth and development of the wind manufacturing sector in India is illustrated in Table 4.

Table 4 Checkboard for policy levers deployed to facilitate wind manufacturing in India

Policy levers	Financial incentive	Eligibility for public projects	Tariff measure	Non-tariff measure
Accelerated depreciation (AD)	✓	✓		
Generation-based incentives (GBI), 2009	✓	✓		
Revised List of Models & Manufacturers (RLMM)		✓		✓
Concessional Custom Duty Exemption Certificates (CCDCs)	✓		✓	

Source: Authors' analysis

Lithium-ion batteries

The foundations of lithium-ion battery manufacturing in India are closely associated with the decarbonisation of the transportation sector and, as such, the policies initiated are closely linked with this sector. The *Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India* (FAME) scheme was introduced to provide demand incentives for increasing the uptake of electric vehicles in the country. In its latest iteration, phase two of the scheme was introduced at a budgetary expense of INR 10,000 crore (USD 1.25 billion) by the Ministry of Heavy Industries (MHI)(PIB 2023b).

Recent policy support for battery manufacturing and the indigenisation of technology started with the introduction of the National Programme on Advanced Chemistry Cell (ACC) Battery Storage in 2021. The total outlay of the scheme was INR 18,100 crore (USD 2.26 billion) with the expectation that 50 GWh of manufacturing capacity swould be installed (PIB 2022). It is expected that an investment of USD 4.5 billion may be required to set up 50 GWh of lithium-ion cell and battery manufacturing plant under the PLI scheme. To date, 30 GWh of battery manufacturing capacity has been allocated to three companies, and 20 GWh is in the process of tendering. Additionally, India plans to install 4,000 MWh of battery energy storage system (BESS) projects by 2030–31, with viability gap funding support from the government (PIB 2023b) and an outlay of INR 9,400 crore (USD 1.17 billion).

While several announcements have been made about setting up production lines for these components, India lacks large-scale production of these technologically complex and high-value-added products. Conversations with stakeholders about clean energy manufacturing in India indicate a lack of or delay in investments in the solar PV modules and ACC battery PLI segments, leading to a potential delay in the PLI timelines. It has been estimated that only 21 per cent of the total targeted investments have been reported under both tranches of the solar PLI (Sahu 2024). Progress has been made in the battery PLI, but there have been several delays with the 20 GWh worth of capacity allocation (Vaid and Jagota 2023).

Globally, investments in the upstream segments – critical minerals – have also been lukewarm, with mining investments slowing in 2023 compared with 2022 (IEA 2023a). The conservative response can be attributed to higher lead times in mining activities and technology changes at the end-product level, making investment decisions risk intensive (IEA 2023e). A similar trend is being observed in India, where critical mineral mining auctions have received limited response from the industry (Kumar 2024). The policy development for lithium-ion battery manufacturing in India is illustrated in Table 5.

Table 5 Checkboard for policy levers deployed to facilitate battery manufacturing in India

Policy levers	Financial incentive	Eligibility for public projects	Tariff measure	Non-tariff measure
Advanced Cell Chemistry (ACC) Production-Linked Incentive (PLI) Scheme, 2021	✓			✓
Viability Gap Funding (VGF) *Scheme* for stationary battery storage, 2023	✓	✓		
Basic customs duty (BCD)			✓	

Source: Authors' analysis

3.2 Global developments pose a challenge to the competitiveness of Indian manufacturers

Global price, trade and policy factors are affecting the competitiveness of Indian manufacturers. The challenges are often dynamic, impacting the domestic market as well. A strong domestic demand and adaptive industries can ensure that certain risks associated with the global market can be hedged against. The following section identifies these factors.

The capacity equation and falling prices

India has deployed 15.03 GW of solar capacity in FY 2023–24 (MNRE 2024d). The cumulative manufacturing capacity for solar PV modules and cells in the country stands at 64.5 GW and 5.8 GW, respectively, as of December 2023 (Mercom 2024b). We observe that supply significantly outweighs the deployment. Moreover, the solar PLI scheme is expected to add 48.34 GW of new manufacturing capacity to the Indian market (PIB 2023c). Given the current pace of deployment, overcapacity in solar module manufacturing is expected to remain.
It is essential to note that not only in India but also globally, there is a significant overcapacity across the solar module manufacturing value chain. For instance, the global solar module manufacturing capacity is currently around 800 GW (IEA 2023d). Additionally, solar module prices have decreased significantly in the global markets, dropping to as low as USD 0.10/Wp (INR 8/Wp) (InfoLink n.d.a). The prices of Indian modules have been compared with those produced in other countries in Table 6.

Table 6 Chinese modules remain the most affordable option across several regions

Country	Price* (USD/Wp)
The People's Republic of China	0.100
India	0.180
United States	0.250

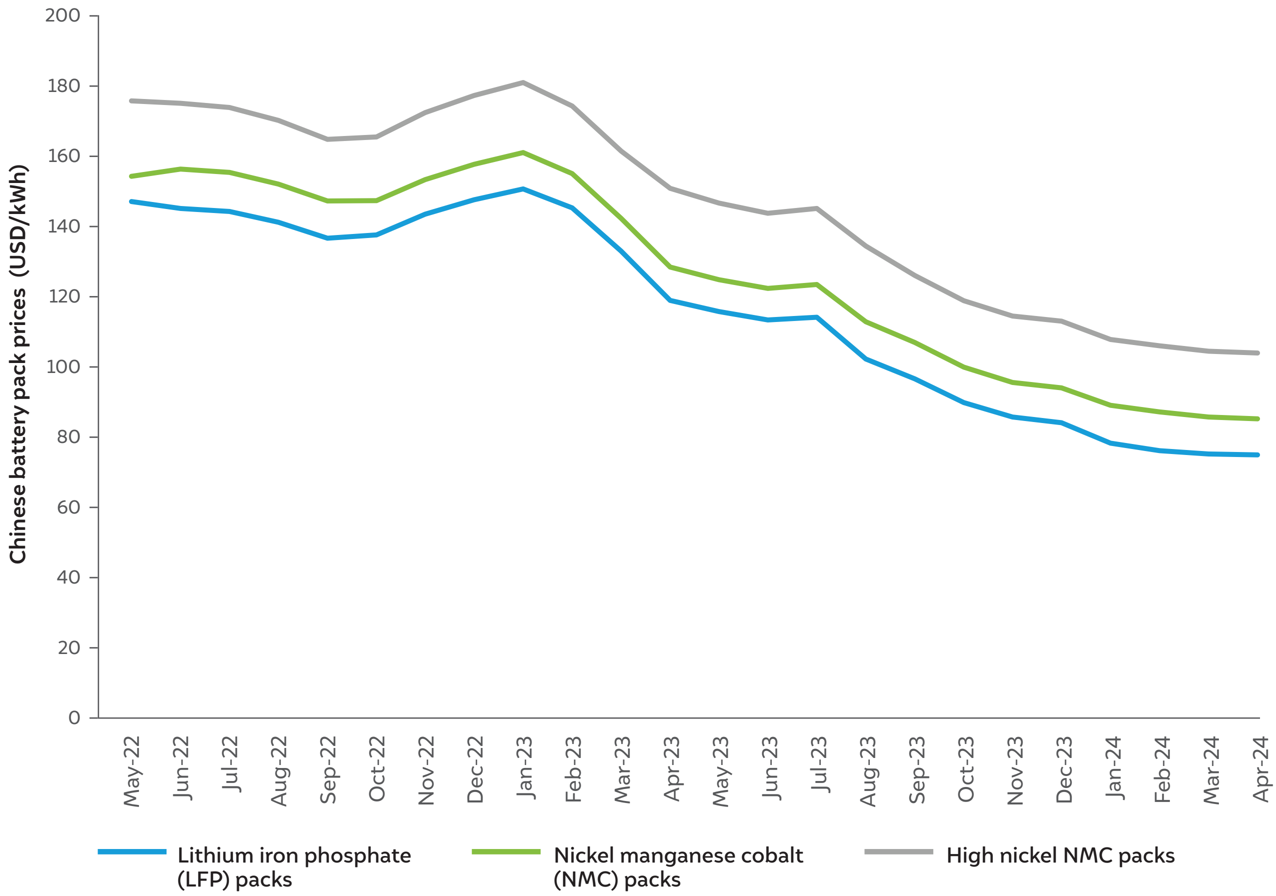
Source: Authors' compilation based on spot data price tracked by InfoLink. n.d.a. "Wafer Spot Prices." Last accessed August 8, 2024. https://www.infolink-group.com/spot-price/.

*Prices for mono-PERC modules (182 mm × 182–210 mm) for June 2024.

In batteries, the demand for battery energy storage is expected to reach 27 GW/108 GWh by 2029–30 (CEA 2023). The battery storage capacity installed as of March 2024 was 219.1 MWh (Mercom 2024a), indicating a large demand-supply gap in storage. Additionally, for electric vehicles, by 2030, only 13 per cent of total battery cell demand is expected to be sourced domestically, while the rest may be fulfilled by imports (Das 2024). Therefore, there is a need to scale up domestic manufacturing of energy storage technologies to meet the increasing demand from use in the grid and transport sectors.

From the perspective of lithium-ion batteries, recent analyses indicate that as of 2020, India could be amongst the cheapest producers of lithium-ion cells, with production costs of USD 92 per kWh (IEEFA-JMK 2022). In 2024, the prices of lithium-ion battery packs in the PRC are also reaching a historic low (Figure 17). However, economies of scale are a major contributor to the final cost of cell manufacturing, potentially responsible for nearly 30 per cent of the cost decline in lithium-ion batteries (Mauler, Duffner, and Leker 2021; Ziegler, Song, and Trancik 2021).

Figure 17 **Lithium-ion battery pack prices in the People's Republic of China have reached an all-time low in 2024**



Source: Authors' compilation based on McKerracher, Colin. 2024. "China's Batteries Are Now Cheap Enough to Power Huge Shifts." Bloomberg, July 9, 2024. https://www.bloomberg.com/news/newsletters/2024-07-09/china-s-batteries-are-now-cheap-enough-to-power-huge-shifts.

Note: LFP refers to lithium iron phosphate; NMC refers to nickel manganese cobalt, which includes prices for NMC111, NMC532, and NMC622 batteries. High-nickel NMC includes NMC811, NMC955, and NCA.

To become competitive in the global market, Indian battery manufacturers need to develop economies of scale and cost-competitive production of lithium-ion cells. There has been progress in India in ramping up battery production facilities with companies such as Reliance, Suzuki, Tata, Godi India, Good Enough Energy, and others that plan to set up gigafactories across the country (The Economic Times 2023; Garg 2024; HinduBusinessLine 2024; Reuters 2024).

In the wind sector, turbines produced in India are relatively expensive, ranging from INR 5.6 crore to 6.3 crore per MW, nearly 30 per cent higher than their Chinese counterparts (GWEC and MEC+ 2023). Table 7 shows the cost comparison of wind turbines manufactured in India and those produced elsewhere. There is an uncertain domestic demand for certain wind sub-components such as casings, amidst intense competition from the PRC (GWEC and MEC+ 2023). Overall, India must close the price gap in wind components to exploit the sector's export potential.

Table 7 Cost differential of various turbines manufactured in India and abroad

Type of turbines	Cost per MW	
	EUR (million)	INR (crore)
European OEMs manufactured in India	0.67–0.71	5.9–6.3
Indian turbines	0.64–0.67	5.6–5.9
Components imported and assembled in India	0.52–0.54	4.6–4.8
Chinese turbines	0.39–0.43	3.4–3.8

Source: Authors' compilation based on GWEC and MEC+. 2023. From Local Wind Power to Global Export Hub. Brussels: Global Wind and Energy Council.

The Indian market is very price sensitive, and domestic manufacturers have not been able to compete with Chinese suppliers. However, stakeholder consultations suggest that in the recent years, the demand for non-Chinese products in domestic and international markets has increased exponentially. Given the significant price differential between Indian and Chinese companies, the competition with the Chinese will remain tough. While the Indian government has implemented many import barriers, domestic manufactures will need to find new markets that are willing to pay premiums for alternative supply chains.

Trade barriers and global manufacturing incentives

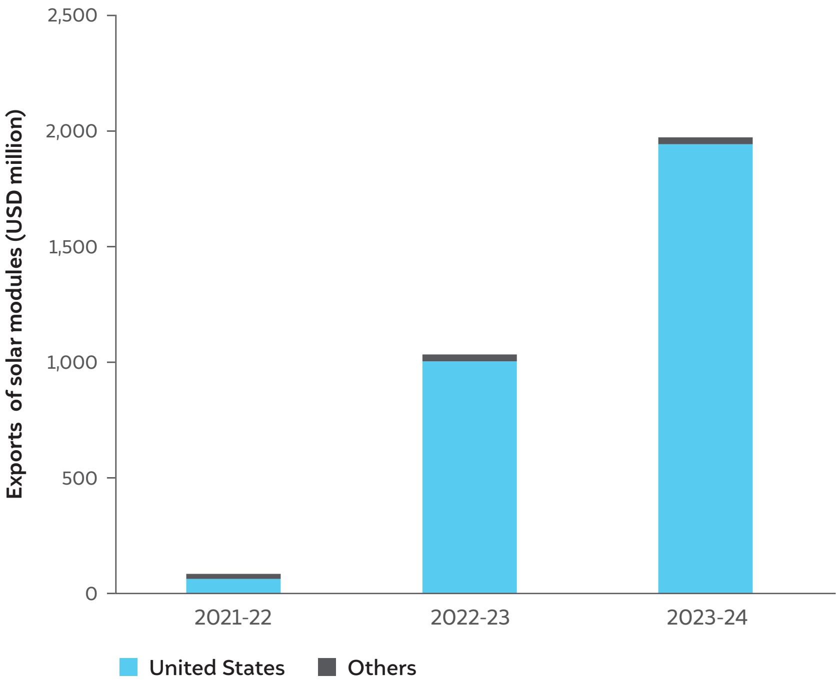
The political economy of global clean energy manufacturing is leading many countries – both developing and developed – to capture larger shares of the domestic and international demand. Successive announcements from companies in the People's Republic of China, the United States, and Europe have added to existing overcapacities across the supply chains of both solar PV and battery manufacturing globally (IEA 2023e). Additionally, near-shoring and friend-shoring of supply chains are currently underway, with policies – such as the United States's Inflation Reduction Act (IRA), the European Union's (EU) Net-Zero Industrial Act (NZIA), Future Made in Australia Act, and Made in China 2025 – making it increasingly harder for companies to enter these markets. The IRA was a landmark development in clean-tech policy with global impacts in the United States. Enacted in August 2022, with approximately USD 370 billion allocated to energy and climate investments, the IRA provided over USD 60 billion to boost domestic clean energy manufacturing through production tax credits and consumer incentives, as well as authorising the use of certain defence-related funds for clean energy technologies (IEA 2023e). Since the launch of the IRA, over USD 100 billion in investments in solar and storage manufacturing have been announced (SEIA 2023). Moreover, under the electric vehicle scheme of the IRA, EV components and products, such as batteries, produced in countries that have FTAs with the United States are also eligible for critical mineral subsidies per the IRA. Thus, several countries, including Australia, Canada and Mexico, will attempt to utilise their preferential access to the North American market and attract investment to set up domestic manufacturing capacity.

The 'small-yard, high-fence' approach of the United States under the IRA assigns higher import tariffs to international suppliers for strategic goods. Indian manufacturers have also been benefiting from the 'China Plus One' sentiment, exporting 98.5 per cent of India's export value to the United States in FY 2023–24 (Figure 18).

For batteries, Europe is also aiming to indigenise 40 per cent of EU's annual deployment by 2030 (Official Journal of the European Union 2024). Southeast Asian countries such as the Republic of Indonesia are also trying to indigenise battery manufacturing at globally competitive prices (Medina 2024). India's current lithium-ion battery exports (Figure 19) indicate a general trend and an opportunity to develop capacities for export markets as well. The export market is increasing for Indian manufacturers leading with Germany, Japan and the Republic of Indonesia as destinations.

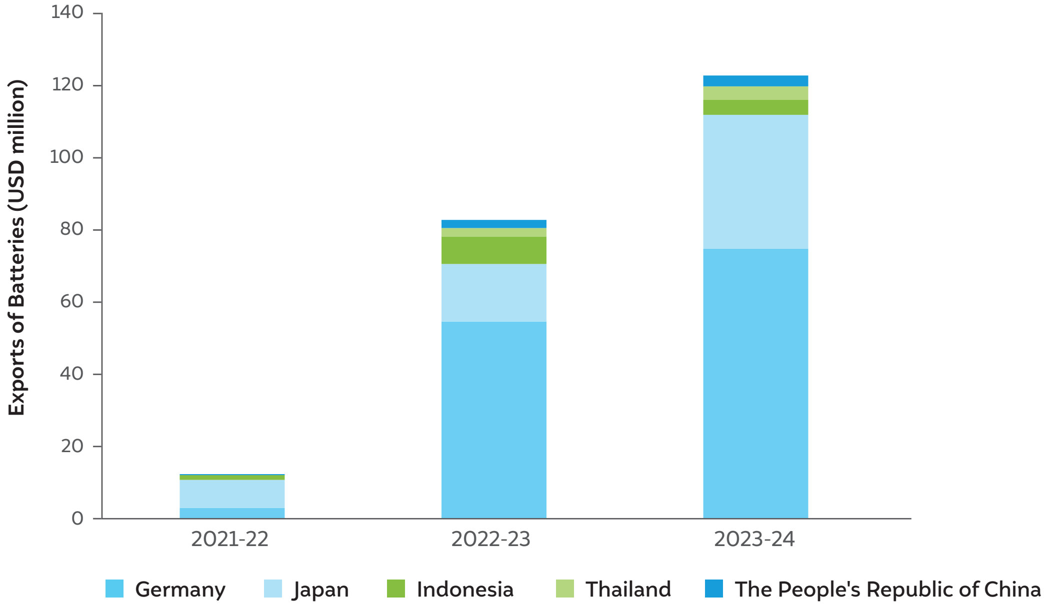
Similarly, the current market for Indian-made wind generators is primarily Europe and the United States (Figure 20). Demand from these markets may be affected by indigenisation policies. Hence, potential tariff barriers and manufacturing incentives in foreign countries may negatively impact Indian manufacturers in the long run.

Figure 18 Nearly all exports of solar modules from India were destined for the United States



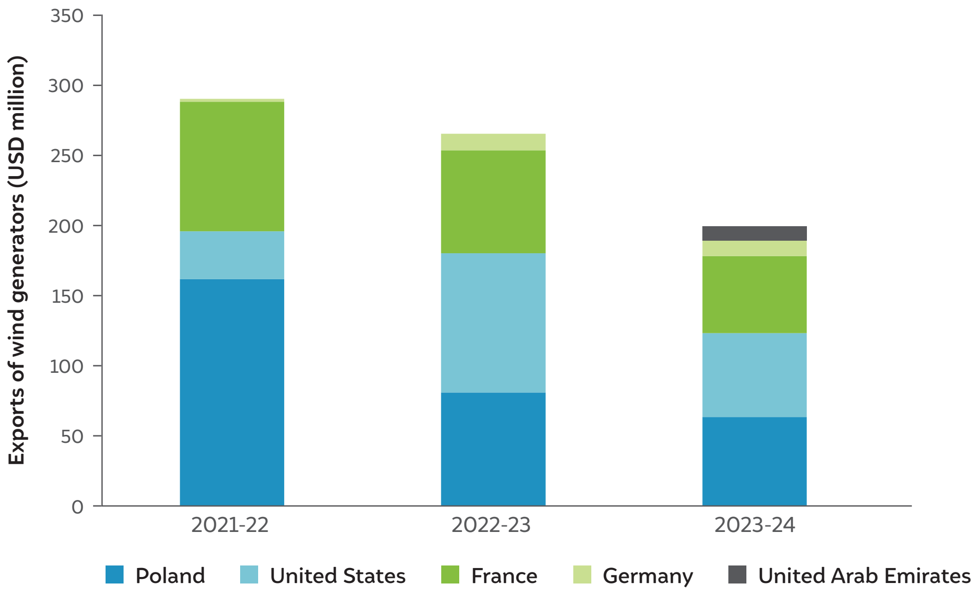
Source: Authors' analysis from Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp. Note: HS code 854143

Figure 19 India is steadily increasing its lithium-ion battery exports, with Germany and Japan as the largest markets



Source: Authors' analysis from Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp. Note: HS code 850760

Figure 20 India's wind generator exports are to Europe and the United States



Source: Authors' analysis from Department of Commerce. 2024. "Total Trade." Last accessed August 9, 2024. https://tradestat.commerce.gov.in/eidb/default.asp. Note: HS code 850231

There are also non-tariff barriers – such as ESG indicators and emission-intensity thresholds – which may be implemented in the future in certain markets. For example, the new battery regulation approved by the EU includes mandatory carbon footprint reporting for batteries (Kupferschmid 2023). Europe could potentially mandate ESG criteria for local solar manufacturers under the NZIA. Major solar manufacturers have committed to reducing GHG emissions per unit of electricity consumed. Some Chinese companies such as JinkoSolar and LONGi have initiated zero-carbon factory certifications for factories that operate on clean energy (JinkoSolar 2023; LONGi 2023). Indian manufactures can also actively work to reduce their emission intensity to avoid disruptions in their export demand.

3.3 Indian manufacturers lack access to the input materials, machinery, and manufacturing enablers needed to take advantage of the PLIs

Critical minerals are essential building blocks of clean energy manufacturing. The raw materials needed for manufacturing solar, battery, and wind components require extensive use of these critical minerals. However, the geographic concentration of critical mineral resources and processing make supply chains for critical minerals vulnerable to disruptions and coercive actions. The current concentration of critical minerals value chains can be attributed to natural resources, technical capabilities, and long-term investments in the sector. Critical mineral endowments are highly concentrated with 55 per cent of select critical minerals available in only 15 countries as of 2022 (CEEW et al. 2023). These minerals include cobalt, copper, graphite, lithium, manganese, nickel, and rare-earth elements (REEs). Additionally, there are long-term mineral offtake agreements and mining investments by large global battery manufacturing firms, which are looking to vertically integrate their operations. Therefore, securing access becomes a challenge for smaller firms (IEA 2023a).

Other than the upstream requirements for critical minerals, access to machinery and technical resources for manufacturing clean energy products is a challenge for Indian manufacturers. Most of the winners of the PLI scheme have supply chains and service partners primarily from the PRC, where the existing global manufacturing capacity is concentrated. There is a dependence on the equipment for manufacturing required for the assembly lines in India, which can induce long-term dependence on foreign sources for spare parts and after-sales service (LiveMint 2024).

Finally, the availability of finance at competitive rates remains a major challenge for domestic manufacturers, which significantly reduces their competitiveness in the export market. It is important to note that manufacturing facilities continue to attract higher rates than both global competitors and domestic clean energy projects. For instance, the Indian Renewable Energy Bank – Indian Renewable Energy Development Agency Limited (IREDA) has higher interest rates (up to 135 basis points) for manufacturing facilities compared to renewable energy projects in India. Manufacturing (solar and wind) and related ancillaries have interest rates ranging from 9.5 per cent to 10.25 per cent. For EV manufacturing, this rate can range from 10.5 per cent to 11.5 per cent in INR terms (IREDA 2024). In comparison, Chinese manufacturers can avail themselves of interest rates around 3–4 per cent in USD terms (China Energy News 2023). Additionally, stakeholders have often raised concerns about the limited availability and high rates of working capital. Therefore,, it is imperative to reduce the lending interest terms for clean energy manufacturing to enable the ecosystem to scale up and compete in the global market.

The availability of finance at competitive rates remains a major challenge for domestic manufacturers, which significantly reduces their competitiveness in the export market

4. A new, focused policy agenda for India's clean energy manufacturing

Indian policymaking can benefit from market research interventions in various components of clean energy value chains.

We believe that the next stage of Indian clean energy industrial policy should focus on strategic sectors that will (i) drive manufacturing competitiveness and resilience and (ii) enable building of a high-tech manufacturing and innovation ecosystem. With significant investment already made due to numerous government initiatives, we now aim to highlight areas where intervention by Indian policymakers can be pivotal:

1. Strengthen segments that are crucial to the competitiveness and resilience in the production of clean energy products but currently lack sufficient domestic scale.
2. Identify supply chain segments where India could be a world leader and capitalise on the ubiquitous 'China Plus One' sentiment to gain a larger share in the international market.

3. Build capabilities in ‘complex’ (discussed in Section 4.2) and technology-intensive clean energy technology segments to leverage spillover effects that will enable broader structural transformation (discussed in Section 1.4).

In this section, we address the prioritisation challenge in two ways: first, by evaluating clean energy supply chains from a bottom-up perspective through stakeholder consultations and a literature review. Based on our findings, Section 4.1 highlights key focus areas that should be prioritised for intervention. In Section 4.2, we use the product space map tool developed by the Harvard University, based on the concept of economic complexity, to provide a top-down prioritisation framework that considers the broad range of clean energy products and components. However, as explained in Section 4.2, this approach uses a more abstract and less causal lens for clean energy supply chains.

Indian policymaking can benefit from market research interventions in various components of clean energy value chains

4.1 Technology-specific focus areas for Indian policymakers: Market research approach

Indian policymaking can benefit from market research interventions in various components of clean energy value chains. This includes technological, economies of scale, efficiency, corporate upscaling (through acquisitions and investments) market interventions that may lead to faster development of components, consumables and end-products in clean energy equipment of solar, wind and batteries.

Areas of focus in the solar value chain

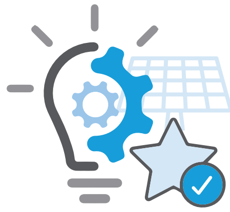
1. Solar wafer manufacturing

As part of the PLI scheme, MNRE has allocated 37.54 GW of wafer manufacturing capacity to eight companies[6] (MNRE 2021, 2022a). As mentioned in section 2.1 earlier, wafer manufacturing is the most capital-intensive and energy-intensive step in solar manufacturing. Currently, India does not have commercial production of wafers. In the PV supply chain, the stage most susceptible to single-country dependency is polysilicon and wafer manufacturing, as 83 per cent and 98 per cent of global manufacturing, respectively, happens in the PRC (EPIA 2024; ISA 2023c). Hence, it is imperative to develop technologies to manufacture wafers at cost-competitive prices.

Currently, the wafer prices are at record low. For instance, the average price of mono P-type wafers (210 mm/150 µm) and mono N-type wafers (210 mm/130 µm) as of June 2024 is USD 0.212 (~INR 17) and USD 0.22 (~INR 17.6), respectively. The 210 mm wafer is approximately 10 W leading to a unit price of INR 1.7–1.8/W (InfoLink n.d.b). Given such low prices, any material wastage can reduce the competitiveness of the manufacturer. For instance, polysilicon wastage, which arises during when ingots are cut, adds to the cost of wafers along with energy costs. The diamond wire cutting (DWC) technology, which is a state-of-the-art ingot-cutting method, currently dominates the market. The DWC uses diamond wires to slice polysilicon ingots into thin wafers. In addition to precision cutting, the DWC can potentially save up to 25 per cent of the polysilicon wastage in the ingot-to-wafer manufacturing step, thereby helping to reduce the overall cost of manufacturing a wafer and making it more cost competitive. It should also be noted that currently there are no manufacturers of wafer-cutting equipment in India.

6. The allocated crystalline wafer manufacturing capacities are as follows: PLI 1 – 8,737 MW and PLI 2 – 28,800 MW.

Furthermore, building capabilities in next-generation wafer manufacturing technologies, such as epitaxial wafer growth and direct wafering, which do not rely on wire-based sawing of wafers, can give India an early advantage. This advantage could help India become a leading player in these technologies, eventually licensing them and capitalizing on their increasing market share in the coming decades. A recent example of this is the strategic partnership agreement between Reliance and NexWafe for manufacturing 'green solar wafers' (Nexwafe 2021).[7]



Building capabilities in next-generation wafer manufacturing technologies can give India an early advantage

2. Additives, such as silver paste, for solar cell manufacturing

A major step in the manufacturing of solar cells is coating them with metallisation pastes that collect the current electric current. This process contributes to 9–25 per cent of the overall cost and is one of the most expensive raw materials, following the silicon wafer in solar cell production (IEA 2022b). Due to its limited domestic demand – as solar cell manufacturing has not achieved economies of scale – and the complex manufacturing process, the paste is not manufactured in India, leading to complete dependency on imports (Bhargava 2024).

But this challenge also presents opportunities for countries like India to become part of the value chain by building manufacturing capabilities. It is expected that the annual global additions of solar modules will increase to 888 GW by 2030 from the current deployment rate of 444 GW per year (Bellini 2024). India has an opportunity to tap into the global silver paste market going forward. However, there are currently no domestic silver paste manufacturers. Researchers around the world are also working to replace silver with aluminium or copper. Although these efforts are still in the early stages, a few organisations in Australia, the People's Republic of China and Germany have already shown promising results (Carroll 2022; PV2+ 2024). Therefore, India's focus on developing metallisation pastes indigenously could make it a pivotal link in the global solar value chain.

Areas of focus in wind value chain

The outlook for wind generation is relatively more optimistic, as risks are lower due to a distributed global market. As one of only five nations capable of producing each of the six main components of a wind turbine – nacelles, blades, towers, generators, gearboxes, and bearings – India is a major hub for wind energy production. However, attention should be focused on the following areas in domestic wind manufacturing:

1. Strengthening the medium and small enterprise sectors involved in manufacturing wind turbine components

India has ample technological capabilities for manufacturing a variety of components used in wind turbines such as hub castings and gearbox castings. However, due to uncertain demand and competition from globally dominant players, these industries are unable to achieve a competitive advantage. Small-scale private players and medium and small enterprise sectors (MSMEs) are often involved in manufacturing components such as bearings. However, due to a lack of economies of scale and demand for sub-components, they pivot away and diversify into other sectors (Lal 2023).[8] Reduced demand has led to a decrease in the number of MSMEs engaged in the wind sector from 4,000 to about 1,000 and a reduction in jobs in the wind energy sector from 2 million to about 63,000 (Upadhyay 2022).

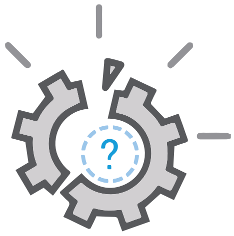
7. NexWafe is developing and producing monocrystalline silicon wafers directly from inexpensive raw materials, going straight from the gas phase to finished wafers. This proprietary process obviates the need for costly and energy-intensive intermediate steps such as polysilicon production and ingot pulling, which traditional wafer manufacturing relies on.

8. Also verified from stakeholder interaction.

Hence, to strengthen India's wind manufacturing ecosystem, MSMEs that supply OEMs need to be supported through variety of measures, including initiatives that lead to greater indigenisation of their procurement.

2. Rare-earth permanent magnet manufacturing facilities for the offshore wind energy supply chain

It is expected that the offshore wind turbine market will see significant growth in the coming decades. For instance, 25.2 GW of offshore wind turbines are anticipated to be deployed by 2035 (World Economic Forum 2022). Since offshore wind turbines have a larger capacity, rare-earth permanent magnets (REPMs) are used in manufacturing these turbines and come in various grades. REPMs increase generator efficiency by creating strong and stable magnetic fields necessary for power generation. The current global market share of wind turbines using REPM generators is approximately 32 per cent of land-based wind turbines and 76 per cent of offshore wind turbines. REPM production is concentrated, with up to 92 per cent, in a few geographies (GWEC 2023). Moreover, the production and processing of rare-earth oxides – precursor materials for REPMs – is concentrated up to 90 per cent in the PRC (GWEC 2023). Therefore, countries such as the People's Republic of China, which dominate rare-earth processing, can establish robust supply chains for REPM production. This can be a potential challenge, as any shortages of rare-earth magnets and the raw materials used in their manufacturing (rare-earth oxides) could significantly disrupt the offshore wind supply chain. Various national research centres, such as International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) in India, are developing rare earth magnet production capabilities (Ramesh 2022). However, dependence on the PRC will persist until large-scale REPM facilities are established.



Any shortages of rare-earth magnets and the raw materials used in their manufacturing could disrupt the offshore wind supply chain

Areas of focus in lithium-ion battery value chain

As India strives to enhance its position in the global battery manufacturing landscape, it faces both opportunities and challenges in developing key materials and technologies. With the growing demand for lithium-ion batteries, particularly in the electric vehicle (EV) sector, the country must navigate the complexities of securing raw materials, advancing production capabilities, and meeting sustainability standards. From focusing on lithium metal phosphate (LMP) cathode active materials to leveraging its resources for anode material production, India's strategy will need to balance technological advancements with economic feasibility. Moreover, as next-generation battery technologies such as sodium-ion batteries emerge, India's potential to innovate and compete on a global scale will hinge on strategic investments and the ability to scale production efficiently. The following sections delve into the critical areas where India can assert its competitive edge and address the barriers that may hinder its progress in the rapidly evolving battery industry.

1. Lithium metal phosphate material manufacturing

While India should continue its technology-agnostic approach to cell manufacturing technologies, it could focus on developing domestic capabilities in lithium metal phosphate (LMP) cathode active materials (CAMs). Production costs and profit margins (Greenwood, Wentker, and Leker 2021), as a share of the final cell cost, are also higher for LFP CAM production than NMC CAM production (Warrior, Tyagi, and Jain 2023). Additionally, a recent trend has emerged wherein active material production is located near cell manufacturing facilities to minimise logistics costs associated with transporting active materials (Volta 2023).

Finally, the low capital intensity of CAM production compared to other battery materials production could make it an attractive avenue for investments.

More than 95% of all lithium ferro-phosphate material globally is produced in PRC – and this dominance is not expected to change drastically in the coming years

While LFP use is being driven by supply chain disruptions of minerals, cell manufacturers could face a different type of supply risk when it comes to sourcing LFP-active materials. More than 95 per cent of all LFP material globally is produced in just one country – the People's Republic of China – and this dominance of capacity is not expected to change drastically in the coming years (Inclán 2023). With LFP having particular importance in cost-sensitive markets (World Economic Forum 2021), this concentration could lead to additional supply risks for countries in the Global South. An important point is that, in most cases outside of the PRC, major market players in one cathode chemistry, such as NMC, are not generally major producers of LFP CAM materials (Volta 2023). The processes are also not interchangeable and require different precursor synthesis procedures and calcination conditions (Schmuch et al. 2018).

However, challenges include the need for securing access to lithium and phosphoric acid, the inherent risks associated with industry-standard, long-term offtake commitments for lithium, and the technology risks related to the rapidly changing lithium-ion battery chemistries. Scaling any CAM will also require companies – and skilled workers – with expertise in powder metallurgy. Lithium metal phosphates come in many types, and recent announcements of manganese 3 phosphate (M3P) and lithium manganese iron phosphate (LMFP) chemistries being used could pose a technology risk for investors, assuming that LMP chemistries retain a significant market share (Volta 2023). While these cathode materials will continue to be used in future solid-state batteries, they will not be required for sodium-ion batteries, which will still utilise several other components previously used in lithium-ion batteries, adding further potential market risk.

2. India can manufacture globally competitive anode materials by leveraging its access to pitch tar and petro-coke feedstock

The global supply of anode-active material is amongst the most concentrated of cell components; India can look to develop its synthetic graphite production capacities, allowing it to bypass concerns about access to flake graphite resources and refining capabilities. Anode materials contribute around 10 per cent of the value of the battery pack (Argonne National laboratory 2023). The production of synthetic graphite will be limited by access to high-quality, low-sulphur coke feedstock. Crude oil refining residues and coal tar produced through the coking of coal are important feedstocks. Countries with developed petroleum or coal refining industries are best placed to use these feedstocks. However, a first step would be the development of calcination and dehydration capabilities to convert these fossil fuel by-products into high-purity needle coke or pitch coke. Importantly, while coal or petroleum is used during production, these carbon sources are not released into the atmosphere; rather, the carbon is embedded into the anode.

Synthetic graphite producers will need to set up graphitisation furnaces, which are highly energy-intensive. Further, similar to natural graphite-based anode material producers, they will use spheroidisation kilns and furnaces for coating, which are also energy-intensive processes. Additives used during the graphitisation determine the quality of the synthesised graphite (Heimes and Kampker 2019), while the coating process is important for the final quality of the active material (Schmuch et al. 2018). Several countries have already gained experience in the production of synthetic graphite electrodes for electric arc furnaces used in the production of steel, iron, and non-ferrous metals.

Economies of scale are an important factor in driving prices down in the lithium-ion battery cell manufacturing sector

Indian manufacturers are also predisposed to additional challenges such as the availability of cheap electricity. Synthetic graphite production is highly energy-intensive, requiring over 10 MWh of energy per tonne of graphite produced or nearly twice the energy used in natural graphite production (NITI Aayog 2023). It can also be a highly polluting process and can lead to adverse health and environmental outcomes (Dutta 2018). Therefore, stringent measures to control air pollution and locate synthetic graphite production facilities away from populated areas will be crucial.

3. Aluminium foil rolling and aluminium cell casing sheet production

India boasts a robust aluminium sheet manufacturing ecosystem that has developed alongside a mature aluminium smelting industry. With giants such as Vedanta and NALCO leading the charge, Indian aluminium manufacturing stands out for its cost efficiency on the global stage. Given the limitations of the domestic market's scale – even if India's market reached 100 GWh per annum by 2030 – Indian manufacturers should target the export market to achieve cost competitiveness. India must address critical factors such as energy prices for energy-intensive processes. While cheap energy remains a primary requirement for aluminium production, the global shift towards sustainability demands a dual focus on the use of clean energy in the aluminium supply chain. The use of electric arc furnaces or green hydrogen in the smelting process may require government support. For Indian players aiming to supply markets in Europe and East Asia, aligning with carbon emission standards will be crucial to maintain competitiveness. The Hindalco group is also planning to invest INR 8,000 crore (USD 1 billion) to build a battery foil manufacturing plant in Odisha, India (Gupta 2023). Venturing into the copper foil market might be more challenging for Indian producers, as copper foil with a thickness of less than 10 microns may require electro-depositional techniques rather than regular cold rolling techniques (Schmuch et al. 2018).

4. Manufacturing lines for next-generation technologies such as dry coating or sodium-ion batteries should be scaled up

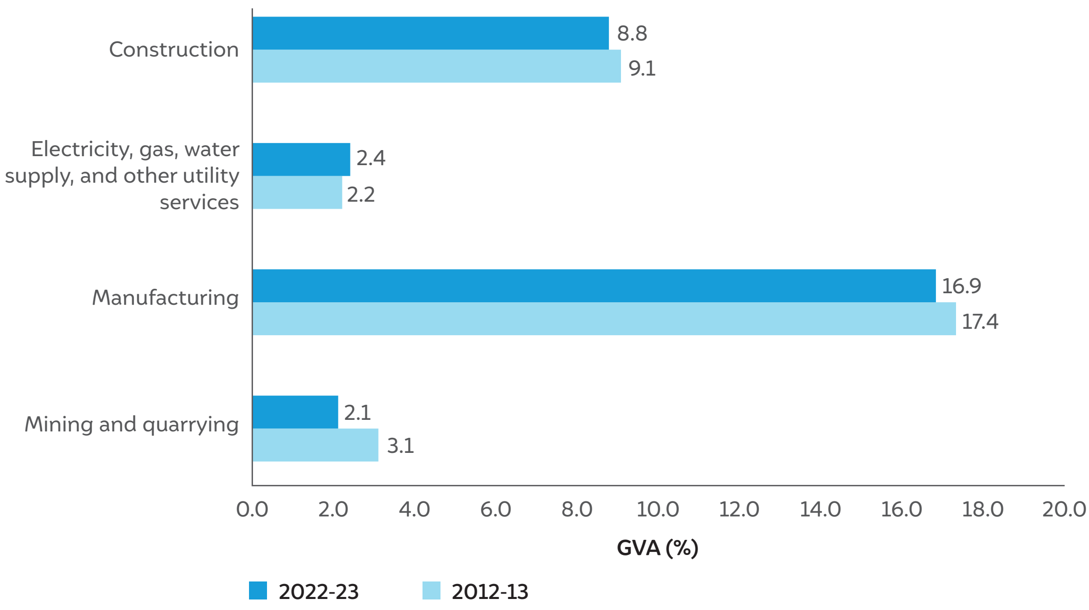
Economies of scale are an important factor in driving prices down in the lithium-ion battery cell manufacturing sector. India is unlikely to match global manufacturing capacities by 2030. It will remain a small regional player and, as such, will not be able to compete on a global scale. Hence, India should identify the next window of opportunity in cell technology and begin piloting the manufacturing of these technologies. In this way, Indian manufacturers can attempt to enter emerging markets and advance next-generation technologies at lower costs. To support the piloting of Indian innovations or attract global innovators, the Indian government could establish cell fabrication and testing centres, which would facilitate innovations – such as sodium-ion cells or dry electrode production – from the lab to the market.

4.2 Product space mapping: Identifying avenues for increasing India's participation in clean energy value chains

The clean energy technology supply chains continue to be concentrated, and countries around the world are trying to build resilience in their domestic supply chains. There is political support for developing industrial policies that de-risk clean energy supply chains through indigenisation, near-shoring, and protectionism. Policies such as the IRA, PLI schemes, NZIA, and Future Made in Australia Act are designed to mobilise public finance and private capital to create domestic manufacturing capacity across countries while restructuring the global value chains (GVCs) in the process.

The overall percentage share of gross value-added by industries has stagnated in India, including manufacturing (Figure 21). As part of the broader initiative, we recommend a focus on deepening clean energy manufacturing by increasing the scale and competitiveness of high-value supply chain segments. However, there are risks associated with capacity development throughout the value chain due to the need for deep technical expertise and know-how to compete globally. Integrating the entire value chain for domestic manufacturing may not be financially feasible, given that achieving cost competitiveness in certain intermediary products would be challenging.

Figure 21 Percentage share of gross value-added by manufacturing has regressed



Source: Ministry of Statistics and Programme Implementation (MoSPI); accessed May 2024. https://www.mospi.gov.in/publication/national-accounts-statistics-2024.

India can enter the GVCs for clean energy technologies by selecting specific products in which the country may achieve competitiveness faster. Choosing particular segments and products within the value chain may be a more efficient way to allocate capital and resources, maximising India's benefits without being fully exposed to the market risks associated with complete value chain integration.

Various methodologies may be utilised to identify competitive segments or products within clean energy value chains. The basis of such measurements is linked to technologies, product know-how, infrastructure, market assessment and productivity, amongst others. Frameworks such as input–output tables use statistical analysis based on formal trade data as policy indicators for competitiveness (United Nations 2018). Moreover, performance measures such as mark-ups, profits, innovation, and productivity may also be used to evaluate market competitiveness and identify winners (OECD 2021). Consumer and business surveys are also widely used for assessing product identification and viability.

India can enter the global value chains for clean energy technologies by selecting specific products in which the country may achieve competitiveness faster

An alternative approach to determining segment/product selection is recognising a country's production capability through trade data analysis. The underlying assumption is that if a country has a revealed comparative advantage (RCA) in a product, it is producing or can produce it competitively (Mealy and Teytelboym 2020). This approach relies on measuring the product complexity of a country's goods production base, the proximity of these products to each other, and the RCA of each product. Consequently, a 'product space' may be created for a country's goods, with nodes (for each product), linkages between products, and identified RCA for specific products. This methodology may help identify products (and industries) in which India either already has a comparative advantage or can develop one more rapidly. This approach also allows us to identify a family of products based on the technological complexity involved in producing them.

The analysis tool for product space mapping and its application to globally traded products was developed by the Harvard University's Growth Lab and may serve as a valuable resource for informing industrial policy. As part of our analysis for this report, we have utilised product space mapping to identify clean energy technology products in which India may aim to build competitiveness. Furthermore, this analysis can be extrapolated to identify complementary industries and products that may contribute to the clean energy manufacturing value chain in India; however, such an analysis is beyond the scope of this report.

We aim to highlight that product space analysis may serve as an analytical tool to evaluate product competitiveness. It is based on the strong correlation between a country's trade data and its capability to produce competitive products. Product space provides an initial direction on which products may be or become competitive, but there are limitations to this approach. Several unaccounted factors, including input costs, macroeconomic dynamics, market variables, and technological challenges, can restrict a sector's ability to become competitive within GVCs.

A 'product space' approach allows for a preliminary assessment of clean energy products and components by evaluating their broader product families. We aim to use India's product space as a tool to identify areas of opportunities for expanding manufacturing and highlights ways in which the this approach could guide policymaking. However, it is important to caveat any such analysis, as the economic complexity framework cannot identify true causal linkages between products and lacks visibility on domestic production and demand, with analysis conducted exclusively on global export trends.

The product space approach provides us with a preliminary assessment, which we build upon with bottom-up analysis and insights in the subsequent portion of this section. The applications of product space mapping are shown in Figure 22.

Figure 22 Use cases of the product space map

Assistance in strategic decision-making	**Identification of comparative advantages** Helps identify a country's comparative advantages by highlighting offerings where it has revealed comparative advantage	**Identification of avenues for export diversification** Offers insights into probabilities of co-exporting similar classes of products, enabling export diversification	**Identification of strategic investment opportunities** Involves identifying and leveraging existing capabilities to move into higher-value and more sophisticated exports
Application in strategic decision-making	**Trade policy formulation** Assists in designing trade policies that are aligned with a country's strengths and aids in crafting export promotion strategies	**Skill enhancement in the center of product space** Aids in nuancing national policymaking through identification of key sectors for development and growth	**Trade risk assessment** Provides insights for managing risks. associated with export concentration, enabling proactive measures to diversify both in terms of products and geographical markets

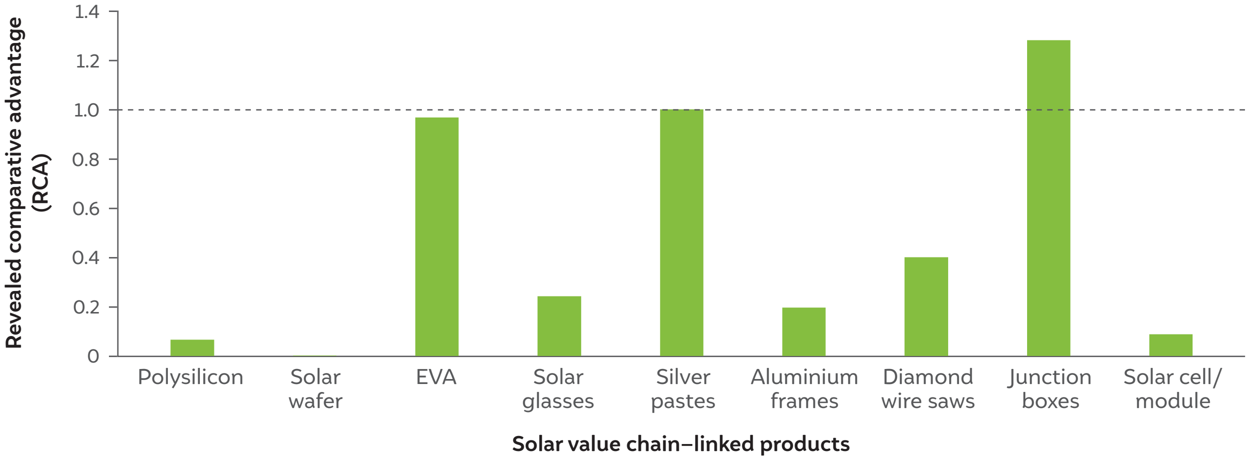
Source: Authors' analysis

The relevance of RCA in identifying key components for competitiveness in clean energy technologies

There are metrics such as RCA, to depict the relative advantage of countries in producing a good, with products classified based on harmonised system (HS) codes (assigned for the trade of goods). RCA can help identify the export value of clean energy products. An RCA greater than unity means that a country has a competitive advantage for that product.

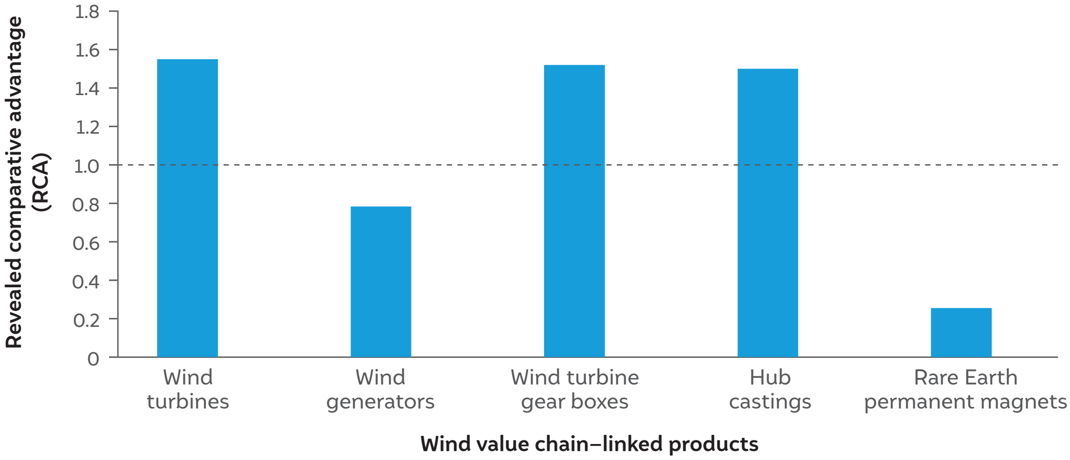
Figures 23, 24, and 25 show the solar, wind, and battery products, respectively. Each chart may depict the clean energy–relevant product families in which India could be close to achieving a comparative advantage. India has opportunities to explore product families that include products such as EVA and silver paste (Figure 23). These products could potentially achieve comparative advantage, whereas in the product family for junction boxes, there may already be an existing advantage due to an established local industry. Similarly, vis-à-vis the wind value chain, India has a comparative advantage in product families related to turbines, gearboxes, and hub castings, indicating that these wind value chain components may already be competitive in export markets due to the indigenisation of the industry (Figure 24). Lastly, Figure 25 shows that there is an opportunity to gain a comparative advantage in a product family that includes synthetic graphite for batteries. The battery value chain manufacturing capacity is still nascent in India, with high potential for domestic growth.

Figure 23 As of 2021, amongst product families in the solar supply chain, EVA and silver paste are potentially very close to achieving RCA



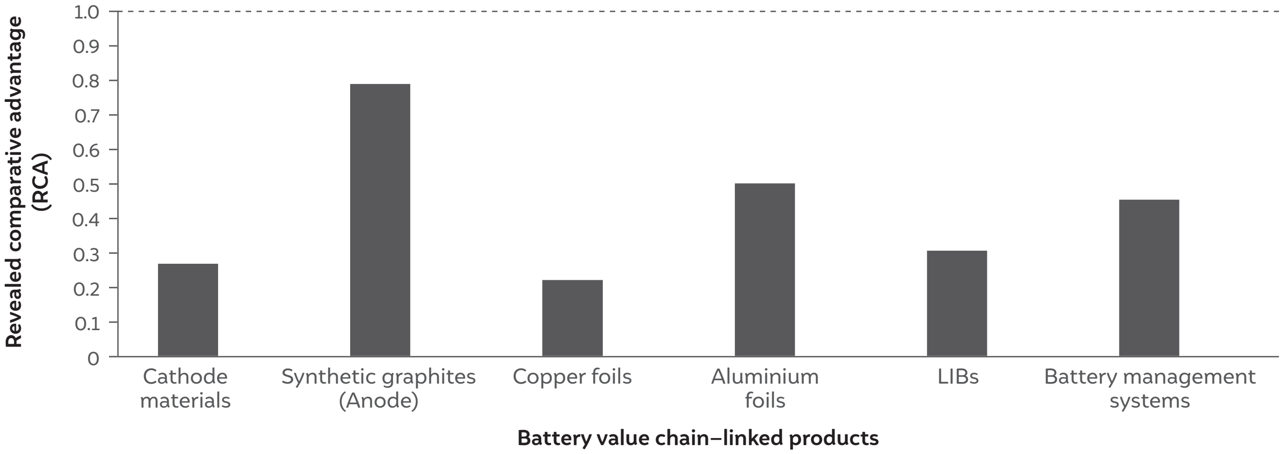
Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Figure 24 As of 2021, in wind-relevant product families, products such as REPMs face the largest gap in achieving RCA



Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Figure 25 As of 2021, no key battery-related product families have achieved an RCA of 1, indicating that they face varying degrees of gaps in achieving competitiveness



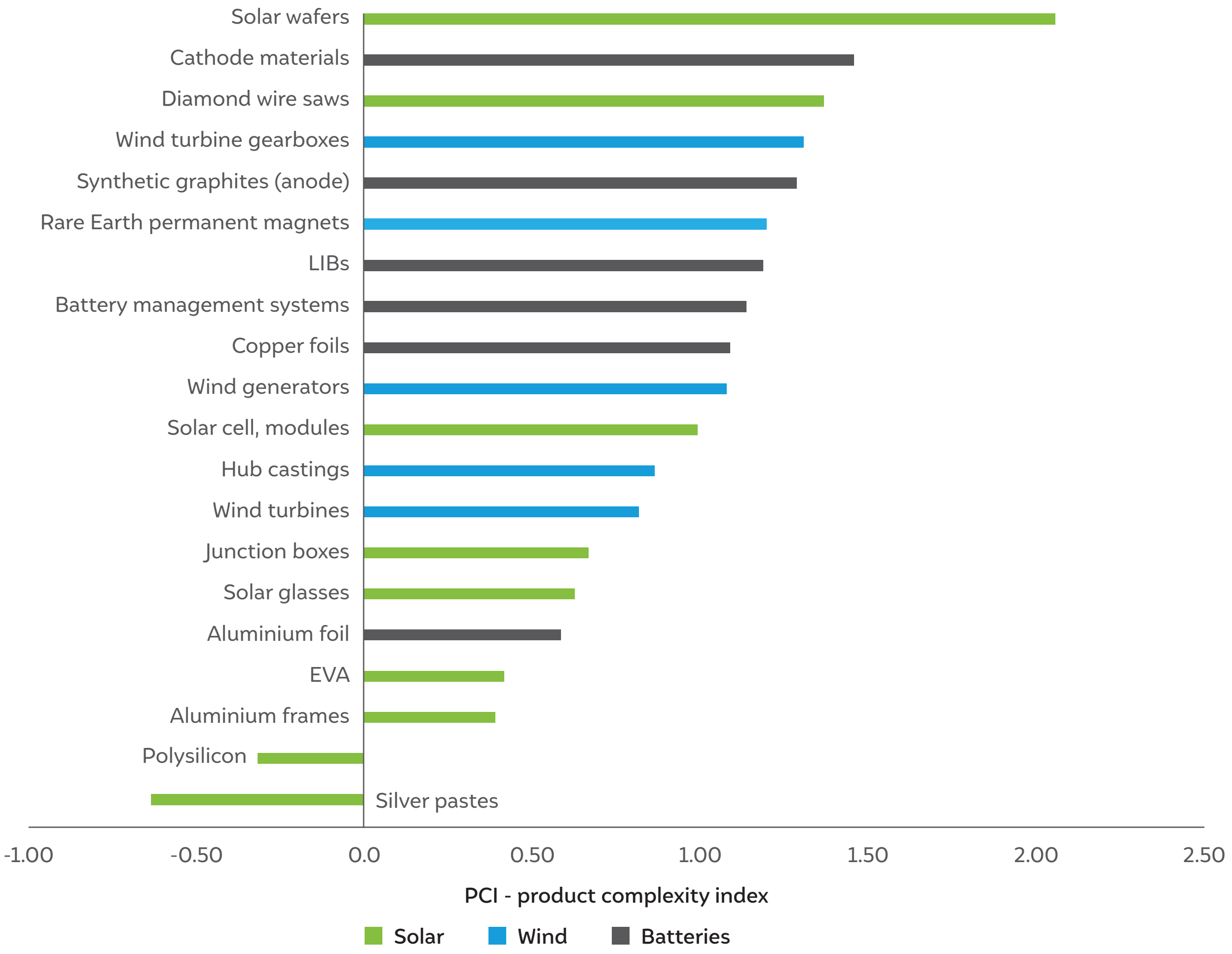
Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Product complexity and its relevance to the structural transformation of the economy

The productive capabilities and know-how to create increasingly complex products are an important metric of the economic growth as well as an important feature of developed economies. Transitioning to the manufacture of high-tech and complex products signifies growing economic complexity. To achieve structural transformations within an economy and sustain innovation and value addition, increasing the complexity of manufactured products is essential.

In clean energy technology manufacturing, increased GVC participation along with the indigenisation of high-tech products achieves the twin goal of domestic value capture and economic transformation over the long run. As part of this analysis, we have identified 20 product family codes relevant to the clean energy sector. Details of the product families are provided in Annexure 1. The relevant Product Complexity Index (PCI)[9] scores for clean energy products can be seen in Figure 26.

Figure 26 **An analysis of PCI for the clean energy product families shows high complexity in several solar and battery components as of 2021**



Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Note: The above PCI is for specific family of HS codes, which are shared in Annexure 1. The products relevant to clean energy supply chain in that HS code are highlighted in the chart above.

9. The Product Complexity Index (PCI) developed by Harvard's Growth Lab ranks the diversity and sophistication of the productive know-how required to produce a product. Products with a high PCI value – the most complex products that only a few countries can produce – include electronics and chemicals. Products with a low PCI value – the least complex products that nearly all countries can produce – include raw materials and simple agricultural products. The PCI was last updated in 2021.

The higher the product complexity score, the greater the complexity. It should be noted that the range of PCI score varies from –3.37 (tin ore concentrates) to +2.31 (photographic plates and film, exposed and developed, other than motion-picture film). Products that form an important part of the clean energy value chains are included in this analysis and consist of solar, wind, and battery components.

There are certain clean energy–relevant product families in which India has already achieved an RCA, making products export-competitive (Table 8).

Table 8 Clean energy–relevant product families in which India has already achieved an RCA

Four-digit HS code product family	Application in clean energy value chain	Sector
8535	Junction box	Solar
7106	Silver paste	Solar
8483	Wind turbine gearbox	Wind
8503	Hub castings	Wind
8412	Wind turbine	Wind

Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

However, within the family of clean energy products, there are certain products for which we can achieve an RCA, wherein the distance[10] is low, making it relatively easy to achieve global competitiveness.

Identification of new products for export competitiveness

To identify certain clean energy products that may be relatively complex and have a lower distance, a feasibility space map using the PCI perspective is utilised. This approach helps policymakers focus on achieving domestic value capture and export competitiveness. A relatively complex indicator of a country's opportunities to increase its value chain participation is a country's feasibility space vis-à-vis solar, wind, and battery value chains. The feasibility map showcases the relationship between selected clean energy products and variables such as the PCI and distance, as shown in Figure 23. The PCI "ranks the diversity and sophistication of the productive know-how required to produce a product"(Harvard University 2024a). The proximity of a country to gaining an RCA for a product is related to the range of its distance from 0 to 1 (RCA achieved).

Using a methodology[11] that considers normalisation and the root means square method to optimise for the product families with a high PCI and low distance, the top six clean energy–relevant product families in which India can achieve export competitiveness are shown in Table 9. The product families are highlighted within a box in Figure 27.

10. A product's distance (measured from 0 to 1) indicates a country's capability to make that product, measured by that product's relation to the country's current exports.

11. The method involves using max–min normalisation and the statistical root means square (RMS) method of averages to identify the product families in the feasibility space. These families have a combination of high PCI or opportunity gain (OG) and low distance to maximise export competitiveness and structural transformation respectively . This is approached through the PCI as well as the OG perspectives.

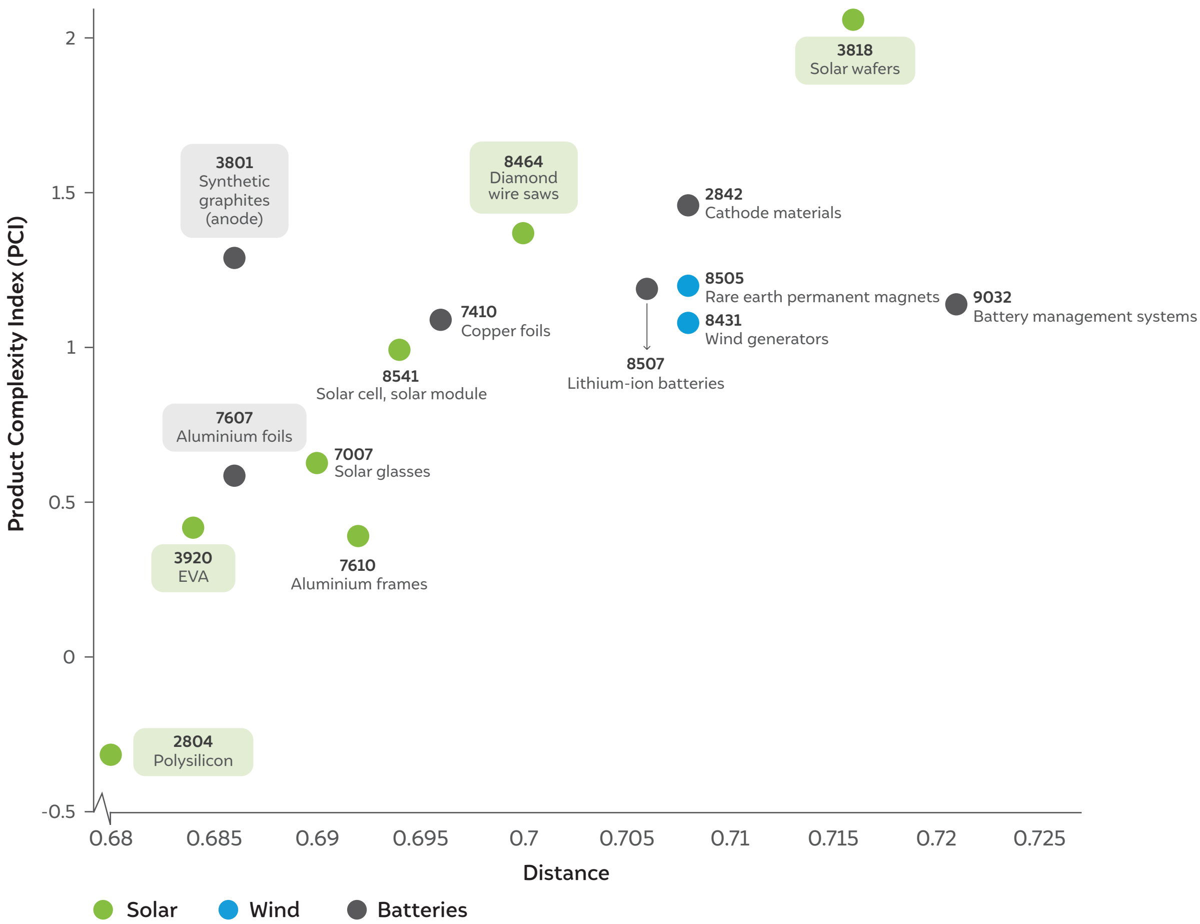
Table 9 Top six clean energy–relevant product families in which India can achieve export competitiveness earlier

Four-digit HS code product family	Application in clean energy value chain	Sector
3801	Synthetic graphite (anode)	Batteries
3818	Solar wafer	Solar
2804	Polysilicon	Solar
3920	EVA	Solar
7607	Aluminium foil	Batteries
8464	Diamond wire saw	Solar

Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Clean energy–relevant product families – such as EVA (HS 3920), polysilicon (HS 2804), solar wafer (HS 3818), and diamond wire saw (HS 8464) – are components of the solar value chain. Developing these products for greater participation in the global solar value chain may be desirable from an export-competitiveness perspective. Similarly, in the battery value chain, synthetic graphite (HS 3801) and aluminium foil (HS 7607) are identified as clean energy–relevant product families that may be targeted first to achieve a comparative advantage with low complexity in the manufactured product.

Figure 27 India's feasibility map as of 2021 for select clean energy technology products: PCI perspective identifying product families (HS92) in which India can achieve export competitiveness



Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Identification of new products for the structural transformation of the economy

To identify clean energy products with opportunities for diversification and a shorter distance so that policymakers can focus on achieving domestic value capture and structural transformation of manufacturing, a feasibility space map – opportunity gain (OG) perspective – is utilised.

The feasibility map showcases the relationship between select clean energy products and variables, namely OG and distance (Figure 28). The OG denotes the contribution of a new product in terms of opening doors to the development of more complex products in the vicinity. The higher the OG, the greater the probability of unlocking more complex products for an economy. A relatively high OG may translate into sustained growth through the future acquisition of highly productive capabilities. A product's distance – measured from 0 to 1 – indicates a country's capability to produce that product, based on the product's relation to the country's current exports.

Using the same methodology employed in India's feasibility map – PCI perspective – we have identified the top six clean energy–relevant product families with high OG and low distance, wherein India can achieve structural transformation in manufacturing. These product families are shown in Table 10 and highlighted within a box in Figure 28.

Table 10 Top six clean energy–relevant product families that may lead to structural transformation within the manufacturing industry in India

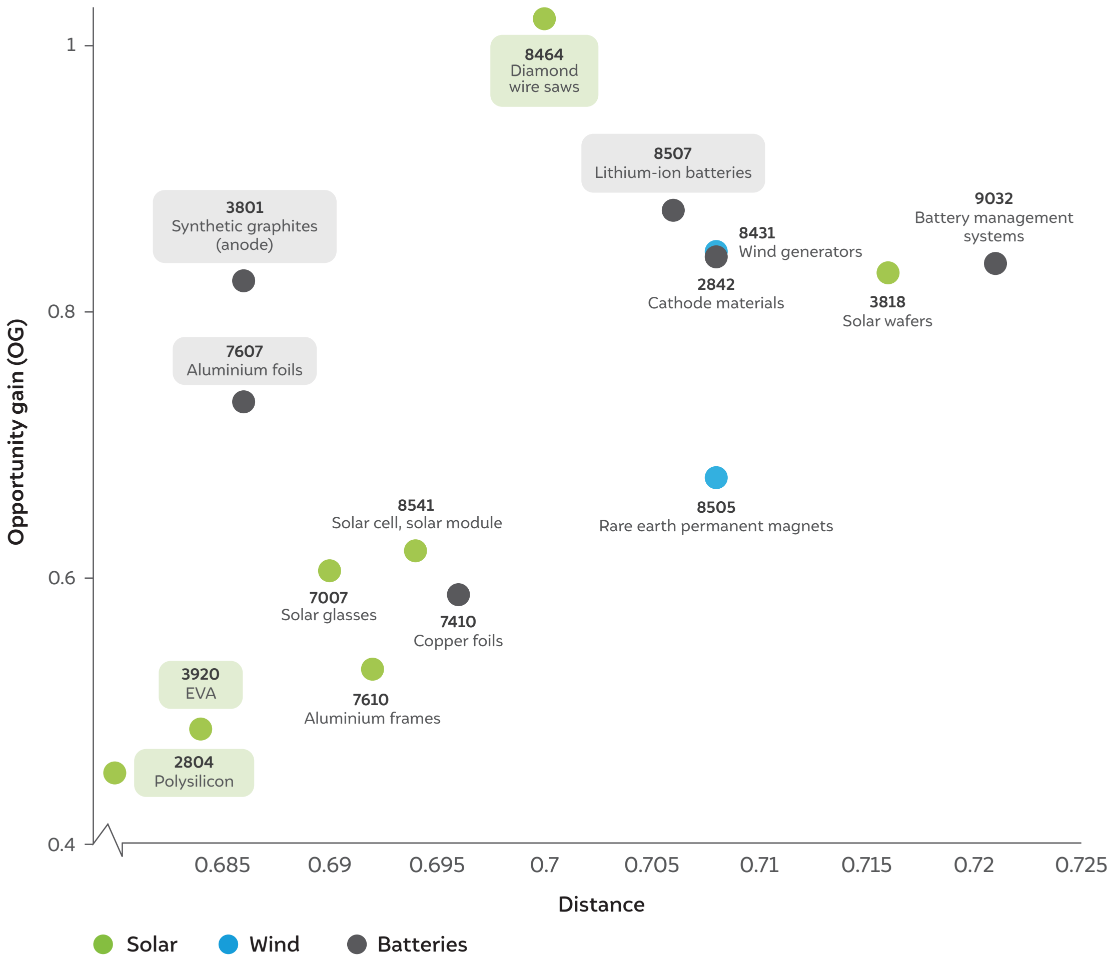
Four-digit HS code product family	Application in clean energy value chain	Sector
8464	Diamond wire saw	Solar
3801	Synthetic graphite (anode)	Batteries
2804	Polysilicon	Solar
7607	Aluminium foil	Batteries
3920	EVA	Solar
8507	Lithium-ion battery	Batteries

Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

Clean energy–related product families – such as synthetic graphite (HS 3801), aluminium foils (HS 7607), and lithium-ion batteries (HS 8507) – are key components of the battery sector. The development of these products could lead to more complex innovations in the field, transforming the structure of clean energy manufacturing over time. Additionally, clean energy–related solar products – such as diamond wire saw (HS 84864), polysilicon (HS 2804), and EVA (HS 3920) – may also unlock many high-tech products connected with relevant complementary industries in the sector.

Overall, the feasibility map tool can help policymakers identify opportunities for policy action, allowing the clean energy manufacturing sector to maximise strategic benefit and develop a sustainable, economically vibrant, and globally competitive manufacturing ecosystem.

Figure 28 **India's feasibility map, as of 2021, for select clean energy technology products – opportunity gain perspective identifying product families (HS92) that may lead to structural transformation**



Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

The development of clean energy-related product families could lead to more complex innovations in the field, transforming the structure of clean energy manufacturing over time.

Image: Suzlon

5. Recommendations

Government initiatives have successfully fostered significant momentum and optimism in India's clean energy manufacturing sector over the years. However, our analysis indicates the need for additional measures to ensure the success of existing policies or to enact new regulations and strategies. Further targeted efforts can open up new economic opportunities for India, paving the way for economic growth and new jobs while achieving the dual aims of energy transition and energy security. Strategic areas of priority for policymakers are elaborated in Figure 29.

Figure 29 Strategic priorities will enable the advancement of India's clean energy manufacturing sector

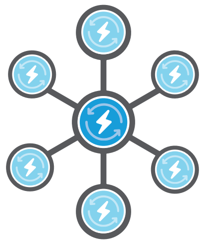
Recommendations		
Building competitiveness	**Increasing demand**	**Strengthening ecosystem**
Tapping markets with stringent manufacturing emission norms	Raising domestic deployment ambitions	Securing the supply of critical minerals – primary and secondary
Mobilising finance for CapEx	Using import tarrifs judiciously	Improving testing infrastructure
Developing upskilling programmes to meet industry requirement	Leveraging International partnerships to access new markets	Adopting a whole-of-government approach
		Facilitating coherent, consistent, and aligned policymaking

Source: Authors' analysis

According to these strategic priorities, this report provides 10 recommendations designed to address the policy gaps highlighted and enhances the scale and competitiveness of the Indian clean energy manufacturing sector:

1. **Build on our strengths but with a whole-of-government approach**: Indian clean energy equipment manufacturers have predominantly relied on importing components and assembling them domestically. Despite recent government initiatives encouraging manufacturers to increase their value addition through manufacturing, stakeholder consultations reveal that solar and battery companies continue to face multiple obstacles. Developing local capabilities in key components such as solar cells, glass, battery cells, anodes, cathodes, and silver paste remains difficult. We recommend a more targeted approach, strategically encouraging selected products that can generate substantial spillover effects and create additional jobs. We have highlighted key products and product families within the supply chains in this report. While further research will be essential due to rapid technological advancements, new materials, and efficiency improvements, adopting the recommended strategic view will ensure that domestic manufacturers become competitive by receiving support tailored to technologies and markets.

In India, multiple central government ministries, regulatory bodies, public sector companies, research institutions, and academic labs are dedicated to advancing the *Make in India* initiative for clean energy technologies. However, a lack of alignment in their priorities can impede progress. Ministries such as the MNRE, MHI, Ministry of Power, Ministry of Mines, Department of Science & Technology, and Ministry of Finance play crucial roles in setting priorities and allocating budgets. Without proper coordination, strategic policies risk achieving limited results. The clean energy sector would significantly benefit from enhanced inter-departmental and inter-institutional coordination to ensure that government efforts are aligned and directed towards the common goal of *Make in India*. Establishing a high-level committee on resilient supply chains for energy transition, consisting of representatives from various government departments, is recommended to ensure that policies across ministries are well coordinated and aligned.



The clean energy sector would significantly benefit from enhanced inter-institutional coordination towards the goal of *Make in India*

2. **Tapping markets with stringent emission norms**: In recent years, countries globally have started to aim to reduce the emission intensity of imported goods. ESG standards, encompassing environmental, social, and governance impacts of business activity, have become an important determinant of trade, credit, and goodwill. Hence, norms related to transparency policies, community impacts, emissions, and other environmental effects are now becoming entry barriers to participating in international business (Banker 2023). For instance, adopted in 2023, the EU's Sustainable Battery Regulation aims to reduce social and environmental impacts across the battery lifecycle by requiring sustainability, safety, labelling, and end-of-life management measures, tailored to different battery types (IEA 2023c). Countries such as France and the Republic of Korea already have similar regulations (Bellini 2019).

   In 2022, the Indian government made it easier for small industries and commercial consumers to access clean energy through the Green Open Access Rule (PIB 2022b). A few states have already notified the rules, and the regulations are expected to support domestic manufacturing by allowing companies to charge a premium for their low-carbon intensity. In addition to reducing the emission intensity of its products, the government can establish effective ESG reporting, disclosure, and certification standards according to India's trade needs and requirements. In parallel, trade negotiations with countries and blocs will be critical to ensure that the manufacturing industry is supported and not penalised by protectionist measures from importing countries. Finally, the government can fund pilot projects for low-carbon components and material manufacturing plants, which will require novel manufacturing methods, such as using green hydrogen for refining and processing materials used in clean energy manufacturing (Warrior, Tyagi, and Jain 2023a).

3. **Need to mobilise finance for infrastructure capex**: Currently, most policies provide support only after factories produce clean energy equipment. For instance, PLI winners will benefit only if they meet the bid criteria and can sell the products. It is important to note that in the National Programme on Advanced Chemistry Cell(ACC) Battery Storage (ACC PLI), winners can also be penalised if they do not meet the threshold levels of indigenisation in target years. However, as mentioned earlier, as manufacturers move upstream to solar cells, solar wafers, battery cells, cathodes, anodes, magnets, etc., manufacturing, the upfront infrastructure cost becomes a significant challenge for private players entering these markets. For example, Table 11 highlights the very high capital

intensities, that is, capex expenditure recovery rates from sales, for separator and anode material manufacturing. Domestic manufacturers of solar components also pay three to four times as much interest as their Chinese competitors, struggling to obtain debt capital at competitive rates (Jain, Dutt, and Chawla 2020). Given the evolving geopolitics and lack of competitiveness, many lenders remain averse to lending to manufacturing projects. New industrial policies in North America and Europe could also divert investment away from Indian manufacturers.

Table 11 Anode material and separator production exhibit high capital intensities

	Annual sales (million USD/GWh) in 2022	Capex (million USD/ GWh) in 2022	Capital intensity ratio
Cathode material	56	14	0.3
Anode material	7	7	1.0
Separator	10	14	1.4
Copper foil	11	8	0.7
Lithium-ion cell	120	90	0.8

Source: Authors' compilation based on 1. Volta Foundation. 2023. Annual Battery Report 2023. San Francisco: Volta Foundation.2. BloombergNEF 2023b. New Energy Outlook India. New York: BloombergNEF. 3. Argonne National Laboratory. 2023. "BatPaC 5.1." Lemont.

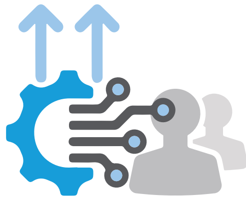
Interest rates can significantly impact a factory's competitiveness, and it is important to note that manufacturing facilities continue to attract higher rates than renewable projects. For instance, IREDA offers higher interest rates (up to 135 basis points) for manufacturing facilities compared to renewable energy projects, which often reduce competitiveness of production (Table 12). Stakeholders have raised concerns about high rates of working capital, which need to be reduced further. The MNRE should work with the Ministry of Finance and national and international banks to ensure the provision of competitive debt capital as we scale up our manufacturing ambitions.

Table 12 Interest rates by IREDA for various projects

Sector	Grade I (%)	Grade II (%)	Grade III (%)	Grade IV (%)	Grade V (%)	Installed capacity ≥ 500 MW/TPD (%)	Installed capacity ≥ 500 MW/TPD (%)	Installed capacity ≥ 500 MW/TPD (%)
Rooftop solar, wind energy, grid-connected solar PV, hybrid wind and solar, floating solar	8.90	9.15	9.40	9.65	9.90	—	—	—
Manufacturing (solar and wind) and related ancillaries	—	—	—	—	—	9.50	9.75	10.25
EV and EV infrastructure, CBG	10.00	10.25	10.50	10.75	11.00	—	—	—
EV manufacturing	For EV-related manufacturing, an additional interest rate of 50 bps to be charged over and above the EV and EV infrastructure sector rate.							

Source:IREDA. Accessed march 2024. "Interest Rate Matrix." https://www.ireda.in/interest-rate-matrix.

4. **Develop upskilling programmes to meet industry requirements**: As manufacturing evolves, the complexity and dynamics of the industry change significantly, necessitating a competent and skilled workforce. India has one of the largest youth populations with backgrounds in science, technology, engineering, and mathematics (STEM), and this potential must be tapped. Between 2021 and 2022, 9.85 million Indian students enrolled in higher education were in STEM courses (Department of Higher Education 2022). The Ministry of Education, the Department of Science & Technology, and the National Skills Development Corporation must work closely with the MNRE, the Ministry of Mines and the MHI to ensure that a sufficient skilled workforce is developed to meet the upcoming demand from manufacturing industries. For instance, the PRC undertook a similar initiative and developed an action plan for undergraduate majors and cross-disciplinary education in energy storage from 2020 to 2024 (British Council 2020). There has been progress in India's human capital as evidenced by an overall increase in the country's PCI (see Annexure 2). However, the growth of the human capital component is slower compared to the growth in energy needs and technological structural changes. Further effort is needed to optimise human resources to move up the value chain towards more high-tech manufacturing.



Further effort is needed to optimise human resources to move up the value chain towards more high-tech manufacturing

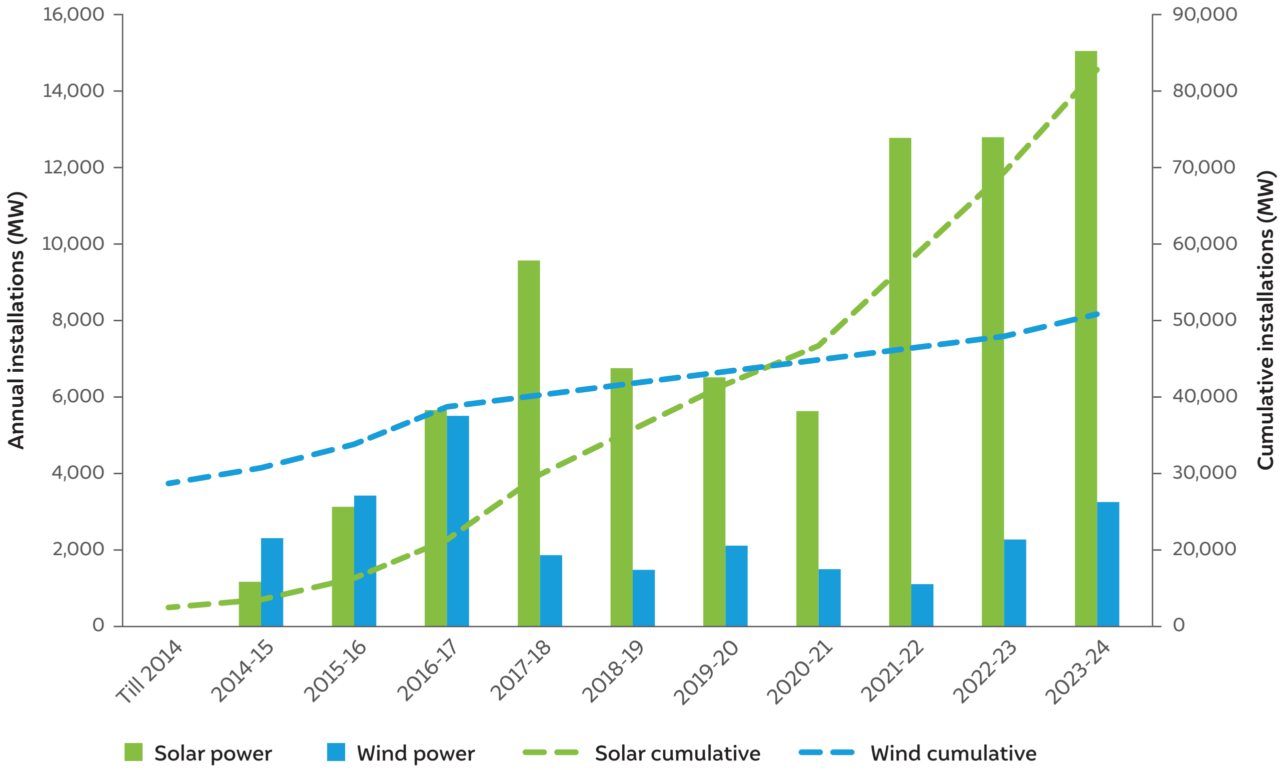
5. **Raise domestic deployment ambitions**: India aims to install 500 GW of non-fossil power capacity by 2030. While there are no specific technology targets, according to the National Electricity Plan (NEP), India may install 339 GW–365 GW of solar and 92 GW–121 GW of wind power by 2031–32 (PIB 2023a). However, based on the current trends, achieving such large installations appears challenging. For instance, India would need to install more than 9 GW of wind power and more than 33.3 GW of solar power annually, compared with the 2.3 GW and 12.8 GW, respectively, installed in FY 2022–23 (Figure 30). On the supply side, as clean energy technologies such as batteries and solar panels approach price parity with their alternatives, the demand side response should also catch up.

   To support existing – and build new – manufacturing facilities, India will need a sufficiently large market for manufacturers to survive. In this regard, it is important for the government to increase the deployment of clean energy technologies to meet the Nationally Determined Contributions targets and support the manufacturing sector. Government support and strong deployment ambitions will further help to reduce offtake-guarantee risk in financing, thus improving supply-side issues by demonstrating strong demand.

6. **Use import tariffs but judiciously**: Since the domestic clean energy manufacturing industry has not achieved economies of scale and global competitiveness, India has implemented import tariffs on many products and raw materials. Such a duty structure aims to bring parity between products manufactured in India and those imported. The BCD for some of the key components is provided in Table 13.

   Additionally, imports of components often do not incur duties to ensure that the final product can be manufactured at competitive rates. However, to indigenise the value chain, the government could consider imposing duties on key components and raw materials currently undergoing indigenisation. For instance, the customs duty on solar cells may be increased from 25 per cent to 40 per cent with a two-year timeline. This change will also align with the facilities being established under PLI schemes and will support the domestic manufacturing of solar modules. Hence, to move forwards, the duty must be but with a clear visibility window of at least two years. Similarly, there is no import duty on solar wafers or polysilicon. However, as PLI facilities are set up in India, the government may want to signal that wafers and polysilicon manufacturing could start attracting duties from

Figure 30 Solar and wind installations are rising in India



Source: Authors' analysis from Ministry of New and Renewable Energy. 2024. "Year wise Achievements" Last accessed August 9, 2024. https://mnre.gov.in/year-wise-achievement/

Table 13 Customs duties for key components

Component	Duty structure (%)
Solar module	40
Solar cell	25
Wind turbine	10
Lithium-ion batteries	10–20*

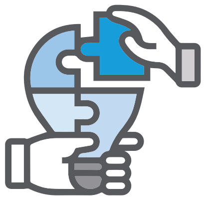
Source: CEEW analysis from multiple sources

*Lithium-ion batteries are imported for different use cases under various HS codes, resulting in a range of applied duty structures.

FY 2026 or FY 2027. Policy certainty is vital for attracting steady investments. Therefore, the government should publish a potential five-year tariff plan detailing the planned tariff trajectory to protect the industry for a set number of years, eventually sunsetting tariffs to encourage long-term competition.

7. **Facilitate coherent, consistent, and aligned policymaking**: Apart from the lack of coordination and inconsistency in government support, conflicting and shifting priorities can also deter long-term investments and disrupt market confidence. For instance, the SGD imposed in 2018 caused significant confusion and planning issues due to unclear applicability. The duty was set for a two-year period, which was insufficient to support manufacturers effectively. Investors found this time frame too short to establish

new manufacturing facilities. Consequently, project developers continued to rely on imports, anticipating compensation under the contract's "Change in Law" clause. This strategy backfired for manufacturers, as imported products remained cheaper than domestic ones, rendering the SGD ineffective. For new bids, manufacturers favoured imported modules because either the SGD was set to expire soon or its 15–20 per cent range still made imports less expensive (Jain, Dutt, and Chawla 2020). This situation highlights the need for coherent planning with foresight and comprehensive support for manufacturers. Facilitating this will require ensuring that all policies are aligned with a national clean energy manufacturing strategy so that the disparate goals related to trade, industrialisation, decarbonisation, and energy policy can be harmonised. Encouraging inter-departmental collaboration to address potential conflicting effects, market signal errors, or overlaps will further this endeavour.



India must strategically collaborate with countries seeking to diversify, negotiate trade agreements, and reduce any artificial barriers making Indian products less competitive

8. **Leveraging international partnerships to access new markets**: Several countries are seeking to address high trade and manufacturing concentrations by diversifying their procurement of clean energy equipment. Countries may sign FTAs or enter into economic cooperation to boost trade, although these measures can also be exclusionary. For instance, companies manufacturing in India are not eligible for incentives under the United States' IRA. India must strategically collaborate with countries seeking to diversify, negotiate trade agreements, and reduce any artificial barriers making Indian products less competitive. Through India's Exim Bank financing, overseas clean energy projects can be required to utilise *Make in India* products, alongside competitive interest rates and reduced emission intensity. Further, the Indian government, via the Export Credit Guarantee Corporation of India, can provide exporter credit insurance to Indian manufacturers. Such measures would mitigate risks for both Indian manufacturers and foreign project developers, enhancing the competitiveness of domestic products. For instance, Chinese financing entities play a significant role in funding energy projects in developing nations, posing competition to Indian banks. By leveraging its expertise in financing solar projects abroad, Exim Bank can spearhead this initiative.

9. **Secure the supply of critical minerals – primary and secondary**: A recent analysis of India's G20 presidency suggests that by 2050, more than 40–80 per cent of the demand for minerals such as copper, nickel, cobalt, and lithium will come from clean energy technologies (CEEW et al. 2023). Accordingly, it will be important for India to secure the mineral supply chain. India has recently signed an agreement with the Argentine government to explore five lithium mines (PIB 2023d) and, more recently, auctioned more than 40 blocks of critical minerals across the country (PIB 2024b). Additionally, India has become a member of the Mineral Security Partnership and the EU's Critical Minerals Club, which is expected to provide the country with access to critical minerals abroad. While these steps are encouraging, more needs to be done at a much faster pace due to the long gestation period for operationalising mines, which can take more than 10 years. In the short term, Khanij Bidesh India Limited (KABIL) can be strengthened financially and coordination between institutions focused on critical minerals – such as Coal India and Indian Rare Earth Limited – can be improved to ensure that their efforts do not compete with each other.

In the long term, India can aim to set up critical mineral stockpiles in collaboration with other countries to address any short-term disruptions. Additionally, as the manufacturing industry advances, it will be important to ensure that the manufacturing processes incorporate elements of circularity. This will ensure that the most important components and materials can be recovered after the end of their useful life. The government can also provide financial and institutional support for manufacturing products with higher levels of material and mineral recovery. Government labs such as the Council of Scientific and Industrial Research (CSIR) can also be tasked with innovating to achieve higher recovery rates. Finally, to ensure the supply chain's readiness and recovery of minerals, the government can encourage start-ups and large industries to venture into mineral and material recovery enterprises.

10. **Improve testing infrastructure**: Technical certification is mandatory for any clean energy equipment sold in India. However, stakeholders have often voiced their concern about the limited number of labs available for this purpose (Table 14). Given the regular changes and technological improvements, labs must adapt to these changes and issue certificates in a timely manner. The National Test House (NTH), with branches in Kolkata, Mumbai, Chennai, Ghaziabad, Jaipur, Guwahati, and Varanasi, is making significant strides towards becoming a future-ready, multidisciplinary testing laboratory. With its recent efforts in establishing EV battery-testing centres, it is laying the foundation for enhanced testing infrastructure in India, which should be extended to other clean-tech equipment as well (MINT 2022).

Table 14 Number of labs for product testing for solar and battery technologies

Indian Standard (IS) codes	Details	No. of labs
Solar		
61730	Photovoltaic module safety qualification	14
14286	Crystalline silicon terrestrial photovoltaic modules	12
Battery		
16046	Secondary cells and batteries containing alkaline or other non-acid electrolytes; safety requirements for portable sealed secondary cells and for batteries	37
16047	Secondary cells and batteries containing alkaline or other non-acid electrolytes; secondary lithium cells and batteries	2

Source: CEEW analysis

The revival of industrial policies, the slowdown of globalisation, and the urgent need for decarbonisation are reshaping global priorities. Proactive policymaking will determine India's future position on the world stage.

Image: iStock

6. Conclusion

Many countries around the world are grappling with three key challenges: energy transition, energy security, and job creation. Clean energy has the potential to address all of these challenges, but only if actions are tailored to the needs of a country's citizens and industries. Polar opposite interventions, such as excessive control or inaction, can either delay or increase the cost of the energy transition and energy security without creating additional jobs. As one of the fastest growing economies, India has adopted a very holistic approach to indigenising domestic manufacturing. However, global geopolitics has led to parallel efforts by other countries aiming to solve the same problem.

Despite the significant competition from emerging manufacturers, India should continue to lay the groundwork for a future clean energy manufacturing hub

We recommend that, despite the significant competition from incumbent and emerging manufacturers, India should continue its efforts and lay the groundwork for a future clean energy manufacturing hub. However, the success of both old and new policies will be contingent on timely and prudent interventions with a long-term view. As we discuss in this report, if India can focus on specific interventions, it can not only solve domestic challenges but also accelerate the global energy transition while ensuring the country's energy security.

In subsequent research, we aim to build on the recommendations of this report with both qualitative and quantitative analysis, and we hope to continue working with stakeholders across the spectrum to address one of the most important problems of this decade.

Annexures

Annexure 1

Key product families by harmonised system code in the clean energy value chain

Table A1 Table of product families relevant to clean energy value chains (CEVC)

Four- digit HS code	Class of products	Application in CEVC	Product complexity score (2021)
8541	Semiconductor devices (for example, diodes, transistors, and semiconductor-based transducers); photosensitive semiconductor devices, including photovoltaic cells, whether or not assembled in modules or made up into panels; light-emitting diodes (LEDs), whether or not assembled with other LEDs; and mounted piezoelectric crystals	Solar cell and module	0.993
3818	Chemical elements doped for use in electronics in the form of discs, wafers, or similar forms; chemical compounds doped for use in electronics	Solar wafer	2.06
7610	Aluminium structures (excluding prefabricated buildings of heading 9406) and parts of structures (for example, bridges and bridge sections, towers, lattice masts, roofs, roofing frameworks, doors and windows, and their frames and thresholds, balustrades, pillars, and columns); aluminium plates, rods, profiles, tubes, etc., prepared for use in structures	Aluminium frames	0.391
3920	Other plates, sheets, films, foils and strips of plastics, non-cellular and not reinforced, laminated, supported, or similarly combined with other materials	EVA	0.418
7007	Safety glass, consisting of either toughened (tempered) or laminated glass	Solar glass	0.627
8535	Electrical apparatus for switching or protecting electrical circuits or for making connections to or in electrical circuits (for example, switches, fuses, lightning arresters, voltage limiters, surge suppressors, plugs, other connectors, and junction boxes) for voltage exceeding 1,000 volts	Junction box	0.669
2804	Hydrogen, rare gases, and other non-metals	Polysilicon	−0.316
7106	Silver (including silver plated with gold or platinum), unwrought or in semi-manufactured forms or in powder form	Silver paste	−0.634
8464	Machine tools for working stone, ceramics concrete, asbestos cement, or similar mineral materials, or cold working glass	Diamond wire saw	1.37
8483	Transmission shafts (including cam shafts and crank shafts), cranks; bearing housings and plain shaft bearings; gears and gearing; ball or roller screws; gear boxes and other speed changers, including torque converters; flywheels and pulleys, including pulley blocks; clutches and shaft couplings (including universal joints)	Wind turbine gearbox	1.31
8503	Parts suitable for use solely or principally with the machines of heading 8501 or 8502	Hub castings	0.866

Four- digit HS code	Class of products	Application in CEVC	Product complexity score (2021)
8412	Other engines and motors	Wind turbine motors	0.819
8505	Electromagnetic; permanent magnets and articles intended to become permanent magnets after magnetisation; electromagnetic or permanent magnet chucks, clamps, and similar holding devices; electromagnetic couplings, clutches and brakes; electromagnetic lifting heads	Rare-earth permanent magnets	1.2
8431	Parts suitable for use solely or principally with the machinery of headings 8425 to 8430	Wind generators	1.08
8507	Electric accumulators including separators, whether or not rectangular (including square)	Lithium-ion batteries	1.19
7607	Aluminium foil (whether or not printed or backed with paper, paperboard, plastics, or similar backing materials) with a thickness (excluding any backing) not exceeding 0.2 mm	Aluminium foil	0.586
3801	Artificial graphite; colloidal or semi-colloidal graphite; preparations based on graphite or other carbon in the form of pastes, blocks, plates, or other semi-manufactured forms	Synthetic graphite (anode)	1.29
2842	Other salts of inorganic acids or peroxo acids (including alumino-silicates, whether or not chemically defined), other than azides	Cathode materials	1.46
7410	Copper foil (whether or not printed or backed with paper, paperboard, plastics, or similar backing materials) of a thickness (excluding any backing) not exceeding 0.12.5 mm	Copper foils	1.09
9032	Automatic regulating or controlling instruments and apparatus	Battery management systems	1.14

Source: Authors' analysis based on Harvard University. n.d. "Atlas of Economic Complexity." Last accessed August 8, 2024. https://atlas.cid.harvard.edu/.

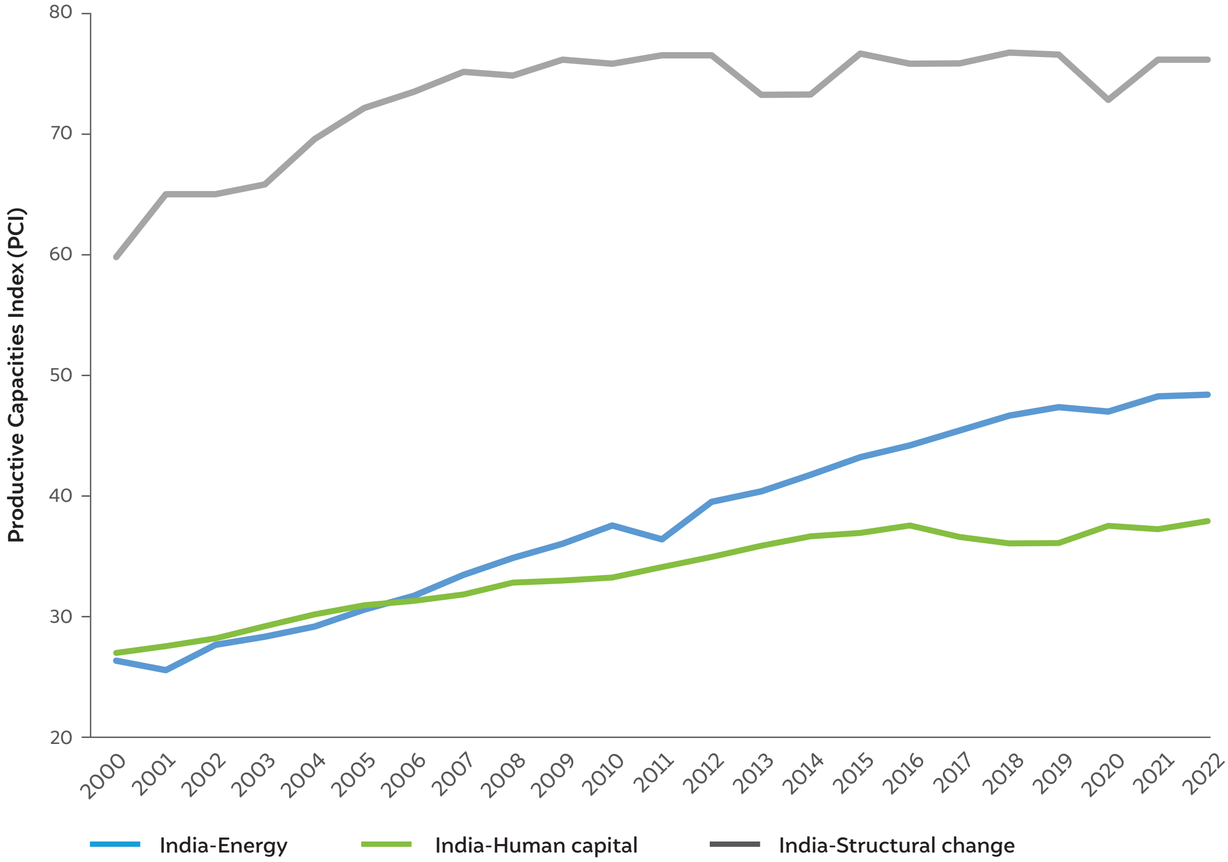
Annexure 2
India's productive capacity

In this section, we provide an overview of India's manufacturing capabilities and the country's current policy landscape for supporting manufacturing in clean energy technologies, which aim to build the necessary competitiveness to meet domestic demand and compete in the global market. Decadal trends show that India's Productive Capacity Index (PCI)[1] has increased over the years and has recently surpassed the trends seen in middle-income developing economies. As a country's productive capacity[2] increases, so does its ability to produce more goods and services. This leads to an increase in overall economic activity and potentially higher GDP. However, significant improvements are required on India's part to match the levels of developed economies.

Amongst parameters of the PCI, India's performance improvement in the energy component, which measures the "availability, sustainability and efficiency of power sources," has far exceeded its improvement in the human capital components, which measure education, research, skills, health, and gender conditions (UNCTAD 2024). This reflects both the success of recent power sector reforms and the need to redouble efforts on human capital and education. The structural change component has traditionally been significant in India and has also seen substantial improvement in recent decades. This component is an indicator of the movement of labour and other resources from low-productivity to high-productivity economic activities (Figure A1).

1. The PCI was developed by the United Nations Conference on Trade and Development (UNCTAD) to provide country-specific insights and guide domestic policies for economic development. It covers 194 economies from 2000 to 2022, wherein productive capacities are mapped across 42 indicators. These indicators are grouped into eight categories: human capital, natural capital, energy, transport, information and communication technology (ICT), institutions, private sector, and structural change. These categories have an independent PCI ranking for each country/class with scores ranging from 1 to 100. The overall PCI score is calculated as the geometric mean of the category scores.
2. The UNCTAD defines productive capacities as "the productive resources, entrepreneurial capabilities and production linkages that together determine a country's ability to produce goods and services that will help it grow and develop"(UNCTAD 2024).

Figure A1 Comparative trends indicate significant growth in PCI for structural change, energy, human and capital for India within two decades



Source: Authors' analysis based on UNCTADstat. 2023. "Productive Capacities." https://unctadstat.unctad.org/datacentre/.

Acronyms

ACC	advanced cell chemistry
AD	accelerated depreciation
ADD	anti-dumping duty
Ag	silver
Al BSF	aluminium back surface field
Al_2O_3	aluminium oxide
ALD	atomic layer deposition
ALMM	Approved List of Models and Manufacturers
BCD	basic customs duty
BESS	battery energy storage system
BMS	battery management system
CAM	cathode active material
CCDC	Concessional Custom Duty Exemption Certificate
CPSU	central public sector undertaking
c-Si	crystalline silicon
CSIR	Council of Scientific and Industrial Research
DCR	domestic content requirement
DFIG	doubly fed induction generator
DWC	diamond wire cutting
ESG	environmental, social, and governance
EU	European Union
EV	electric vehicle
EVA	ethylene vinyl acetate
FTA	Free Trade Agreement
GBI	generation-based incentives
GDP	gross domestic product
GVC	global value chain
GW	gigawatt
GWh	gigawatt-hour
HS	harmonised system
IEA	International Energy Agency
ICT	information and communication technology
IPPs	independent power producers
IRA	Inflation Reduction Act
IREDA	Indian Renewable Energy Development Agency
IRENA	International Renewable Energy Agency
IT	Information technology
KABIL	Khanij Bidesh India Limited
LFP	lithium ferro-phosphate
$LiPF_6$	lithium hexafluorophosphate
LMFP	lithium manganese iron phosphate
LMP	lithium metal phosphate
M3P	manganese 3 phosphate
MHI	Ministry of Heavy Industries
MNRE	Ministry of New and Renewable Energy
MSME	medium and small enterprise sector
MW	megawatt
NCA	nickel cobalt aluminium
NEP	National Electricity Plan
NMC	nickel manganese cobalt
NTH	National Test House
NZIA	Net-Zero Industrial Act
OEM	original equipment manufacturer
OG	opportunity gain
OPEC	Organization of the Petroleum Exporting Countries
PCI	Product Complexity Index
PERC	passivated emitter and rear contact
PLI	production-linked incentive
PM-KUSUM	Pradhan Mantri Kisan Urja Suraksha Evam Utthan Mahabhiyan
PMSG	permanent magnet synchronous generator
PRC	(the) People's Republic of China
PV	photovoltaic
R&D	research and development
RCA	revealed comparative advantage
REE	rare-earth elements
REPM	rare-earth permanent magnets
RLMM	Revised List of Models and Manufacturers
SGD	safeguard duty
WTG	wind turbine generator

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