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Manufacturing for India and the World

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List of Abbreviations

Abbreviations	Full Form
ACC	**Advanced Chemistry Cell**
AHWR	**Advanced Heavy Water Reactor**
AI	**Artificial Intelligence**
ALMM	**Approved List of Models and Manufacturers**
BESS	**Battery Energy Storage System**
BoP	**Balance of Plant**
CEA	**Central Electricity Authority**
CBAM	**Carbon Border Adjustment Mechanism**
CCUS	**Carbon Capture Utilization and Storage**
DC	**Direct Current**
DPR	**Detailed Project Report**
DRDO	**Defense Research and Development Organization**
EDM	**Electro Discharge Machining**
EFI	**Electronic Fuel Injection**
EE	**Energy Efficiency**
EIA	**Environmental Impact Assessment**
EPC	**Engineering, Procurement, and Construction**
ESCO	**Energy Service Company**
EV	**Electric Vehicle**
FDI	**Foreign Direct Investment**
FTA	**Free Trade Agreement**
GHG	**Greenhouse Gas**
GI	**Geographical Indication**
GST	**Goods and Services Tax**
GW	**Giga-Watt**
HVDC	**High Voltage Direct Current**
IEA	**International Energy Agency**
IEC	**International Electrotechnical Commission**
INR	**Indian Rupee**
IPCC	**Intergovernmental Panel on Climate Change**
IREDA	**Indian Renewable Energy Development Agency**
ISO	**International Organization for Standardization**
ITC	**Indian Trade Classification**
LCOE	**Levelized Cost of Energy**
LPG	**Liquefied Petroleum Gas**
LT	**Low Tension**
ML	**Machine Learning**
MNC	**Multinational Corporation**
MNRE	**Ministry of New and Renewable Energy**
MoEFCC	**Ministry of Environment, Forest and Climate Change**
MoP	**Ministry of Power**
MW	**Mega-Watt**
NABL	**National Accreditation Board for Testing and Calibration Laboratories**
NABARD	**National Bank for Agriculture and Rural Development**
NBFC	**Non-Banking Financial Company**
NREL	**National Renewable Energy Laboratory**
NPCIL	**Nuclear Power Corporation of India**
NTPC	**National Thermal Power Corporation**
OEM	**Original Equipment Manufacturer**
PTC	**Power Trading Corporation**
PLI	**Production Linked Incentive**
PPA	**Power Purchase Agreement**

R&D	**Research and Development**
RE	**Renewable Energy**
REIA	**Renewable Energy Implementing Agency**
RPO	**Renewable Purchase Obligation**
SERC	**State Electricity Regulatory Commission**
SEZ	**Special Economic Zone**
SHP	**Small Hydro Power**
SME	**Small and Medium Enterprise**
SOE	**State-Owned Enterprise**
STI	**Science, Technology, and Innovation**
T&D	**Transmission and Distribution**
TWh	**Terawatt-hour**
UHV	**Ultra High Voltage**
VAT	**Value Added Tax**
VGF	**Viability Gap Funding**
WTO	**World Trade Organization**
WtE	**Waste to Energy**

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Executive Summary

The deployment of clean energy is accelerating at an unprecedented pace each year. With the opportunity to serve both domestic and international markets, clean energy manufacturing in India stands at a pivotal moment. Amid a fragmented global market, India has the potential to become a highly competitive manufacturing hub on the world stage. However, this opportunity comes with several risks, including global manufacturing overcapacity, minimal profit margins, and uncertainties surrounding domestic demand. These challenges put at risk the INR 53,982 crore in investments pledged by governments to stimulate this emerging sector through Production-Linked Incentive (PLI) schemes[1]. The strategic policy decisions made now will be crucial in determining whether Indian clean energy technology manufacturers rise as global leaders or continue to rely heavily on government support in the short to medium term. Focused and well-crafted policies and strategic decisions are vital to harmonize the broad economic benefits of indigenization with India's energy security and transition objectives.

Several key factors are driving India's green manufacturing initiatives, including global regulatory requirements, competitive market dynamics, evolving customer expectations, and the strategic allocation of climate-focused capital. Indian industries are increasingly aligning themselves with international sustainability frameworks to maintain their competitiveness in a fast-changing global marketplace. The momentum towards clean energy manufacturing is further strengthened by growing investor confidence in sustainable business practices, as companies committed to environmental responsibility are better placed to attract investment and achieve long-term financial resilience. This transition calls for robust policy measures, strategic collaborations, and ongoing innovation to keep Indian industries at the cutting edge of the global green economy. The synergy between government backing, industry adaptability, and international cooperation will be crucial in shaping the success of India's green transformation.

Accordingly, this report critically examines the challenges faced by the solar, wind, battery energy storage (BESS), green hydrogen electrolyser and power transmission manufacturing sector in expanding the respective manufacturing capacities and puts forward strategic recommendations in achieving this goal. We also examine the key policy and regulatory enablers which have helped these technologies grow in India and its dependency on critical minerals for each of these technologies. Additionally, we have highlighted the key emerging technologies such as carbon capture utilization and storage (CCUS), offshore wind, pumped hydro storage (PHS), biofuels and small modular reactor (SMR) and the challenges they face, providing recommendations to aid their growth in India.

By thoroughly examining the critical strategic priorities and pinpointing essential areas where policy intervention is most needed for specific clean energy technologies, our objective is to offer well-informed, focused recommendations tailored for India. These insights are intended to guide the development of sustainable, forward-looking, and globally competitive segments within the clean energy value chain. Moreover, the guidance provided may also serve as a valuable framework for other developing nations seeking to strengthen their clean energy manufacturing capabilities. Through this targeted approach, we aim to support building resilient and innovative clean energy industries that can thrive in a rapidly evolving global market while contributing to long-term economic growth and environmental sustainability.

[1] Solar PLI 1: INR 4,455 crore; solar PLI 2: INR 13,937 crore; ACC PLI: INR 18,100 crore; SIGHT scheme: INR 17,490 crore, as published by Ministry of New and Renewable Energy (MNRE) and Ministry of Heavy Industries (MHI)

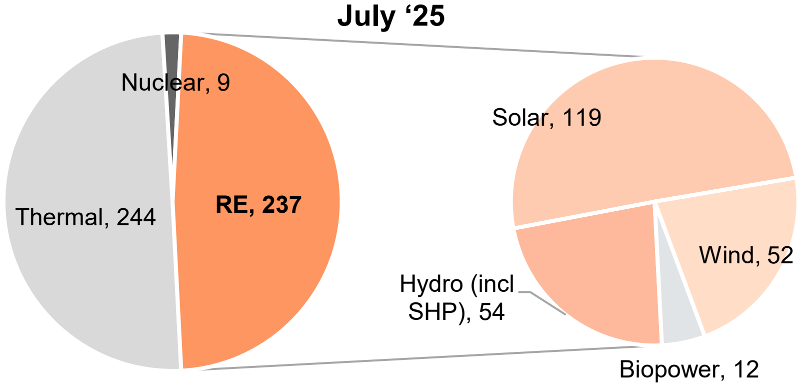
1. Introduction

India has made notable advancements in its energy sector, successfully managing the dual objectives of meeting growing electricity demand and promoting sustainability. As one of the fastest-growing major economies, India is central to the global energy transition, with its energy consumption expected to rise more rapidly than any other major nation. According to the International Energy Agency, emerging economies like India will account for the bulk of global electricity demand growth in the coming years, and India's share in global primary energy consumption is projected to double by 2035. Over the past decade, the country's power sector has expanded significantly, with electricity generation increasing from 1,168 billion units in 2015–16 to an estimated 1,824 billion units in 2024–25 and installed capacity growing from 305 GW to a projected 475 GW. This growth has been supported by major reforms and initiatives such as the national power grid integration, the Deen Dayal Upadhyaya Gram Jyoti Yojana for rural electrification, and the SAUBHAGYA scheme for universal household electrification. Power shortages have been nearly eliminated, dropping from 4.2% in 2013–14 to just 0.1% in 2024–25, while per capita electricity consumption has risen by nearly 46% over the same period. India's energy mix is among the most diverse globally, encompassing both conventional sources like coal, gas, hydro, and nuclear, and renewable sources such as solar, wind, biomass, and small hydro. As demand continues to rise, India remains committed to expanding its energy infrastructure to support long-term economic growth and environmental goals.

1.1. Current RE scenario of India

India is undergoing a transformative shift in its energy landscape, driven by an ambitious vision to decarbonize its economy and achieve energy security through sustainable means. With a target of 500 GW of non-fossil fuel-based installed capacity by 2030, the country is rapidly expanding its renewable energy (RE) portfolio. As of July 2025, India's cumulative RE capacity stood at 237 GW, with solar energy contributing the largest share at 50%, followed by wind energy at 22% and hydro projects at 23%. This growth is not only a testament to India's policy-driven approach but also reflects the country's commitment to global climate goals, including its pledge to reach net-zero emissions by 2070.

Power installed capacity (GW) in India as of July '25



Solar energy has emerged as the cornerstone of India's renewable strategy, with capacity increasing more than 39 times over the past decade—from just 2.82 GW in 2014 to 119 GW by July 2025. Wind energy, too, has seen robust growth, with installed capacity rising from 21 GW in 2014 to 52 GW by July 2025. States like Gujarat, Karnataka, and Tamil Nadu continue to dominate wind power generation, accounting for 98% of new additions in 2025. India now ranks fourth globally in wind power, and is making strides in offshore wind development, hybrid projects, and grid integration to further enhance its wind energy potential.

Biomass and small hydro projects, though smaller in scale, play a crucial role in diversifying India's RE mix and supporting rural electrification. Biomass technologies not only contribute to clean energy generation but also promote circular economy principles by converting agricultural and municipal waste into energy. Small hydro projects, with their localized impact and minimal environmental footprint, continue to support decentralized energy access in remote regions.

A major leap in India's clean energy journey is the launch of the National Green Hydrogen Mission, which aims to position India as a global hub for green hydrogen production and export. With a target of producing

5 million metric tonnes per annum (MMTPA) by 2030, the mission is expected to attract investments worth INR 8 lakh crore, create over 600,000 jobs, and reduce fossil fuel imports by INR 1 lakh crore annually[2]. Green hydrogen is poised to decarbonize hard-to-abate sectors such as steel, fertilizers, and refineries, and will play a pivotal role in achieving long-term climate goals.

However, the rapid expansion of RE also brings challenges, particularly in terms of grid stability and energy reliability. As renewable penetration into the grid increases—reaching 20% and beyond—maintaining grid stability becomes increasingly complex due to the intermittent nature of solar and wind generation. To address this, Energy Storage Systems (ESS) are being deployed at scale. These include Battery Energy Storage Systems (BESS) and Pumped Hydro Storage (PHS), which help balance supply and demand, enable peak shifting, and provide ancillary services. According to the National Electricity Plan (2023), India's energy storage requirement is projected to grow from 82.37 GWh in 2026–27 to 411.4 GWh by 2031–32, and further to 2,380 GWh by 2047. To bridge this gap, the government launched a Viability Gap Funding (VGF) scheme with ₹9,400 crore to support 4 GWh of BESS capacity by 2030–31. Additionally, the Production Linked Incentive (PLI) scheme for Advanced Chemistry Cell (ACC) battery storage aims to attract ₹45,000 crore in investments and build 50 GWh of domestic manufacturing capacity. The Ministry of Power has also introduced a long-term Energy Storage Obligation (ESO) trajectory, mandating obligated entities to gradually increase their storage capacity from 1% in FY 2023–24 to 4% by FY 2029–30, with at least 85% of stored energy sourced from renewables.

India's RE journey is not just about capacity expansion—it is about building a resilient, inclusive, and future-ready energy system. The sector is creating millions of jobs, improving energy access in remote areas, reducing dependence on fossil fuels, and driving innovation across industries. With strong policy support, technological advancements, and global collaboration, India is setting a benchmark for emerging economies in clean energy transition. The integration of diverse renewable sources, coupled with advanced storage solutions and green hydrogen, positions India as a global leader in sustainable energy and a key player in the fight against climate change.

1.2. RE manufacturing scenario in India

India's RE manufacturing sector has seen a dramatic expansion in 2025, positioning the country as a rising force in the global clean energy supply chain. Solar photovoltaic (PV) module manufacturing capacity surged from just 2.3 GW in 2014 to an impressive 100 GW by August 2025, while solar PV cell capacity tripled in just one year—from 9 GW in 2024 to 25 GW in 2025. This growth has been fuelled by the government's Production Linked Incentive (PLI) Scheme, which attracted investments worth INR 41,000 crore and created over 11,000 direct jobs[3]. India also commissioned its first ingot-wafer manufacturing facility, marking a step toward full vertical integration in solar manufacturing.

Despite this progress, India remains heavily reliant on imports—especially from China, which still dominates global solar manufacturing. However, the reimplementation of the Approved List of Models and Manufacturers (ALMM) in April 2024 has begun to shift this dynamic. The policy mandates that government solar projects use domestically produced modules, leading to an 83% drop in imports in Q2 2024 and boosting local production.

In wind turbine manufacturing, India ranks third globally in turbine and component manufacturing, with an annual domestic capacity of 18 GW across 14 original equipment manufacturers[4]. Yet, only 4.15 GW was installed in 2024–25, highlighting underutilization due to grid bottlenecks and inconsistent demand. India holds 7% of global nacelle assembly capacity, but lacks offshore wind nacelle facilities, unlike China, which has 20 operational and 47 planned offshore nacelle plants.

Overall, India's RE manufacturing landscape in 2025 reflects a strong push toward self-reliance, supported by strategic policies and incentives such as the PLI schemes and Aatmanirbhar Bharat initiatives. While challenges remain—particularly in grid infrastructure and technology access—the country is steadily building the foundation for a globally competitive clean energy manufacturing ecosystem.

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[2] https://www.pib.gov.in/PressReleasePage.aspx?PRID=1888547, last accessed on 28th August 2025
[3] https://www.pib.gov.in/PressReleasePage.aspx?PRID=2117501, last accessed on 28th August 2025
[4] https://mnre.gov.in/en/wind-manufacturing/#:~:text=The%20current%20annual%20production%20capacity,turbines%20is%20about%2018000%20MW., last accessed on 29th August 2025

1.3. Benefits of Indigenous Manufacturing

Clean energy manufacturing not only provides crucial pathways for decarbonization but also enhances energy independence, promotes value addition within manufacturing, and generates positive spillover effects on growth and innovation. Localizing this sector supports multiple, interconnected strategic benefits for the Indian economy, including increased resilience and security, greater domestic value capture, expanded export potential, and broad structural transformation. In shaping future policies, it is essential for India to carefully balance the significant yet uncertain advantages of export-driven growth, value addition, and techno-economic transformation with the important but comparatively limited gains in energy security. Trade balance

Benefit	Description
Energy security	Decreases dependence on foreign imports and strengthens energy security by promoting domestic production
Domestic value addition	Enhances the balance of payments, may contribute to greater energy price stability, and generates more employment opportunities
Export opportunities	Creates significant export opportunities by aligning local industries with international demand, thereby stimulating economic growth
Transformation of manufacturing sector	Generates knowledge synergies and spillover benefits across multiple key manufacturing sectors

1.3.1. Energy security

Indigenization of supply can enhance energy security by shifting dependencies and mitigating potential risks. However, these risks represent only a limited threat to overall energy security. From this perspective, disruptions in the supply of clean energy technologies present less immediate concern. Challenges that may arise include difficulties in replacing retiring technologies and obstacles to scaling up clean energy capacity to meet rising demand. Moreover, any security advantages gained through indigenization must be balanced against possible cost increases, since domestically produced components often come at a higher price compared to cheaper imports. Therefore, while energy security remains an important factor, the benefits of domestic manufacturing in this area may be limited.

Supply disruptions can also result from geopolitical conflicts, a recurring global issue in recent years. Consequently, enhancing resilience can be supported through indigenization efforts. For countries reliant on energy imports, indigenizing clean energy supply offers an opportunity to avoid merely replacing fossil fuel import dependence with reliance on imported renewable technologies, which carries long-term geopolitical and economic implications. Developing domestic production capabilities enabled by renewables can shift these dependencies and enhance a nation’s geopolitical standing. Certain segments of supply chains, which experience long lead times can benefit from localized manufacturing to improve resilience against potential disruptions. Thus, the impetus for expanding clean energy manufacturing extends beyond security concerns to include economic objectives and geopolitical ambitions.

1.3.2. Domestic value addition

Focusing on indigenizing manufacturing in select strategic supply chain segments offers a dual opportunity: reducing import dependence while capturing high value-addition segments. Though developing capabilities for these complex and concentrated products will be challenging, it will secure a stable supply of critical components necessary for India’s clean energy ambitions and support progress toward renewable energy goals.

Moreover, investing in the manufacturing of the sophisticated and often costly components can help Indian producers tap into high value-added markets. However, to maximize benefits, an export-oriented approach is essential. Accessing global markets through exports will enable domestic manufacturers to achieve economies of scale, enhance competitiveness, and improve product quality due to increased market pressure.

1.3.3. Export opportunities

The annual market for clean energy is projected to reach USD 640 billion by 2030[5]. This demand is expected to be geographically well-distributed, with China, Europe, and the United States each accounting for approximately USD 140 billion. In comparison, India's market is anticipated to be significantly smaller, estimated at around USD 40 billion, representing roughly 6 percent of the global market. By positioning its clean energy industries to compete globally, India could access a substantially larger market. Additionally, India stands to secure a greater portion of the estimated 14 million clean energy manufacturing jobs projected worldwide by 2030.

Securing a share of the global export market has the potential to drive export-led economic growth and create high-skilled employment opportunities. In light of supply concentration and geopolitical tensions, many countries are actively seeking to diversify their supply chains. This evolving landscape, marked by technological advancements and geopolitical shifts, presents a significant immediate export opportunity for India. Consequently, India must adopt a strategic approach and avoid excessive reliance on export markets, which are subject to uncertainties such as fluctuating demand, protectionist trade policies, and geopolitical conflicts. In the near term, India can capitalize on the 'China Plus One' strategy, targeting exports to nations with ambitious deployment goals but limited domestic manufacturing capacity, and those eager to reduce dependence on China. Additionally, countries imposing import duties on China-made solar PV cells and modules offer further prospects for Indian exports.

A long-term export strategy will necessitate identifying new competitive advantages beyond cost, such as adherence to environmental, social, and governance (ESG) standards, low-carbon manufacturing processes, or distinctive performance criteria. Recently, many nations have prioritized lowering the emission intensity of imported goods by implementing 'green' industrial policies. Meeting emission and ESG requirements is likely to become a critical factor for securing export licenses and attracting private investment in the medium to long term.

1.3.4. Transformation of manufacturing sector

One of the key advantages of clean energy manufacturing lies in its potential to drive widespread structural transformation across the economy. Innovation, which is central to the energy transition, serves as a primary engine of modern economic growth. Such growth emerges when innovation shifts output from low-productivity to high-productivity sectors, often through the introduction of advanced technologies. Beyond this structural shift, manufacturing technologically advanced products also leads to higher wages and reduced competition in export markets, as fewer countries possess the capability to produce and market these specialized goods.

The three primary technological domains within RE—solar, wind, and storage—demonstrate significant knowledge spillovers predominantly within their own fields, a phenomenon known as intra-technology spillovers. Innovations in solar and storage technologies contribute minimally to the knowledge base of other power generation technologies, which are referred to as inter-technology spillovers. However, these fields generate substantial spillovers to sectors outside power generation, known as external spillovers. Notably, external technology spillovers are especially pronounced in storage, solar, and hydropower, suggesting that expanding clean energy technologies will broaden opportunities for India in other high-tech industries. Beyond knowledge spillovers, there exist application synergies; for example, technologies that utilize common materials and share manufacturing infrastructures can accelerate adoption and innovation. The use of carbon fiber in vehicles and aircraft has similarly spilled over into the development of lightweight wind turbine components.

Although India has made significant progress in overall technological innovation, there remains substantial room to catch up with other nations in the field of clean energy innovation. The clean energy innovation landscape is dominated by a few countries that reap the associated economic benefits. This gap presents a clear opportunity for India to compete with technologically advanced countries. Beyond economic transformation and export potential, establishing leadership in technology and innovation can enhance India's geopolitical standing, providing a degree of security against the significant risks affecting clean energy supply chains.

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[5] https://iea.blob.core.windows.net/assets/8834d3af-af60-4df0-9643-72e2684f7221/WorldEnergyInvestment2023.pdf, last accessed on 29th August 2025

2. Solar manufacturing in India

The Indian solar photovoltaic (PV) manufacturing sector is at a pivotal inflection point, transitioning from a nascent, assembly-focused industry to a large-scale, vertically integrated manufacturing ecosystem. This transformation is fuelled by a confluence of robust domestic demand, strategic policy interventions, and a global push towards supply chain diversification. This chapter provides a comprehensive assessment of the current solar module manufacturing landscape, analysing the key demand drivers, the evolution of the manufacturing base, key technological trends, and the critical enablers shaping its future trajectory. The key topics discussed in this chapter are the current solar manufacturing landscape in India, value chain analysis, investments required, challenges within solar manufacturing sector and the strategic recommendations.

2.1. Current solar manufacturing landscape in India

2.1.1. Demand size assessment: Market sizing and key demand avenues

India's solar PV market is characterized by policy-backed demand visibility and diversified end-use segments. The underlying drivers for the solar PV market are (a) affordability of solar power, (b) national decarbonization commitments, and (c) push for electrification of processes across consumer segments.

The foundational driver for the expansion of India's solar PV manufacturing capabilities is the sheer scale of its domestic demand, which is among the largest and fastest growing in the world. The Government of India's ambitious renewable energy targets, including the goal of achieving 500 GW of non-fossil fuel energy capacity by 2030, has created a significant and sustained demand pipeline for solar PV modules.

This substantial demand is channelled through the following key avenues:

- **Utility-Scale Projects:** This segment remains the largest consumer of solar PV modules in India. Large scale solar parks and standalone projects, often developed through competitive bidding auctions conducted by Renewable Energy Implementation Agencies (REIAs), and state nodal agencies, constitute the backbone of India's solar capacity addition. Furthermore, demand from Commercial and Industrial (C&I) sector for utility scale open access projects is key driver for increase in utility scale installations in India. The demand from this segment is characterized by a focus on cost-competitiveness, module efficiency, and long-term reliability to optimize the Levelized Cost of Energy (LCOE).

  Quarter wise demand in MWp terms for utility scale Solar PV is shown in **Figure 1.** There was decreasing trend in demand from Q1 2022 to Q3 2023 due to policy & regulatory uncertainty around BCD, ALMM applicability, and high module prices during this period. Module prices were near record low during Q4 2023, and there was significant uptick in construction progress in utility scale during Q1 2024. This led to record demand of about 9.3 GW during Q1 2024. Increasing

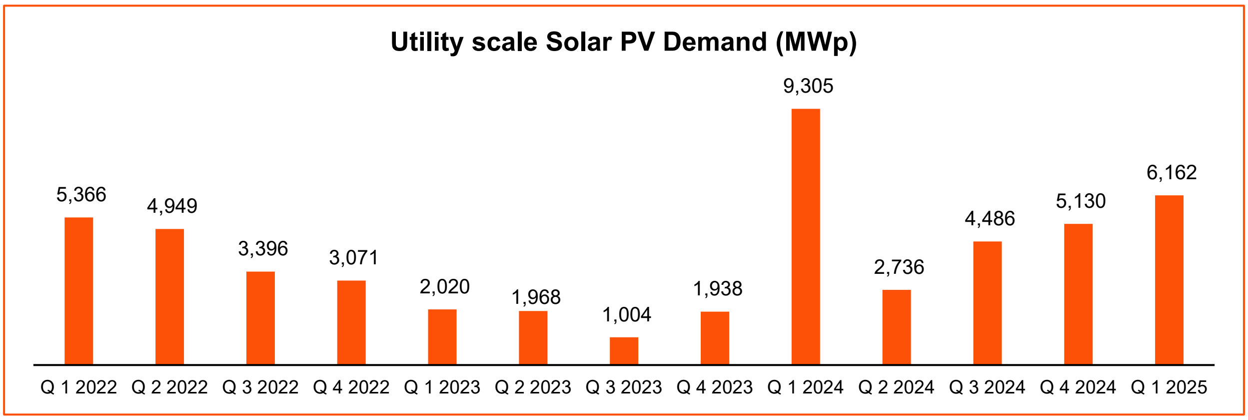

Figure 1: Utility scale solar PV Demand (MWp) *Source: CRISIL*

trend in demand is observed from Q2 2024 onwards due to consistent lower module prices (due to global oversupply of modules in 2024).

- **Rooftop Solar (C&I and Residential):** The rooftop solar segment, particularly in the C&I space, is a rapidly growing demand avenue. For C&I consumers, rooftop solar offers a hedge against rising grid tariffs and a tangible way to meet sustainability goals. The residential rooftop market, while historically slower, is gaining momentum due to simplified subsidy schemes and increasing consumer awareness. This distributed generation market requires a different supply chain and product focus, often prioritizing aesthetics, smaller form factors, and robust warranties. Quarter wise demand in MWp terms for rooftop Solar PV is shown in **Figure 2**.

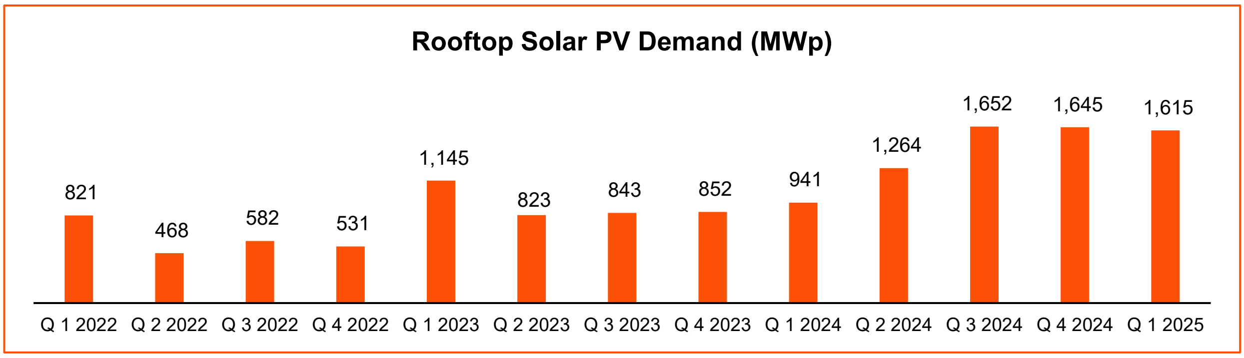

Figure 2 Rooftop solar PV Demand (MWp) *Source: CRISIL*

- **Off-Grid and Agricultural Applications:** This segment, while smaller in volume, holds immense strategic importance for energy access and rural development. Government initiatives such as the Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) scheme, which promotes the solarization of agricultural pumps, create a dedicated demand for domestically manufactured modules. Furthermore, upcoming agrivoltaics concept allows for improving land use efficiency as same land is used for both agricultural and photovoltaics electricity generation. Other applications include solar street lighting, microgrids, and telecom tower power, which contribute to a diverse demand portfolio. Quarter wise demand in MWp terms for off grid Solar PV is shown in **Figure 3**.

2.1.2. Evolving solar manufacturing landscape

India's solar PV manufacturing landscape has undergone a profound structural transformation over the past five years. The industry's evolution can be understood as a strategic shift from import dependency to a concerted push for self-reliance and vertical integration (wafers, cells, and modules).

The current manufacturing landscape is characterized by:

- **Integrated manufacturing**: Leading domestic manufacturers and new entrants have announced and are executing plans for multi-gigawatt integrated manufacturing facilities. By 2030, it has been estimated that there will be 160 GW of module manufacturing capacity, and 120 GW of cell

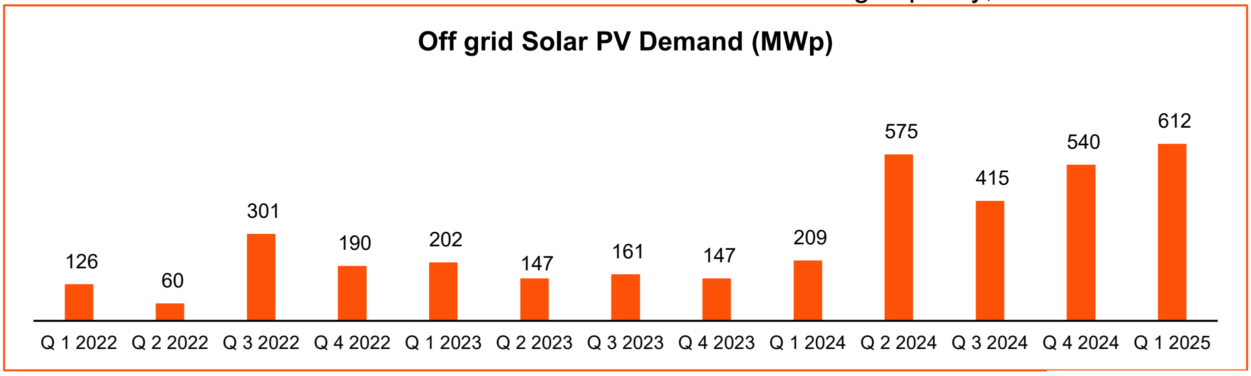

Figure 3 Off grid solar PV Demand (MWp) *Source: CRISIL*

manufacturing capacity[6]. On 13th August 2025, India achieved the landmark milestone of 100 GW of solar module manufacturing capacity along with 25 GW of cell manufacturing capacity, and 2 GW of ingot - wafer manufacturing capacity[7].

- **Deepening Vertical Integration**: The most critical evolution is the move upstream in the value chain. While module assembly remains the final step, significant investments are flowing into establishing cell manufacturing lines. Furthermore, several pioneering companies are investing in the production of solar wafers and even polysilicon, aiming to capture the entire value chain from "sand to module" within India. This strategic move is essential for building long-term resilience and reducing supply chain risks. By 2030, it has been estimated that there will be about 100 GW of wafer manufacturing capacity, and 100 GW of polysilicon manufacturing capacity[2].

- **Emergence of large integrated players**: The sector is witnessing the entry and expansion of well-capitalized corporations. These players bring not only financial strength but also extensive project management expertise and a long-term investment horizon, lending significant credibility and stability to the domestic manufacturing ecosystem. This marks a shift from a fragmented industry of smaller players to one anchored by large, integrated champions.

2.1.3. Technology scan and emerging technologies

PV modules are intricate assemblies of individual solar cells fabricated from advanced semiconductor materials. Significant advancements in semiconductor technology have driven a remarkable evolution in PV module design, primarily focusing on enhancing conversion efficiency and reducing degradation. This technological progression has resulted in higher energy yields and improved long-term reliability of solar PV installations.

Historically, the solar PV industry has witnessed a continuous evolution in cell architectures. Prior to 2018, Back Surface Field (BSF) technology utilizing polycrystalline Silicon (poly C-Si) dominated the market[8]. The introduction of the BSF layer, typically an aluminium layer at the rear of the cell, marked a substantial improvement, elevating cell efficiency[9] from approximately 14% to 17%. This enhancement was attributed to reduced recombination losses, improved heat dissipation, and optimized electrical interconnections within the panel. The paradigm shifted significantly with the widespread adoption of Passivated Emitter and Rear Cell (PERC) technology on p-type monocrystalline Silicon (mono C-Si).

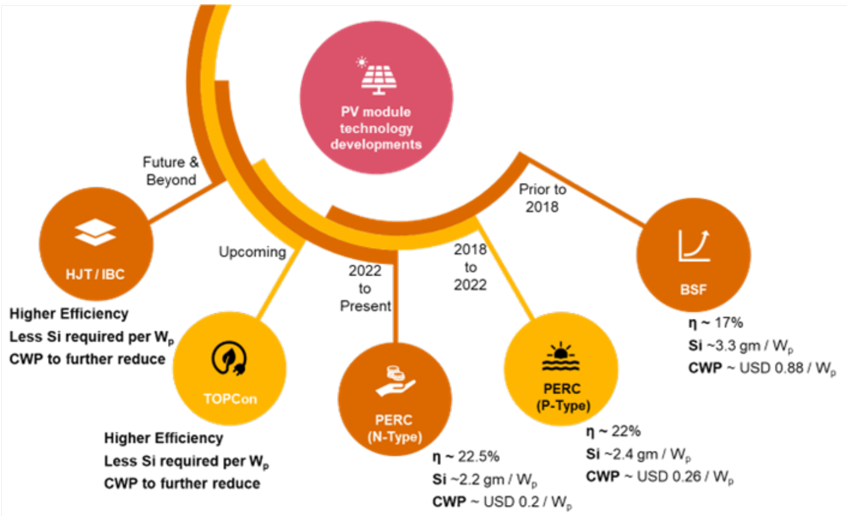

Figure 4: Solar PV module technologies

As per Fraunhofer's Photovoltaic Report 2024, PERC on p-type mono C-Si constituted the majority of panels produced in 2023. PERC technology fundamentally improved upon BSF by integrating a dielectric passivation layer on the rear surface of the solar cell. This structural modification minimized electron-hole recombination at the rear surface, leading to enhanced light absorption and reduced optical and electrical losses. The transition from BSF to PERC technology yielded a substantial increase in panel efficiency from

[6] SolarPower Europe (2025): Global Market Outlook for Solar Power 2025-2029, last accessed on 3rd September 2025
[7] https://www.pib.gov.in/PressReleasePage.aspx?PRID=2156173, last accessed on 3rd September 2025
[8] Fraunhofer's Photovoltaic Report 2024
[9] NREL's solar manufacturing cost analysis

17% to 22%, concurrently reducing manufacturing costs per Watt-peak (Wp) from approximately USD 0.88 to USD 0.23. The technology progress in PV modules has been summarized in adjacent figure.

Beyond PERC, advanced technologies such as Tunnel Oxide Passivated Contact (TOPCon), Heterojunction Technology (HJT), and Interdigitated Back Contact (IBC) are gaining traction. These technologies offer superior efficiencies compared to PERC panels, albeit currently at higher manufacturing costs now. Technologies like TOPCon and HJT, with their superior temperature coefficients and increasing affordability, are becoming strong candidates for high-performance installations in hot climates. However, PERC N-type offers a compelling balance between cost and efficiency, making it ideal for large-scale, budget-conscious projects.

The Table 1 gives a broad comparison based on efficiency, temperature coefficient, panel area per W_p and cost per W_p (in international market) for various panel technologies.

Table 1 Comparison of different PV panel technologies

Technology	Efficiency	Temperature Coefficient	Cost (USD/Wp)	Panel area/Wp (cm2/Wp)	Remarks
N-Type PERC	~22.5%	-0.35%/°C	~ 0.20	44.5- 46.5 (Source[10])	Enhanced efficiency, reduced degradation rates, currently prevalent panel technology, hence widely available.
P- Type PERC	~22%	-0.50%/°C	~ 0.26	46.1- 47.8 (Source[11])	Earlier prevalent technology, widely available, improved performance than its predecessor technologies
TOPCon	~23%	~-0.32%/°C	~ 0.26	43.1– 45.3 (Source[12])	Lower temperature coefficient than N-type PERC, poised to be prevalent technology if costs reduce below N-type PERC
HJT	~26%	~-0.24%/°C	~ 0.34 (Source[13])	41.9-43.75 (Source[14])	HJT panels combine crystalline and thin-film layers to deliver high efficiency and temperature resilience, optimizing energy generation. Due to current high costs these panels are not widely available.

2.1.4. Key Market Enablers

The rapid and transformative growth of India's solar manufacturing sector is not an organic phenomenon alone; it is the result of a deliberate and multi-pronged policy and market strategy. The key enablers that have catalysed this change are:

- **Supportive government policies**: Government has implemented a robust policy framework aimed directly at fostering domestic manufacturing ecosystem. The key policies are:
    1. **Production linked incentive (PLI) scheme**: Direct financial incentives is provided to manufacturers of high efficiency solar modules, cells, wafers, and polysilicon. The scheme is designed to reward scale and vertical integration, making domestic production cost

[10] Panel datasheet, https://www.jasolar.com/uploadfile/2022/1124/20221124101212393.pdf
[11] Panel datasheet, https://static.longi.com/Hi_MO_5m_LR_5_72_HPH_540_560_M_35_35_and_15_G2_V16_b8597c604e.pdf
[12] Panel datasheet, https://waaree.com/wp-content/uploads/2024/02/ELITE-SERIES-BiN-08-570-600-WEL-EPD-570-600-144-BiN-HC-08-20.06.2024_33mm.pdf
[13] Cost per Watt for HJT and TOPCon as per web article, https://www.pv-magazine.com/2025/04/01/us-solar-module-prices-rise-as-market-absorbs-tariffs/
[14] Panel datasheet, https://cdn.enfsolar.com/z/pp/2024/8/4w2wxlsdr2330qi/gsd8j66h-740wt-bifacial-dual-glass-half-cut-hjt.pdf?_gl=1*6sgum8*_gcl_au*MTI4MDI4NDY3MC4xNzQ2NTI0MTgw

competitive against imports. Higher incentives are available for manufacturers producing modules with higher domestic content. Under tranche 1, 8.8 GW of completely vertically integrated (module + cell + wafer + ingot) manufacturing capacity was awarded[15]. While in tranche 2, 15.4 GW of completely vertically integrated (module + cell + wafer + ingot) manufacturing capacity, 16.8 GW of vertically integrated (module + cell + wafer) manufacturing capacity, and 7.4 GW of upstream (module + cell) manufacturing capacity was awarded[16]. Financial outlay of PLI scheme under both tranches is INR 24,000 Crores for supporting 48.3 GW of solar PV module manufacturing capacity in India.

2. **Basic customs duty (BCD)**: The imposition BCD on imported solar cells and modules act as critical trade barrier, creating a price advantage for domestic manufacturers. Currently, BCD on imported solar cells is 20%, while BDC on imported solar modules is 40%.
3. **Approved List of Models and Manufacturers (ALMM):** There is mandate for project developers to procure modules from pre-approved list of manufacturers for projects receiving any form of government support. This measure ensures captive market for manufacturers part of ALMM and enforces quality standards. Though ALMM comprises of both domestic and international module manufacturers
4. **Domestic Content Requirement (DCR):** The policy was reintroduced in 2018 (earlier introduced with National Solar Mission in 2010) to give mandate for use of indigenously manufactured project components in several central government schemes including PM Surya Ghar Muft Bijli Yojana, and CPSU II scheme.
5. **Approved List of Cell Manufacturers (ALCM):** The policy from MNRE aims to boost domestic solar cell manufacturing by requiring solar module makers to use only cells from approved Indian manufacturers.
6. **ALMM for solar wafers:** MNRE plans to add solar wafers to its ALMM from 1 June 2028, requiring government backed projects to use wafers, cells and modules from registered suppliers.

- **Strong and bankable domestic demand**: The pipeline of domestic projects and tender trajectory for 50 GW per annum on renewable energy (of which about 40 GW expected to be solar PV) provides certainty of large, sustained domestic market. This helps in derisking capital investments required for setting up manufacturing facilities.
- **Ancillary ecosystem**: Manufacturers for other raw materials (such as encapsulants, glass, and aluminium frames) are also present in India that helps in creating positive synergies for the entire value chain.

2.2. Value chain analysis

2.2.1. Supply chain assessment

The solar PV manufacturing value chain is a multi-stage process, beginning with raw materials and culminating in finished modules ready for installation. A granular assessment of India's presence across these stages reveals a landscape of concentrated strengths and significant vulnerabilities.

The value chain can be broadly segmented as follows:

- **Upstream Manufacturing**: This foundational stage involves processing raw materials into the core components of a solar cell.

[15] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2023/08/2023080887.pdf
[16] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2023/08/2023080844.pdf

1. **Polysilicon Production**: This is the most capital- and technology-intensive stage, where high-purity silicon (9N purity or higher) is produced from metallurgical-grade silicon.
2. **Ingot and Wafer Manufacturing**: Polysilicon is melted and grown into large crystalline blocks (ingots), which are then thinly sliced into wafers.

- **Midstream Manufacturing**: This stage involves the conversion of wafers into power-generating units.
  1. **Solar Cell Manufacturing**: Wafers are processed through doping, coating, and printing to create photovoltaic cells. While India has been building capacity in this segment, it has historically been limited compared to the downstream module assembly capacity. The recent Production Linked Incentive (PLI) scheme has catalyzed significant investment announcements here.
- **Downstream Manufacturing**: This is the final assembly stage and the most mature segment of the Indian solar manufacturing industry.
  1. **Solar Module Assembly**: Solar cells are interconnected, laminated with protective materials (glass, encapsulant, backsheet), and framed to produce a finished solar module. India possesses substantial and growing module manufacturing capacity, estimated at 80 GW as of the latest data.

The current supply chain is, therefore, characterized by a structural imbalance. While downstream module assembly is well-established, the upstream and midstream segments—polysilicon, ingots, wafers, and to a lesser extent, cells—remain critically underdeveloped. By 2030, it is expected that upstream segments will have significant manufacturing capacity as well. As per information available in secondary sources and recently published reports[17], the projections for manufacturing capacity across the solar PV module supply chain till 2030 is shown in **Figure 5**.

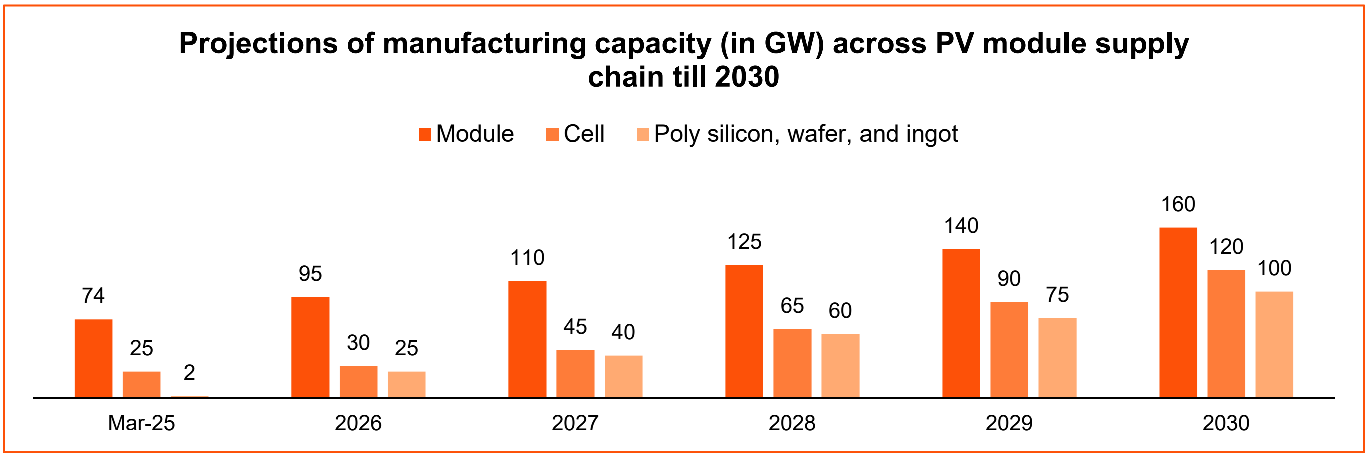

Figure 5 Projections of manufacturing capacity (in GW) across PV module supply chain till 2030

Source: Global market outlook for solar power

For achieving 160 GW of module, 120 GW of cell, and 100 GW of poly silicon, wafer, and ingot manufacturing capacity by 2030, significant CAPEX investments will be required including government investments (INR 24,000 Crores through PLI) and major private investments.

2.2.2. Assessing the Role of Critical Minerals in Localizing the Solar Manufacturing Value Chain

[17] SolarPower Europe (2025): Global Market Outlook for Solar Power 2025-2029, and https://www.pv-magazine.com/2025/04/02/india-reaches-74-gw-of-solar-module-capacity/, last accessed on 18th August 2025

True localization of the solar value chain extends beyond manufacturing plants; it is contingent upon the access to and processing of critical minerals. A secure and cost-effective supply of these raw materials is the bedrock of a self-reliant manufacturing ecosystem.

- **Silicon (Quartz):** The primary raw material for conventional crystalline silicon (c-Si) PV technology is high-purity quartz. While India has abundant quartz reserves, the domestic capability to refine it to solar-grade polysilicon (99.9999999% purity) is not yet established at a commercial scale. Developing this refining capacity is a strategic imperative to capture the highest value segment of the supply chain. In 2023[18], India imported about 169,432 MT of silicon (quartz) of which about 90% was imported from Malaysia, Belgium, and Saudi Arabia.
- **Silver**: Silver is a crucial component used for the conductive paste on the front and back of solar cells. India is a net importer of silver, and its price volatility directly impacts the cost of solar cell production. Innovation in cell technology, such as developing copper-based metallization, is a key long-term strategy to mitigate this dependency. In 2024[19], India imported 2,633 MT of silver (HSN code 710691) of which United Arab Emirates, South Africa, and Poland constituted 95% for the imports.
- **Aluminium**: Aluminium is used for the module frames, while copper is used in busbars, wiring, and other conductive elements. Although India has domestic production capacity for both, but ensuring a stable, cost-competitive supply for the rapidly growing solar sector remains essential. India imported about 2.45 million tonnes of Alumina, and 1.75 million tonnes of aluminium scrap in 2024[20]. Significant aluminium scrap was imported from United States of America, United Arab Emirates, and United Kingdom in 2024.
- **Copper**: Copper is used in busbars, wiring and other conductive elements. There is significant upcoming domestic refining capacity aimed at reducing imports of refined. In FY 2023-24[21], about 363,000 tonnes of refined copper was imported out of which 92% was from Japan, Tanzania, and Mozambique.
- **sSilane**: Silane is a precursor gas in solar manufacturing, primarily used for depositing thin films of silicon, such as amorphous silicon, onto glass or other substrates using Plasma-Enhanced Chemical Vapor Deposition (PECVD). Silane is currently majorly imported in India with Germany, China and the United States accounting for a significant portion of its total imports.
- **Other Minerals (Gallium, Indium, Cadmium, Tellurium)**: While less critical for mainstream c-Si technology, these minerals are vital for certain thin-film technologies (e.g., CIGS, CdTe). As India diversifies its technology portfolio, a long-term strategy for sourcing or developing domestic reserves of these minerals will become increasingly important.

Control over the mining, refining, and processing of these minerals is fundamental to de-risking the supply chain, enhancing value addition within the country, and insulating the domestic market from global price shocks and trade disruptions.

2.2.3. Import Dependency and Domestic Production Capacity

Despite policy interventions, India's solar sector currently remains heavily reliant on imports, particularly for upstream components. This dependency creates a strategic vulnerability and results in significant value leakage from the domestic economy.

[18] https://wits.worldbank.org/trade/comtrade/en/country/IND/year/2023/tradeflow/Imports/partner/ALL/product/250510, last accessed on 18th August 2025
[19] UN Comtrade database, https://comtradeplus.un.org/TradeFlow?Frequency=A&Flows=M&CommodityCodes=710610&Partners=699&Reporters=all&period=2024&AggregateBy=none&BreakdownMode=plus, last accessed on 18th August 2025
[20] https://www.seaisi.org/details/26231?type=news-rooms#:~:text=India's%20primary%20aluminium%20consumption%20stood,into%20surplus%20by%20next%20year, last accessed on 18th August 2025
[21] https://www.pib.gov.in/PressReleasePage.aspx?PRID=2081553#:~:text=(BIS)%20certification.-,In%20FY%202023%2D24%2C%20India%20imported%20about%20363%20Thousand%20Tonnes,be%20granted%20by%20next%20week.

The quarter wise solar PV module availability (in MW terms) and share of domestic and imported module shipments in the module availability is shown in **Figure 5**. The share of imported module shipments increased significantly during Q4 2023 and Q 1 2024 due to record low module prices and global oversupply of PV modules. The domestic shipments have steadily increased from Q2 2024 onwards due to increased domestic manufacturing capacity and strict adherence to DCR requirements for central schemes.

Thus, there is significant import dependency for solar PV panels. With increasing domestic manufacturing capacity, it is expected that the import dependency will reduce in medium term (till 2030).

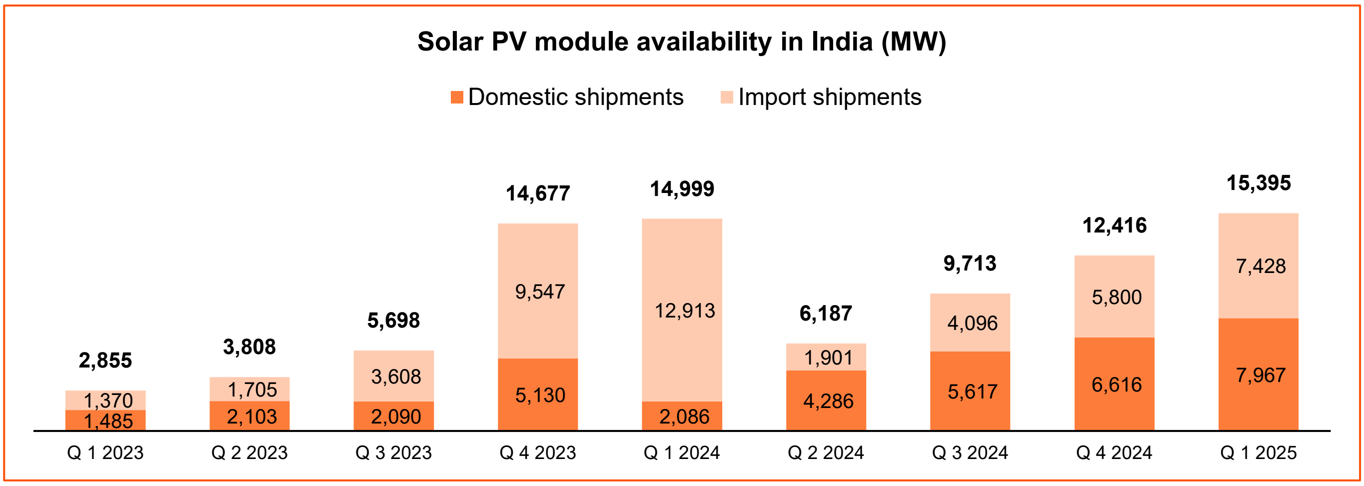

Figure 6 Quarter wise Solar PV module availability in India (MW) *Source: CRISIL*

2.2.4. Significance of Recycling/EoL Waste Management in Fostering Circularity

As India's solar installation base matures, a new challenge—and opportunity—is emerging **End-of-Life (EoL) management of PV modules**. With a typical lifespan of 25-30 years, the panels installed around early 2000’s will soon begin reaching their EoL. This presents a massive waste management challenge but also a significant opportunity to foster a circular economy.

- **Resource Security**: A defunct solar panel is a rich source of valuable materials. A robust recycling ecosystem can recover a significant percentage of glass, aluminium, copper, silicon, and precious silver. This "urban mining" can feed raw materials back into the manufacturing value chain, reducing reliance on virgin resources and mitigating the critical mineral dependencies discussed earlier.
- **Environmental Responsibility**: Landfilling solar panels is environmentally hazardous due to the potential leaching of heavy metals like lead and cadmium. A formal recycling framework, guided by Extended Producer Responsibility (EPR) principles, is essential to ensure these materials are handled safely and sustainably.
- **Economic Opportunity**: Developing a domestic solar recycling industry will create new green jobs in collection, transportation, dismantling, and material processing.

Currently, India's solar recycling infrastructure is in a nascent stage. The Ministry of Environment, Forest and Climate Change (MoEFCC) has brought solar PV modules under the **E-waste (Management) Rules**, making producers responsible for their EoL management. However, building the required capacity, developing cost-effective and high-yield recycling technologies, and establishing an efficient reverse logistics network are critical next steps. Fostering a circular economy is not merely an environmental obligation but a strategic imperative that enhances resource security, creates economic value, and completes the final loop of a truly self-reliant solar value chain.

2.3. Economic and Financial Analysis

2.3.1. Key Cost Considerations

The financial viability of a solar PV manufacturing facility in India is fundamentally determined by its cost structure. These costs can be broadly categorized into initial capital expenditures (CAPEX) and ongoing operational expenditures (OPEX). A nuanced appreciation of each component is critical for accurate financial modelling and strategic decision-making.

- **Capital Expenditure (CAPEX):** The upfront investment to establish a manufacturing plant is substantial and is heavily influenced by the chosen technology and the desired level of vertical integration. The estimated CAPEX requirements based on land requirement, plant & machinery, and EPC costs in India are in range of 31 to 38 million USD per GW for PERC, and between 38 to 46 million USD per GW for TOPCon. About 90% of Indian solar module manufacturers are producing PERC modules whilst rest have upgraded their existing facilities to TOPCon. The key particulars of CAPEX are explained as follows:
    1. **Plant & Machinery**: This constitutes the single largest component of the initial CAPEX. The cost is contingent on the scale of the production line (measured in GW/annum) and the sophistication of the technology deployed (e.g., PERC, TOPCon, HJT). A significant portion of this advanced equipment is currently imported, exposing project costs to currency fluctuations and global supply chain disruptions.
    2. **Land and Civil Works**: The cost of land acquisition and construction of factory buildings, cleanrooms, and associated infrastructure represents another major outlay.
    3. **Utilities and Support Infrastructure:** This includes the setup of essential utilities such as power substations, water treatment plants (especially for wafering), and other ancillary facilities required for uninterrupted operations.
- **Operational Expenditure (OPEX):** Ongoing operational costs are the primary determinant of the final per-watt manufacturing cost and, consequently, market competitiveness. The annual O&M costs for manufacturing facility are typically around 1% of CAPEX cost. O&M costs usually escalate year on year basis to account for increasing labour costs, utilities tariff, and raw materials cost. The key particulars of OPEX are explained as follows:
    1. **Raw Materials**: This is the most significant element of OPEX, often accounting for a vast majority of the final module cost. Key materials include:
    2. **Upstream Inputs**: Polysilicon, ingots, and wafers. The price of these commodities is highly volatile and dictated by global supply-demand dynamics. Securing a stable and cost-effective supply is a primary strategic challenge.
    3. **Cell and Module Components**: Solar glass, encapsulants (EVA/POE), backsheets, aluminium frames, and junction boxes. While some of these are increasingly sourced domestically, price volatility remains a concern.
    4. **Utilities**: Electricity is a major operational cost, particularly for the energy-intensive processes of polysilicon production and ingot pulling. Access to reliable, low-cost power is a critical competitive advantage.
    5. **Labor:** While India possesses a labor cost advantage in absolute terms, the availability of a skilled workforce trained in sophisticated semiconductor and PV manufacturing processes can be a constraint. The cost of skilled technicians and engineers is a notable component of the labor budget.
    6. **Overheads and Maintenance**: This includes plant maintenance, administrative costs, logistics, and compliance with quality and environmental standards.

Ultimately, achieving cost leadership is a function of several interconnected factors: achieving significant economies of scale, deepening vertical integration to capture more value and control input costs, adopting next-generation technology to improve cell and module efficiency, and effectively leveraging government incentives.

2.3.2. Opportunity Size: Investment Required to Meet Demand

India's ambitious renewable energy targets create a vast and protected domestic market for solar PV manufacturers. Government policies, most notably the ALMM, function as a non-tariff barrier that ensures a significant portion of this demand is met by local producers.

The domestic demand for solar modules is projected to be substantial, driven by utility-scale projects, the C&I sector, and rooftop solar installations. Current operational domestic manufacturing capacity, however, falls short of this projected annual demand. More critically, a significant gap exists in the upstream segments of the value chain, including cells, wafers, and polysilicon.

Closing this supply-demand gap necessitates a monumental infusion of capital investment across the entire manufacturing ecosystem. The total investment required can be estimated by mapping the capacity additions needed to achieve self-sufficiency against the per-gigawatt (GW) investment cost for different types of facilities.

For achieving 160 GW of module, 120 GW of cell, and 100 GW of poly silicon, wafer, and ingot manufacturing capacity by 2030, significant CAPEX investments will be required including government investments (INR 24,000 Crores through PLI) and major private investments.

2.3.3. Export Oriented Opportunities

While satisfying domestic demand is the immediate priority, the long-term vision for Indian solar manufacturing must include a robust export strategy. Establishing India as a global manufacturing hub would unlock immense economic value, create high-skilled jobs, and enhance the industry's resilience by diversifying its revenue base.

Many key importing nations are actively pursuing an import diversification strategy to mitigate supply chain risks, creating a significant opening for credible alternatives. In FY 24[22], India exported about USD 2 billion worth of PV modules of which about 99% was towards United States of America. Other key export markets for India include African countries and Southeast Asian countries.

The analysis for opportunities by key export markets is provided as follows:

- **United States of America**: The Inflation Reduction Act (IRA) and existing trade policies have created a highly attractive market for non-Chinese solar modules. Indian manufacturers who can meet the quality, scale, and bankability requirements are well-positioned to capture a meaningful share of this market.
- **Europe**: A similar focus on energy security and supply chain diversification makes the European Union a prime target market for Indian PV exports.
- **Middle East, Africa, and Southeast Asia**: These regions represent growing markets for solar energy where Indian manufacturers can leverage geographical proximity and historical trade relationships.

The key considerations associated with export markets are as follows:

- **Cost Competitiveness**: The ability to match or approach the price points of established global players is non-negotiable. This reinforces the importance of scale, operational excellence, and supply chain control as discussed earlier. In India, the average cost of solar modules (for utility scale solar) varies by technology: Mono PERC at INR ~17.7–17.8/Wp, bifacial at INR ~17.8/Wp,

[22] https://jmkresearch.com/wp-content/uploads/2024/11/Indian-Solar-PV-Exports-Surging_Nov24_updated.pdf

and TopCon at INR ~18.9/Wp. International module prices are about 15% cheaper as these manufacturers hold an edge due to economies of scale, integrated supply chains, lower raw material and financing costs, and advanced technologies.

- **Access to export markets**: The key challenges associated with accessing export markets include intense price competition from international suppliers, trade barriers and anti-dumping duties in some regions, stringent international quality and certification requirements, fluctuations in global polysilicon and module prices, logistics and supply chain bottlenecks, and limited brand recognition of Indian manufacturers in mature global markets.

By leveraging a strong domestic demand base as a springboard, Indian solar manufacturers have a tangible opportunity to expand their footprint globally. Success, however, will be contingent on a relentless focus on cost, technology, and quality.

2.4. Challenges in Solar Manufacturing

This section provides a comprehensive assessment of the primary challenges confronting the Indian solar manufacturing sector. A clear understanding of these obstacles is the first step toward formulating robust strategies to overcome them and realize the nation's full manufacturing potential.

Technology Lag and Obsolescence Risk

The global solar industry is rapidly transitioning from Passivated Emitter and Rear Cell (PERC) technology to higher-efficiency technologies like Tunnel Oxide Passivated Contact (TOPCon) and Heterojunction (HJT). A substantial portion of India's recently established cell manufacturing capacity is based on PERC technology. This creates a significant risk of technological obsolescence, as manufacturers may struggle to find a market for lower-efficiency products. The capital-intensive nature of upgrading production lines presents a formidable barrier to keeping pace with this innovation cycle.

Economies of Scale

The main challenges in scaling up solar manufacturing in India include dependence on imported raw materials (especially wafers, polysilicon, and machinery), lack of advanced technology and R&D compared to global leaders, high capital costs and long gestation periods, quality and reliability concerns versus international standards, inadequate domestic supply chain integration, and operational issues like power costs, logistics, and skilled workforce availability.

Lack of Integrated Manufacturing

The Indian solar manufacturing ecosystem is heavily skewed towards the downstream end of the value chain (module assembly). There is a critical lack of integrated facilities that encompass the entire production process from polysilicon to modules. This fragmentation leads to operational inefficiencies, increased logistical costs, and a weaker control over quality across the value chain.

Quality and Reliability

Establishing a consistent track record for high-quality, reliable, and durable modules is paramount for building bankability and brand reputation. While many manufacturers adhere to international standards, achieving uniform quality control across a rapidly expanding and diverse set of players remains a persistent operational challenge.

Upstream Raw Material Dependency

India has a significant dependence on imports for critical upstream components, including polysilicon, ingots, and wafers. Essential raw materials are sourced from a limited number of countries, primarily China. This over-reliance creates immense geopolitical and price risks, leaving domestic manufacturers vulnerable to supply disruptions and volatile pricing, as witnessed during recent global supply chain shocks.

Inadequate Ancillary Component Ecosystem

Beyond the core silicon value chain, a robust domestic ecosystem for ancillary components—such as high-transmission solar glass, high-quality backsheets, encapsulants (EVA/POE), and aluminum frames—is yet to fully mature. While domestic production of these items is growing, gaps in scale, quality, and cost-competitiveness often compel manufacturers to rely on imports, further complicating the supply chain.

Logistics and Infrastructure Bottlenecks

Inefficient domestic logistics, including port congestion, inadequate road and rail connectivity to manufacturing hubs, and high transportation costs, add to the overall cost of production. These bottlenecks can lead to delays in receiving raw materials and shipping finished goods, impacting production schedules and working capital cycles.

Policy Consistency and Certainty

The solar sector has historically witnessed frequent changes in the policy landscape. For instance, the periodic suspension and reimposition of the Approved List of Models and Manufacturers (ALMM) order, and fluctuations in Basic Customs Duty (BCD) rates, create an environment of uncertainty. Furthermore, there are frequent changes in import duties and safeguard measures, delays in PLI scheme disbursement, complex approval and compliance processes, inadequate R&D and testing infrastructure support, and lack of stable long-term policy clarity. Long-term investment in capital-intensive manufacturing requires a stable, predictable, and long-term policy roadmap to build investor confidence.

Trade Policy Complexities

While trade barriers like BCD are designed to protect domestic manufacturers, they can also increase the overall cost of solar power projects if domestic supply cannot meet demand at a competitive price. This creates a delicate balancing act between protecting nascent industries and achieving national solar deployment targets at the lowest possible cost.

Implementation Timelines and Bureaucratic Hurdles

The execution of well-intentioned policies, including the timely disbursement of incentives under the PLI scheme, can be hampered by bureaucratic delays. Furthermore, lengthy processes for land acquisition, environmental clearances, and other permits can significantly extend project gestation periods for new manufacturing facilities.

Access to Low-Cost Capital

Indian manufacturers face a higher cost of capital compared to their international competitors. Access to long-term, low-interest debt is limited, which puts Indian firms at a significant disadvantage when financing large-scale, multi-gigawatt facilities.

High Working Capital Requirements

The reliance on imported raw materials results in long lead times and, consequently, extended working capital cycles. Manufacturers must lock up significant funds in inventory, which strains liquidity and increases financing costs.

Investor Risk Perception

The combination of technology obsolescence risk, policy uncertainty, and intense competition from established global players elevates the risk perception among private equity and debt investors. Attracting patient, long-term capital requires demonstrating a clear and sustainable path to profitability.

Shortage of Specialized Talent

There is a pronounced shortage of skilled professionals, including R&D scientists, process engineers, and technicians proficient in operating and maintaining sophisticated manufacturing equipment for TOPCon, HJT, and other next-generation technologies.

Inadequate Vocational Training Infrastructure

The existing vocational training and academic curriculum in the country have not kept pace with the specific needs of the solar manufacturing industry. There is a lack of dedicated R&D centers and "train-the-trainer" programs focused on creating a pipeline of skilled manpower for the entire value chain, from polysilicon production to cell and module fabrication.

Need for Research and Development (R&D) Culture

Building a resilient manufacturing ecosystem requires shifting from being a technology adopter to a technology innovator. Fostering a vibrant R&D culture through industry-academia collaboration is essential but currently underdeveloped.

High Utility and Infrastructure costs

The cost of reliable, uninterrupted power is a significant operational expenditure for energy-intensive processes like ingot pulling and wafering. In many states, industrial power tariffs are higher than those in competing manufacturing nations, directly impacting the final cost of the product.

State level readiness

Manufacturers currently encounter significant challenges related to land allocation and navigating multiple layers of approvals, which collectively cause delays in project commissioning. These hurdles not only extend project timelines but also escalate costs and create uncertainty for investors and developers. To address these issues, fostering a robust partnership between national and state governments focused on enhancing the Ease of Doing Business is essential. Such collaboration can streamline regulatory processes, simplify approvals, and harmonize policies across jurisdictions, thereby accelerating project execution.

Water scarcity

Wafer slicing and other stages of PV manufacturing are water intensive. The establishment of large-scale manufacturing plants in water-stressed regions poses a significant operational and environmental challenge, requiring substantial investment in water recycling and conservation technologies.

2.5. Recommendations

The key recommendations and measures that can create an enabling environment for India’s solar manufacturing industry to thrive and fulfill both domestic and export demandsare presented below.

“Giga-Scale" manufacturing solar parks

Establishing dedicated industrial parks specifically designed for manufacturing solar PV technologies can significantly accelerate the growth of solar manufacturing ecosystems. These parks should offer plug-and-play infrastructure, enabling manufacturers to quickly set up operations without delays related to utilities and logistics. Critical components of such infrastructure include seamless connectivity to major transportation networks such as railways, highways, and ports, ensuring efficient movement of raw materials and finished goods. Additionally, these parks must be equipped with dedicated, uninterrupted electricity supply to maintain consistent production and enhance operational reliability. To further streamline the establishment process, governments should facilitate fast-tracked compliance procedures by providing pre-approved clearances for essential approvals related to environmental regulations, land acquisition, and utility connections, thereby reducing bureaucratic hurdles and expediting project timelines.

Ensure policy stability

Establishing a stable, long-term manufacturing policy is crucial for fostering a conducive environment that supports sustained growth and investment in the manufacturing sector. Such a policy should include a clearly articulated roadmap detailing the trajectory of tariffs, including the schedule and structure for BCD, which would provide transparency on cost implications for both domestic manufacturers and importers. Additionally, the policy should lay out firm timelines and frameworks for key incentive schemes, such as the PLI program, ensuring that manufacturers have predictable and assured access to financial support, thus facilitating better planning and capacity expansion. Furthermore, the regulatory framework must be well-defined and consistent, addressing critical aspects like the applicability of DCR and the ALMM. By clearly specifying how these regulations will evolve, the policy will reduce ambiguity and minimize the risk of sudden regulatory changes that could disrupt business operations.

Streamline policy execution

Compliance processes and approvals should be streamlined, requiring only necessary approvals as per strategic discretion of government. This will help reduce bureaucratic delays due to involvement of multiple government departments. The other non-necessary approvals should be properly identified and allowed to be obtained post commissioning of manufacturing facility.

Counter guarantee

Counter guarantee scheme should be launched in India for supporting domestic solar sector manufacturing. Counter guarantee helps cover the downpayments made by solar PV project developers towards their suppliers when they place order for new PV modules. If the supplier fails to meet the contractual obligations, then the developer is entitled to payment. This help reduces the risk for project developers and helps solar PV module manufacturers with necessary risk cover for fulfilling the orders. The reduced risk helps the transaction to be more commercially viable and improves investor confidence across the solar PV supply chain for both developers and manufacturers.

National and cluster level efforts for skill building

To address the growing demand for a skilled workforce in advanced solar PV manufacturing, it is imperative to redesign vocational and engineering curriculum to align closely with the specific requirements of this industry. This involves integrating practical and theoretical knowledge related to the latest manufacturing processes, quality control measures, automation technologies, and sustainability practices relevant to PV production. Updating the curriculum in technical institutes, vocational training centers, and engineering colleges will ensure that graduates are well-prepared to contribute effectively.

Promote R&D

To accelerate technological progress and enhance competitiveness in the clean energy sector, it is essential to foster innovation by establishing dedicated Research and Development (R&D) "Centres of Excellence" within premier academic and research institutions across the country. These centers would serve as hubs for cutting-edge scientific research, technology incubation, and the development of novel solutions tailored to the unique challenges and opportunities of the clean energy landscape in India. By bringing together multidisciplinary experts, state-of-the-art facilities, and industry partnerships, these centers can drive breakthroughs that propel the domestic manufacturing ecosystem forward.

In addition to creating such centers, offering fiscal incentives, such as tax deductions or credits on R&D expenditure, can significantly encourage private sector investments in innovation. This financial support reduces the effective cost of R&D activities, making it economically viable for companies, especially startups and small to medium enterprises, to undertake ambitious research projects. Combined, these measures will cultivate a robust innovation ecosystem, stimulate the development of advanced technologies, and strengthen India’s position as a global leader in solar manufacturing.

Reduce the cost of finance

"Priority Sector Lending" status should be granted to solar manufacturing and associated ancillary manufacturing sector. This will help to reduce interest rates for financing CAPEX for manufacturing facility, leading to decreased cost of finance for the domestic solar manufacturing sector. Furthermore, the status will help to also introduce an interest subvention scheme to lower finance costs for working capital loans. Empower a financial institution like IREDA to offer low-cost, long-tenure debt and create a partial credit guarantee scheme to attract private investment into high-risk upstream projects.

Strengthen Quality Control and Brand Building

The Bureau of Indian Standards (BIS) certification process should be enhanced and aligned with internationally recognized standards to ensure that Indian products meet the highest quality and safety benchmarks. This alignment will not only elevate the credibility and reliability of domestic manufacturers but also strengthen their brand reputation both domestically and globally. By adhering to these top-tier global standards, Indian manufacturers will be better positioned to compete effectively in international markets, thereby facilitating smoother access to export opportunities. Additionally, harmonizing BIS certification with global norms can reduce technical barriers to trade, build consumer confidence, and open doors to new partnerships and collaborations, ultimately contributing to the growth and sustainability of India's solar manufacturing sector.

3. Wind manufacturing in India

India's wind energy sector has potential for supporting globally competitive domestic manufacturing hub catering t significant domestic demand and export markets. This evolution is propelled by a confluence of ambitious national decarbonization targets, favorable policy frameworks, and a robust domestic industrial ecosystem. The country has successfully established a comprehensive value chain, capable of producing wind turbines for both domestic consumption and international markets.

3.1. Current wind manufacturing landscape in India

This section provides a strategic assessment of the current wind manufacturing landscape in India, examining the key drivers of demand, the evolution of the manufacturing base, emerging technological trends, and the critical enablers that will shape its future trajectory. Understanding these dynamics is essential for stakeholders seeking to navigate the opportunities and challenges within this vibrant market.

3.1.1. Demand Size Assessment: Market Sizing and Key Demand Avenues

The demand for wind turbines in India is underpinned by a robust and expanding market, driven by ambitious national energy transition goals. The Government of India has set a target of achieving 500 GW of non-fossil fuel-based energy capacity by 2030, with wind power being a cornerstone of this strategy. The total installed wind power capacity in the country currently stands at approximately 51.2 GW, with annual capacity additions fluctuating in the range of 4 to 5 GW in recent years. The projected demand to meet the 2030 targets necessitates a significant acceleration in annual installations, creating a substantial and sustained order pipeline for turbine manufacturers.

This demand is channeled through several key avenues, each with distinct characteristics and growth potential:

- **Utility-Scale Tenders**: The primary demand driver remains the utility-scale segment, facilitated through reverse auctions conducted by central agencies like the Solar Energy Corporation of India (SECI) and various state-level nodal agencies. These tenders for large-scale wind and, increasingly, hybrid projects ensure a steady, albeit highly price-sensitive, volume for manufacturers.
- **Commercial & Industrial (C&I) Segment**: The C&I market has emerged as a significant and fast-growing demand avenue. Corporates are increasingly procuring renewable power through captive or group captive models and open-access mechanisms to meet their sustainability goals, optimize energy costs, and fulfill Renewable Purchase Obligations (RPOs). This segment often provides better tariff stability and attracts buyers willing to invest in high-performance technology.
- **Repowering of Older Assets**: India possesses a significant fleet of sub-megawatt turbines installed over a decade ago in prime, high-wind resource locations. The repowering of these sites—replacing multiple small, inefficient turbines with fewer, larger, and more efficient multi-megawatt turbines—presents a burgeoning market. This approach enhances the generation capacity from the same land footprint, offering an economically attractive proposition that is expected to unlock about **25.4 GW of potential**[23].
- **Hybrid Projects and Storage Integration**: There is a clear policy-driven shift towards Wind-Solar Hybrid (WSH) projects. These projects offer higher capacity utilization factors (CUF), improved grid stability, and better utilization of transmission infrastructure. The growing number of tenders exclusively for hybrid projects is reshaping turbine technology requirements and creating new demand synergies. The subsequent integration of battery energy storage systems (BESS) represents the next frontier, poised to become a standard feature in future tenders.

[23] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2022/12/2023120715737748582.pdf

- **Offshore Wind**: While still in its nascent stages, the offshore wind sector represents a long-term, high-volume demand opportunity, with a government target of 30 GW by 2030[24]. Initial tenders for projects off the coasts of Gujarat and Tamil Nadu are expected to catalyze the development of a dedicated manufacturing ecosystem for larger-capacity turbines and specialized components.
- **Export**: With a highly localized and cost-competitive manufacturing base, India is well-positioned to serve as an export hub for markets in Southeast Asia, the Middle East, and Africa.

3.1.2. Evolving wind manufacturing landscape

The Indian wind manufacturing landscape has undergone a profound transformation over the past decade. It has evolved from a fragmented industry, heavily reliant on licensed production of dated turbine models, to a consolidated and self-reliant ecosystem characterized by significant domestic value addition and growing R&D capabilities.

Initially dominated by assembly operations for turbines in the sub-2 MW class, the industry has matured significantly. The "Make in India" initiative and a competitive market environment have incentivized manufacturers to deepen their local supply chains. Today, India boasts an annual wind turbine manufacturing capacity of over 18 GW, with a high degree of localization—for critical components such as blades, towers, nacelle assemblies, generators, and power converters.

This evolution is marked by several key trends:

- **Market Consolidation**: The industry has witnessed significant consolidation, with a smaller number of financially robust players—comprising both established Indian firms and leading global Original Equipment Manufacturers (OEMs) with substantial Indian operations—commanding a majority of the market share.
- **Shift to Multi-Megawatt Platforms**: In response to the demand for higher efficiency and lower levelized cost of energy (LCOE), manufacturers have rapidly transitioned their product portfolios. The industry standard has shifted from 2.x MW platforms to the new 3.x MW platforms and beyond, which are specifically designed for India's prevalent low-to-medium wind speed regimes.
- **Development of a Tiered Supply Chain**: A sophisticated, multi-tiered supply chain has been developed to support the OEMs. This includes a network of domestic component manufacturers for both mechanical and electrical systems, creating a resilient and cost-effective production ecosystem. However, dependencies on imports remain for certain specialized components like large-sized bearings and advanced power electronics.

3.1.3. Technology scan and emerging opportunities

Technology is the central catalyst driving the competitiveness of the Indian wind manufacturing sector. The primary technological thrust is aimed at maximizing energy generation from available wind resources, particularly in sites with lower wind speeds (IEC Class III and IV), which constitute a large part of India's untapped potential.

Key technological advancements being manufactured and deployed in India include:

- **Larger Rotors and Taller Towers**: Manufacturers produce turbines with significantly larger rotor diameters, now exceeding 120 meters, to capture more wind energy. This is complemented by an increase in hub heights, with towers reaching 140 meters and beyond, utilizing tubular steel, hybrid, and lattice designs to access stronger and more consistent winds at higher altitudes.
- **Advanced Blade and Drivetrain Technology**: There is a growing adoption of advanced materials like carbon fiber in blade manufacturing to create longer yet lighter blades. In drivetrains, both geared and

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[24] https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1535909#:~:text=The%20Ministry%20of%20New%20&%20Renewable,and%20capacities%20than%20onshore%20turbines.

direct-drive technologies are present in the market, with ongoing innovations aimed at improving reliability and operational efficiency.

- **Digitalization and Analytics**: Modern turbines are integrated with advanced digital solutions, including IoT sensors, predictive maintenance algorithms, and sophisticated software for wind farm management. These technologies help optimize turbine performance, increase the plant CUF, and reduce operational expenditure.

Looking ahead, two major technological shifts present significant manufacturing opportunities:

- **Onshore Technology Enhancement**: The push for even lower LCOE will drive demand for specialized components that enable larger and more efficient turbines. This creates opportunities in domestic manufacturing of high-strength composites for blades, large-diameter pitch and yaw bearings, and advanced power converters.
- **Offshore Wind Technology**: The advent of offshore wind will necessitate a paradigm shift in manufacturing. This includes the production of 10 MW class turbines, massive monopile or floating foundations, corrosion-resistant components, and subsea cables. This represents a greenfield opportunity for both existing players to scale up and for new entrants with expertise in heavy engineering and marine infrastructure.

3.1.4. Key Market Enablers

The growth and sustainability of India's wind manufacturing sector are critically dependent on a supportive ecosystem of policy, financial, and infrastructural enablers. These elements work in concert to de-risk investments, ensure visibility of demand, and foster a competitive environment.

The most critical market enablers include:

- **Policy and Regulatory framework**: Policies such as the waiver of Inter-State Transmission System (ISTS) charges for renewable energy projects, robust enforcement of RPOs, and dedicated policies for repowering and hybrid projects create a stable demand environment.
- **Government Initiatives**: Programs like "Make in India" have been instrumental in promoting domestic manufacturing. **Revised List of Models & Manufacturers** (RLMM) is a list of manufacturers and their models for wind turbines, which is regularly notified by MNRE. Only turbine models mentioned in the list are eligible for installation in India. Till March 2025, **concessional custom duty benefit** was provided to manufacturers listed in RLMM for importing critical components for wind turbine manufacturing.
- **Grid and Infrastructure Development**: The ongoing expansion of the national grid, particularly through the Green Energy Corridors project, is vital for evacuating power from resource-rich regions to demand centers. Furthermore, upgrades to road and port infrastructure are essential to handle the logistics of transporting increasingly larger turbine components.
- **Access to Finance**: The availability of competitive financing from both domestic and international institutions is crucial for project developers to offtake the manufactured turbines. The growing global focus on ESG (Environmental, Social, and Governance) investment has opened new avenues for green bonds and concessional climate finance.
- **Skilled Human Capital**: India possesses a large pool of skilled engineers and technicians. Continuous investment in skill development programs and vocational training, tailored to the specific needs of advanced wind turbine manufacturing and services, is essential to sustain the industry's technological evolution.

3.2. Value chain analysis

This section dissects the Indian wind manufacturing value chain, assessing its supply chain ecosystem, the pivotal role of critical minerals, the dynamics of import dependency versus domestic capacity, and the emerging importance of a circular economy. The domestic content in wind energy projects is about 64% due to the presence of several large-scale wind manufacturers and 2,500 MSMEs supporting the manufacturers with several components and subcomponents[25].

The cost share of several components in wind turbine generator setup is shown in adjacent figure. Tower, blade, gearbox, power electronics, and generator account for 69% of the cost share of wind turbine generator setup. While the rest 31% cost share is for castings, yaw drives, pitch drives, main shaft, and rotor bearing.

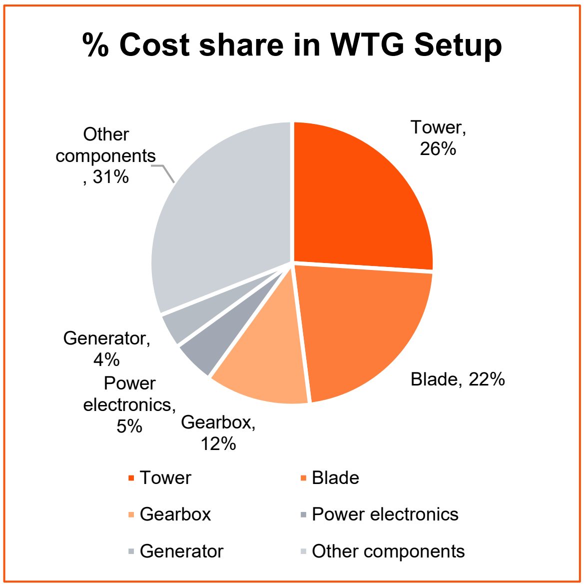


Figure 7: Component wise cost breakup for a WTG

Source: NITI Aayog

3.2.1. Supply chain assessment

The wind turbine manufacturing supply chain in India exhibits a dichotomous character: it is robust and largely localized for major structural components and assembly, yet it remains dependent on imports for certain high-value, technology-intensive sub-components. A component-level assessment reveals the following landscape:

- **Blades**: India has developed a world-class blade manufacturing capability, with several domestic and international original equipment manufacturers (OEMs) operating state-of-the-art facilities. Blades comprise 22% cost share of wind turbine generator setup. Blade manufacturing requires use of balsa wood, foam, pulverized carbon fibre, specialized resins including adhesive resins, high modulus, and glass fibres. Manufacturers are fully importing balsa wood and pulverized carbon fibre, while partially importing specialized resins. Rest of the critical minerals are domestically sourced.
- **Towers**: Towers comprise 26% cost share of wind turbine generator setup. The steel plates used in tower are imported as wind turbines require steel plates of non-standard sizes which are not economical to manufacture domestically due to inconsistent demand and significant CAPEX investment. Tower flanges for wind turbines with diameters greater than 5.5 m are imported due to lack of domestic suppliers. Forged rings for pitch b Paint requirement for the wind turbine is met locally through several domestic suppliers.
- **Nacelle and Hub Assembly**: India possesses a substantial nacelle assembly capacity, with nearly all major global OEMs having established assembly lines in the country. This capacity, estimated at approximately 17.3 GW, supports both domestic demand and exports. However, "assembly" is a key qualifier. While the final integration occurs in India, many of the critical sub-components housed within the nacelle are imported.
- **Nacelle Sub-components**: This is the area of major import dependency.
  - **Gearboxes, Generators, and Bearings**: While some level of domestic manufacturing for smaller-capacity turbine gearboxes exists, large, precision-engineered main bearings and gearboxes for multi-megawatt turbines are predominantly imported. These components require specialized casting, forging, and machining capabilities that are yet to be fully developed at scale in India. Gearbox and generator account for 16% of the cost share of wind turbine generator setup.
  - **Power Electronics**: Key elements like converters and Insulated Gate Bipolar Transistors (IGBTs) are almost entirely imported. These semiconductor-based components are critical for grid

[25] https://www.ibef.org/news/india-can-be-a-global-hub-for-wind-turbines-vice-chairman-of-suzlon-energy-ltd-mr-girish-tanti

integration and power quality control but fall within a technology segment where India has a broader national manufacturing gap.

- **Other components:** Forged rings for pitch bearings and slew/yaw bearings are imported due to lack of domestic manufacturer to forge continuous cast bloom steel for large diameters. Most of the casting products are sourced domestically but challenges exist for larger size turbine models**.**

3.2.2. Assessing role of critical minerals in localizing wind manufacturing value chain

The global transition towards more efficient and powerful wind turbines, particularly direct-drive models, has amplified the strategic importance of critical minerals. For India, securing access to these minerals is a fundamental prerequisite for deepening the localization of its manufacturing value chain.

The most significant minerals in this context are Rare Earth Elements (REEs), specifically Neodymium (Nd), Praseodymium (Pr), and Dysprosium (Dy), which are essential for producing the powerful permanent magnets used in Permanent Magnet Synchronous Generators (PMSGs). These generators are favored in many modern turbine designs for their high efficiency, reliability, and lower weight.

India's current position presents a strategic vulnerability. While the country possesses some REE reserves, its capacity for mining, and more importantly, for the complex metallurgical processes of separating and refining these elements into high-purity oxides and metals, is negligible. Consequently, India is almost entirely dependent on imports for permanent magnets or the processed REEs required to manufacture them. This dependency, concentrated in a few global suppliers, exposes the domestic manufacturing ecosystem to significant geopolitical risks, price volatility, and supply chain disruptions.

3.2.3. Import dependency and domestic production capacity

India manufactures the turbine's visible bulk but imports its technological core, resulting in a substantial value-capture gap and strategic vulnerabilities. The powertrain and control systems are largely sourced from abroad. This creates several import chokepoints that limit true self-reliance:

- **Powertrain Components**: Precision-engineered gearboxes, large-diameter main bearings, and main shafts for multi-megawatt turbines are predominantly imported. This stems from a domestic gap in the specialized, large-scale casting, forging, and advanced metallurgical capabilities required for these critical parts.
- **Advanced Generator Components**: The value chain is highly exposed to geopolitical risk through its reliance on imported permanent magnets, which are essential for efficient direct-drive turbines and are derived from a concentrated global supply of Rare Earth Elements.
- **Power Electronics and Control Systems**: Key enabling technologies, including converters, Insulated Gate Bipolar Transistors (IGBTs), and advanced pitch control systems, are almost entirely imported. This dependency not only affects cost but also constrains indigenous innovation in turbine efficiency and grid integration.

3.2.4. Significance of recycling/EoL waste management in fostering circularity

As wind farms, that were initially commissioned in India, approaches the end of its operational life (typically 25 years), the issue of End-of-Life (EoL) management is transitioning from a future concern to a present-day challenge. Developing a robust framework for recycling and waste management is not only an environmental necessity but also a strategic opportunity to foster circularity and enhance resource security.

The primary EoL challenge lies with turbine blades, which are made from composite materials (glass/carbon fibres embedded in a polymer resin) that are inherently difficult to recycle. Traditional disposal in landfills is unsustainable and represents a loss of valuable materials.

The significance of creating a circular economy for wind turbines is threefold, explained as follows:

- **Resource Recovery**: While blades are challenging, other components are highly recyclable. Steel from towers, copper from wiring and generators, and aluminum from the nacelle housing can be efficiently recovered and reintroduced into the supply chain, reducing demand for virgin materials. It is projected that by 2050[26], the cumulative volume of decommissioned wind turbines in India will reach 275,299 tonnes.

- **Strategic Material Security**: The most compelling circularity opportunity lies in the recovery of critical minerals. Developing cost-effective methods to extract and re-purify REEs from decommissioned permanent magnets would create a valuable secondary resource stream. This would directly mitigate the import dependency and geopolitical risks outlined in Section 3.2.3, creating a closed-loop system that strengthens national self-reliance.
- **Economic Opportunity**: A formal EoL industry for wind turbines will create new business models and employment opportunities in decommissioning services, logistics, material processing, and remanufacturing. Innovative recycling solutions—such as mechanical grinding, pyrolysis, and solvolysis for blades, or co-processing in cement kilns—can transform a waste problem into a value-generating industry.

3.3. Economic and financial analysis

This section provides a comprehensive economic and financial analysis of the sector, dissecting the primary cost structures, quantifying the investment required to meet projected demand, and evaluating the burgeoning opportunities for export. A thorough understanding of these financial dimensions is critical for stakeholders seeking to capitalize on India's clean energy transition.

3.3.1. Key Cost Considerations

The competitiveness of wind turbines manufactured in India is fundamentally tied to a unique blend of cost advantages and specific cost challenges. A granular analysis of the key cost drivers across the value chain is essential for strategic planning and investment decisions.

- **Raw Materials and Components**: This category represents the largest portion of the Bill of Materials (BOM) for a wind turbine.
- **Steel**: Used primarily for towers, steel is a major cost component. India's status as a major global steel producer provides a significant domestic sourcing advantage. However, the type and dimensions of steel components required are non-standard due to which there I .
- **Composites**: Blades are manufactured using composite materials such as fiberglass, carbon fiber, and resins. While the core skills for composite manufacturing are present in India, dependency on imports for certain specialized fibers and resins can expose manufacturers to currency fluctuations and supply chain disruptions.
- **Drivetrain and Nacelle Components**: Key components like gearboxes, generators, bearings, and power electronics constitute a substantial cost. The level of indigenization for these high-technology items varies. While a growing domestic ecosystem exists, certain high-precision bearings and power semiconductors are often imported. The continued development of the domestic component ecosystem is a strategic imperative to further reduce costs and improve supply chain resilience.
- **Rare Earth Elements (REEs)**: For manufacturers producing Permanent Magnet Synchronous Generators (PMSGs), the cost and sourcing of rare earth magnets are critical consideration. Given the global concentration of REE processing, this presents a strategic dependency that requires long-term sourcing agreements or investment in alternative generator technologies.
- **Labor Costs**: India offers a distinct and sustainable competitive advantage in its access to a large pool of skilled and semi-skilled labor at a competitive wage level. This advantage is most pronounced in the manufacturing, assembly, and finishing stages of components like blades and towers, which are labor-intensive. This cost advantage is a primary enabler for India's competitiveness against manufacturers in Europe and North America.
- **Land and Infrastructure**: The capital cost for establishing a new manufacturing facility includes land acquisition and development. While land can be a significant expense, various state governments offer incentives, subsidies, and designated industrial parks or Special Economic Zones (SEZs) to attract investment, thereby reducing the initial capital outlay. Proximity to port infrastructure is a critical factor for large-scale facilities eyeing the export market, as it directly impacts logistical costs for oversized components.
- **Logistics and Transportation**: The sheer scale of modern wind turbine components—with blades exceeding 100 meters and tower sections requiring specialized multi-axle trailers—makes logistics a complex and costly element. Costs are incurred not only in outbound logistics for project sites or ports

[26] https://www.ijfmr.com/papers/2025/4/50341.pdf

but also in inbound logistics for raw materials and sub-components. Infrastructure limitations, such as road width, turning radii, and bridge load capacities, can constrain the transportation of larger turbine models and add to project overheads.

- **Technology and R&D**: To remain competitive, manufacturers must continuously invest in developing larger, more efficient, and more reliable turbines. This involves significant expenditure in research and development or costs associated with technology licensing from global leaders. The strategic choice between in-house R&D and technology partnerships is a key determinant of long-term cost structure and market positioning.

3.3.2. Opportunity size: Investment required to meet demand

India's national climate commitments, including the target of achieving 500 GW of non-fossil fuel energy capacity by 2030, create a massive and predictable domestic demand for wind turbines. This demand serves as the foundational pillar for new investment in the manufacturing sector.

- **Domestic Demand Trajectory**: To meet the national targets, the Indian market is projected to require annual wind capacity additions of 8 GW to 10 GW till 2030. This translates into a consistent and large-scale demand for wind turbine generator (WTG) units, creating a substantial order book for domestic manufacturers. The current installed manufacturing capacity in India is estimated at 17.3 GW per annum, indicating a clear gap and an opportunity for both brownfield expansion by incumbent players and greenfield projects by new entrants.
- **Increase utilization of existing manufacturing capacity**: It is pertinent to improve utilization of existing domestic manufacturing capacity as it will help to improve cost competitiveness of wind turbine manufactured in India.
- **Component Ecosystem Development**: Significant investment is required to strengthen the component ecosystem, which includes investments in manufacturing facilities for gearboxes, generators, and power electronics converters to support the domestic OEM production.

3.3.3. Export oriented opportunities

Beyond the robust domestic market, Indian wind turbine manufacturers are strategically positioned to emerge as significant players in the global export market. This opportunity is driven by a confluence of cost advantages, geographic positioning, and evolving global trade dynamics.

- **Global Market Dynamics**: The increasing global focus on supply chain diversification, often termed the "China Plus One" strategy, has created a window of opportunity for alternative manufacturing hubs. International OEMs and project developers are actively seeking to de-risk their supply chains, and India, with its established manufacturing base and democratic credentials, is a prime candidate.
- **Target Export Markets**: India's geographical location provides it with a logistical advantage for exporting to high-growth wind markets across Southeast Asia, the Middle East, and Africa. These regions often have similar climatic conditions and grid requirements, allowing Indian manufacturers to leverage products developed for the domestic market with minimal customization. India has potential to cater to 10% of global wind energy demand by 2030[27].
- **Competitive Positioning**: Indian manufacturers can compete aggressively on cost, particularly in the workhorse 2 MW to 4 MW onshore turbine segment. The combination of lower labor costs, and economies of scale achieved by serving the large Indian market can enable pricing that is highly competitive against European counterparts. The export of individual components, such as blades and towers, also presents a significant opportunity, allowing India to integrate into the global supply chains of international OEMs.

3.4. Challenges in wind manufacturing

The global trend towards larger, more powerful Wind Turbine Generators (WTGs) presents a dual challenge for the Indian manufacturing landscape. This section provides a structured analysis of the key challenges faced by wind turbine manufacturers in India.

Technology Absorption and Indigenous R&D: A significant portion of the Indian manufacturing sector operates on technology licensed from global parent companies. While this enables access to proven designs, it can limit indigenous Research and Development (R&D) and customization for specific Indian

[27] https://www.ibef.org/news/india-can-be-a-global-hub-for-wind-turbines-vice-chairman-of-suzlon-energy-ltd-mr-girish-tanti

wind conditions. The investment required to establish local R&D centers for developing multi-megawatt turbines is substantial, creating a dependency on foreign technology roadmaps.

Manufacturing Larger Components: The production of longer blades (often exceeding 100 meters) and heavier nacelles require significant capital investment in new moulds, production line re-tooling, and advanced composite materials. Managing the quality control and precision required for these massive components at scale is a persistent operational challenge.

Grid Integration and Stability: Manufacturers must increasingly consider the grid-support capabilities of their turbines, including fault ride-through and frequency regulation, which adds to the technical complexity and cost of the machines.

Testing and Validation Infrastructure: The absence of adequate testing facilities for large-scale turbines and their components within India is a critical gap. Manufacturers often rely on expensive and time-consuming international certification processes, delaying the introduction of new models optimized for the domestic market.

Logistical Bottlenecks: The sheer size of modern turbine components, particularly blades and tower section, creates a logistical nightmare. India's road infrastructure, with its narrow widths, and tight turning radii, is often inadequate for transporting this "Oversized Cargo" (ODC). This not only increases transportation costs and timelines but also limits the deployment of larger, more efficient turbines to remote sites.

Import Dependency for Critical Components: Despite a strong domestic manufacturing base for components like towers and blades, the industry remains reliant on imports for high-tech items such as large gearboxes, pitch and yaw systems, and specialized power electronics. This dependency exposes manufacturers to global supply chain disruptions, currency exchange rate volatility, and international trade policy shifts. The import dependency comprises about 36% of wind energy projects which about a decade ago were only 25%[28]. The increased import dependency is due to the increased size of wind turbines for which domestic component manufacturers have not yet updated their manufacturing capabilities.

Undeveloped Tier-2 and Tier-3 Supplier Ecosystem: While Original Equipment Manufacturers (OEMs) are well-established, the underlying ecosystem of Tier-2 and Tier-3 suppliers for precision-engineered smaller components is less mature. This can lead to issues with quality consistency, delivery reliability, and scalability, forcing OEMs to maintain larger inventories and invest heavily in supplier quality assurance.

Coordination between Central and State Policies: While national renewable energy targets provide a clear direction, their implementation relies on state-level bodies. Manufacturers can face operational issues stemming from a lack of full alignment between central goals and state execution. These issues include delays in processes such as land allocation and grid connectivity approvals, which can lead to an inconsistent demand pipeline and complicated production scheduling.

Changes in the Fiscal and Regulatory Structure: The business environment is sensitive to periodic changes in the fiscal and regulatory framework. Adjustments in customs duties on imported components or modifications to the Goods and Services Tax (GST) can create uncertainty in cost calculations for manufacturers. The absence of a consistent, long-term fiscal framework makes strategic sourcing and financial planning more complex.

Pressure on Profitability: The price-sensitive nature of the market, driven by the reverse auction process, has resulted in downward pressure on margins for turbine manufacturers. This sustained pressure limits the ability to generate internal funds, which are important for reinvesting in plant modernization, technology upgrades, and workforce development.

[28] https://www.ibef.org/news/india-can-be-a-global-hub-for-wind-turbines-vice-chairman-of-suzlon-energy-ltd-mr-girish-tanti

Working Capital Management: The financial condition of some state distribution companies (DISCOMs) can create payment risks that affect the entire supply chain. When developers experience payment delays from DISCOMs, these delays are often passed on to manufacturers. This extends working capital cycles. This requires manufacturers to manage longer payment periods, which can impact on their liquidity and financial health.

Skill Gap in Advanced Manufacturing: The industry faces a shortage of personnel skilled in areas critical to modern turbine production, such as composites technology for blades, precision machining for drivetrain components, and power electronics. There is a disconnect between the curriculum of traditional vocational institutes and the specific needs of industry.

Shortage of O&M Expertise: As turbines become more complex and software-driven, the demand for highly skilled Operation & Maintenance (O&M) technicians with expertise in data analytics, predictive maintenance, and robotics is growing. The talent pipeline for these roles is insufficient to meet projected demand.

Need for Continuous Upskilling: The rapid pace of technological change necessitates continuous training and upskilling of the existing workforce. A structured framework and financial incentives for manufacturers to invest in such programs are largely absent.

3.5. Recommendations

The key recommendations for improving wind manufacturing are as follows:

Stable policy outlook

Policy stability is essential for boosting investor confidence in the wind manufacturing sector. A long-term roadmap should be laid out for customs duty benefits, inclusion in the Revised List of Models and Manufacturers (RLMM), and extension of Production Linked Incentive (PLI) schemes to wind components. This will help reduce uncertainty and encourage sustained investment.

Access for export markets

To enhance access to international export markets, it is crucial for Indian financial institutions to establish local branches in key global regions. These overseas branches would provide exporters with seamless financial services, reducing complexities in cross-border transactions. By offering localized support, such branches can better understand regional market dynamics and regulatory requirements, enabling tailored financial solutions. This presence can also expedite processing of export-related payments and financing, fostering smoother trade flows. Ultimately, these efforts will lower transaction costs, improve liquidity, and strengthen Indian exporters' competitiveness on the global stage.

Demand side aspects

To accelerate the deployment of wind energy, it is imperative that grid planning strategically focuses on regions with abundant RE potential, ensuring that infrastructure development aligns with resource availability. Harmonizing policies, schemes, and regulations across both central and state governments will create a cohesive regulatory environment that simplifies project implementation. Additionally, coordinating the bidding strategies of Renewable Energy Implementing Agencies (REIAs) with specific state-level demand will help expedite the execution and reduce delays in Power Purchase Agreement (PPA) signings. By streamlining these processes, the pace of domestic wind installations can be significantly increased. This accelerated development, in turn, will lead to better utilization of the country's domestic manufacturing capabilities, bolstering the entire value chain.

Standardize the size of the components

The manufacturing of wind turbine towers requires specific steel plates; however, due to the absence of standardized specifications, manufacturers currently rely on imports from countries like China and South Korea. To address this challenge, bodies such as MNRE or NITI Aayog could collaborate with wind OEMs and steel producers to develop and publish a comprehensive standardized specification roadmap for wind turbine towers. This roadmap would provide clear guidelines for steel plate dimensions, quality, and performance standards, allowing domestic steel manufacturers to align their production with the anticipated requirements of the wind energy sector. Implementing such standardization would help reduce India's dependence on imports, creating more reliable and resilient supply chains. Ultimately, this initiative would foster the growth of local manufacturing capabilities for critical components, contributing to the country's self-reliance and supporting the expansion of its wind energy industry.

Streamlining certification and compliance processes

The current procedure for listing wind turbine models in the RLMM requires simplification to encourage greater participation and compliance. Implementing mandatory adherence to international certification standards will ensure stringent quality assurance and type approval, elevating the overall reliability of wind turbine products. Additionally, prioritizing domestic manufacturing for critical components such as hubs and nacelles is essential to enhance local industry capabilities and reduce import dependence. To further streamline operations, the introduction of a single-window clearance system would significantly cut bureaucratic delays, providing a faster and more transparent approval process. This reform would not only facilitate smoother project execution but also create a more conducive environment for business growth and investment in the wind energy sector.

Skill development efforts

To meet the growing demands of the wind energy sector, skill development initiatives must be significantly expanded at both national and regional cluster levels. Educational institutions should revise and update engineering and vocational curriculum to incorporate the latest advancements and technical knowledge related to wind energy technologies. Establishing dedicated training centers across major manufacturing hubs will provide specialized programs tailored for technicians and engineers, focusing on areas such as turbine assembly, preventive and corrective maintenance, and stringent quality assurance practices. These targeted training efforts will help bridge the current skills gap, ensure a competent workforce, and enhance overall industry productivity. By investing in comprehensive skill development, India can build a sustainable talent pipeline that supports the rapid growth and competitiveness of its wind energy industry.

Increasing R&D initiatives

To drive innovation and technological advancement in the wind energy sector, it is crucial to enhance R&D efforts by establishing dedicated Centres of Excellence in partnership with leading academic and research institutions. These centers would serve as hubs for cutting-edge research in areas such as advanced turbine design, materials science, and digital monitoring technologies, fostering collaboration between industry experts and researchers. Providing targeted tax incentives for investments in R&D will encourage companies to increase their expenditure on innovation, reducing financial barriers and enhancing project feasibility. Such fiscal support would stimulate the development of breakthrough technologies, accelerating the industry's growth and global competitiveness. Ultimately, this strategic focus on R&D will empower India to become a leader in wind energy technology, driving sustainable economic development and energy security.

Financial support mechanisms

To accelerate the growth of wind manufacturing, financing mechanisms need to be substantially strengthened to lower the overall cost of capital for developers and manufacturers. Institutions such as the Indian Renewable Energy Development Agency (IREDA) should be empowered with enhanced capabilities and resources to offer low-cost, long-tenure debt financing tailored specifically for wind manufacturing projects. Alongside this, introducing partial credit guarantee schemes can play a pivotal role in mitigating risks for private investors, encouraging greater capital flow into the high-risk upstream manufacturing segment. Implementing a counter-guarantee mechanism, modeled after successful initiatives in the solar sector, would further reduce transaction risks faced by developers and OEMs. Collectively, these financial instruments will enhance the commercial viability of wind manufacturing, stimulating investment, innovation, and industry expansion.

4. Green Hydrogen Electrolyser Manufacturing in India

Electrolysers are specialized devices that use electrical energy to split water into hydrogen and oxygen through the process of electrolysis. These devices, when powered by renewable sources like solar or wind, generate hydrogen with minimal carbon emissions, which positions them as a key technology in green hydrogen production.

In recent years, the global electrolyser capacity has expanded rapidly, which are driven by supportive policy frameworks, technological advancements, and the urgent need to decarbonize hard-to-abate sectors by replacing conventional hydrogen with the green hydrogen. According to International Energy Agency (IEA) hydrogen production data base[29], the operational electrolyser capacity across the globe, has increased form 224 MW to 1488 MW from 2020-till October 2024. The cumulative electrolyser capacity addition is shown in the Figure 8.

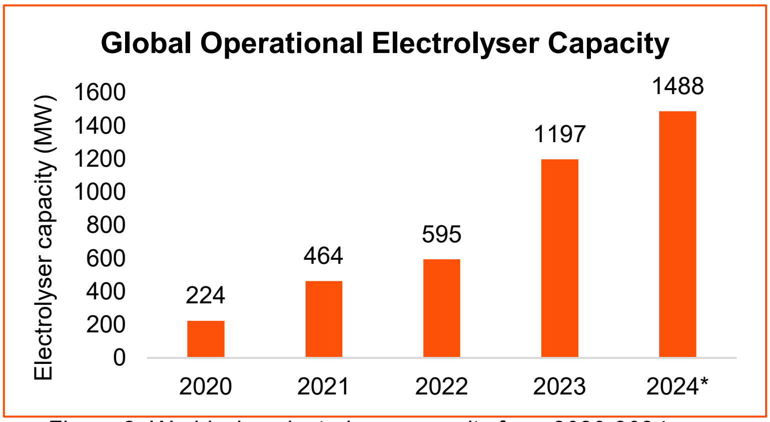


Figure 8: World wise electrolyser capacity from 2020-2024 Source: IEA

China contributed approximately 75% of the new electrolyser capacity which became operational in 2024, raising its global share to 70%[30]. Moreover, Europe and the United States are projected to follow with shares of 15% and 6%, respectively. IEA highlights that, as of 2023, alkaline technology remains dominant, representing over 60% of the installed electrolyser capacity, while proton exchange membrane (PEM) technology accounts for 22%. Despite its relatively smaller share, several mid-sized PEM electrolyser projects have recently commenced operations. Furthermore, based on new announcements, the global electrolyser is projected to reach 230 GW by 2030 under IEA net zero scenario.

4.1. Current electrolyser manufacturing landscape in India

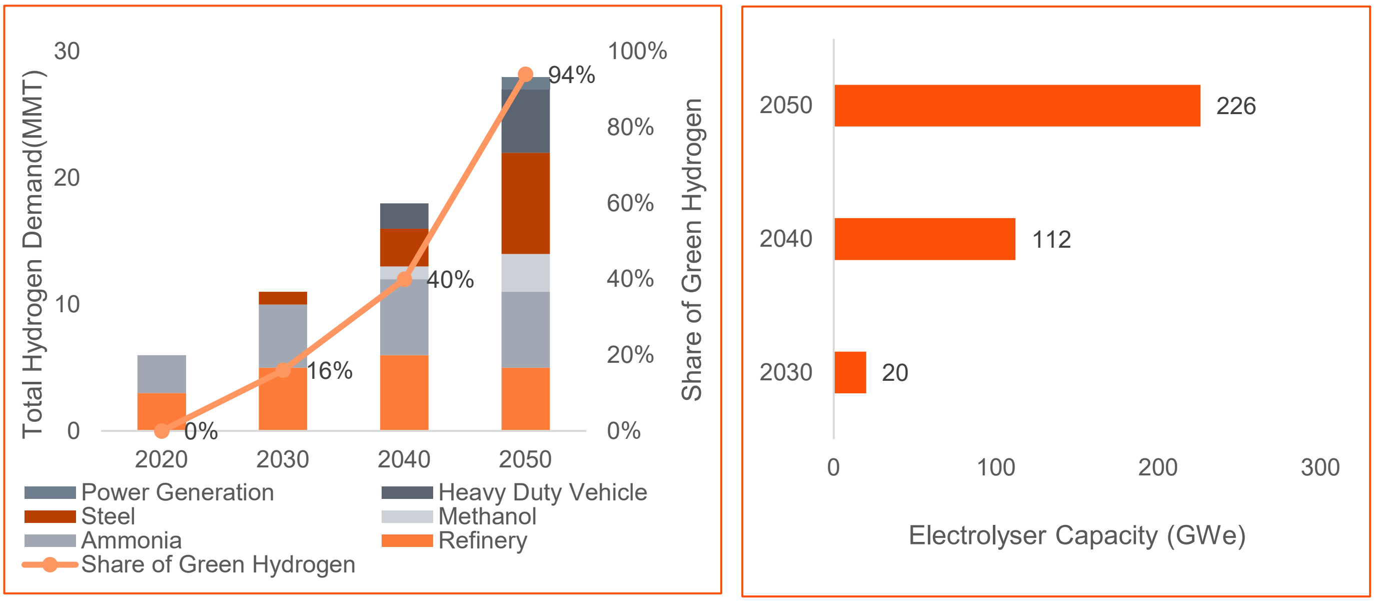
4.1.1. Demand Size Assessment: Market Sizing and Key Demand Avenues

India's hydrogen demand is projected to increase more than fourfold by 2050[31]. In the initial phase by 2030, the demand will be driven primarily by the refinery (5MMT) and ammonia (5MMT) sectors, which are looking to transition into cleaner industrial feedstocks and sustainable chemical processes. In the longer run, the steel industry (8MMT) and heavy-duty transportation (5MMT) especially heavy-duty trucks are projected to become key drivers of hydrogen demand, contributing to nearly 50% of the total demand by 2050. Additionally, a new demand stream from methanol production (3 MMT) is expected to materialize by 2050. The sector-wise breakdown of hydrogen demand and the share of green hydrogen within each sector at cost parity are depicted in Figure 9 below:

[29] https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database#

[30] https://www.iea.org/data-and-statistics/charts/announced-electrolyser-manufacturing-capacity-by-region-and-manufacturing-capacity-needed-in-the-net-zero-scenario-2021-2030

[31] https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf



Source: NITI Aayog

Figure 9: Sector wise demand of Green Hydrogen in India by 2050 and Domestic electrolyser capacity potential

This surge in demand for green hydrogen presents a significant opportunity for India's domestic electrolyser market, which is projected to grow to an installed electrolyser capacity of 226 GW by 2050[31], as shown in the Figure 9 above.

NITI Aayog also highlights that government interventions such as Viability Gap Funding (VGF), regulatory mandates for existing hydrogen consuming sectors like refinery and ammonia/fertilizer, pilots, and cost reduction incentives through preferential electricity tariffs could significantly accelerate the development of the hydrogen market. If these measures are effectively implemented, hydrogen demand could rise to 44 GW by 2030, marking a substantial increase in the near term.

4.1.2. Evolving electrolyser manufacturing landscape

The Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, under the National Green Hydrogen Mission (NGHM) has allocated a budget of INR 4,440 crores in the first year to support electrolyser manufacturing, aiming to scale up India's production capacity to 3 GW annually in two tranches. In the first and second tranche, Solar Corporation of India (SECI) had invited the bids for 1,500 MW of electrolyser manufacturing capacity as shown in Figure 10 below:

Bucket 1: Any Stack technology
1200 MW

Bucket 2: Indigenous Stack technology
300 MW

Bucket 1: Any Stack technology
1100 MW

Bucket 2A: Indigenous Stack technology
300 MW

Bucket 2B: Indigenous Stack technology (Smaller units)
100 MW

Figure 10: Electrolyser bidding under Tranche 1 and 2

In the first tranche, electrolyser manufacturing capacities were awarded to 8 companies under two distinct buckets, with relatively larger allocations in the range of 100 to 300 MW. However, under the second tranche, the bids are allocated to 13 bidders, in which four companies with capacities of 30 MW or less are budded out. A lower capacity bids reflects a strategic intent to encourage participation from smaller and domestic manufacturers. Further, through this approach, the government aims to promote technological self-reliance and build a resilient and scalable electrolyser manufacturing ecosystem in India.

Moreover, the closer examination of the allocated capacities reveals that only one company has submitted bids for PEM electrolysers of the capacity of 137 MW under each of the tranche. Additionally, just 10 MW of Solid Oxide Electrolyser (SOEC) capacity was awarded in the first tranche. This highlights the current dominance of alkaline technology in the Indian electrolyser market, which remains the preferred option due to its technological maturity, cost-efficiency, and suitability for large-scale, stable operations. In contrast, PEM and SOEC technologies are still in the early stages of adoption in India.

Looking ahead, several public and private sector entities have also announced plans to set up electrolyser manufacturing facilities in the country and partnered with international firms to localize production[32]. However, the exact electrolyser manufacturing capacity plans for many of the companies are still not publicly disclosed.

4.1.3. Technology scan and emerging technologies

On a commercial scale, electrolysers are broadly categorized into three main technologies, differentiated by the type of electrolyte or membrane used, operational characteristics, and cost considerations:

Alkaline electrolysers

Alkaline electrolysers use 30 to 40% solution of KOH as the electrolyte instead of water. This alkaline solution provides excess OH^- ions to drive the water-splitting reaction. Further, these OH^- ions are converted into H2O and generate electrons at the anode while also producing oxygen. These electrolysers are known for their low capital cost and long operational history. However, they have a relatively large physical footprint and slower response times, making them best suited for large-scale hydrogen production in stable, continuous operations.

Polymer electrolyte membrane (PEM) electrolysers

PEM electrolyser water splits on the anode side, producing oxygen and H^+ ions, which generate free electrons. Then electrons are transferred to the cathode via a wire completing the circuit, while the H^+ ions are conducted via the membrane and reach the cathode, where they combine with the electrons to produce hydrogen. These electrolysers offer fast response times and a compact design, making them ideal for integration with intermittent renewable energy sources such as solar and wind. Their small footprint also makes them well-suited for on-site hydrogen generation, especially in space-constrained environments.

Solid Oxide electrolysers (SOEC)

SOCE electrolyser water is split at the cathode to produce hydrogen and O^{2-} ions. These O^{2-} ions are transported via the electrolyte medium, and then convert into oxygen (O_2), releasing electrons on the anode side to complete the cell reaction. These electrolysers operate at high temperatures, which allows them to achieve exceptionally high efficiencies, especially when integrated with waste heat from industrial processes. This makes them particularly suitable for industrial environments with abundant thermal energy, such as steel and cement plants, as well as power plants and co-generation facilities.

An overview of the electrolysers by a range of technical and operational parameters that determine their suitability for various applications is shown in the table below:

Table 2: Overview of electrolyser technologies

Metric	Unit	Alkaline	PEM	SOE
Nominal current density	A/cm^2	0.2-0.8	1-2	0.3-1
Voltage range (limits)	Volt	1.4-3	1.4-2.5	1-1.5
Operating temperature	ºC	70-90	50-80	700-800
Cell pressure	bar	<30	<30	1
H2 purity	%	99.9-99.9998	99.9-99.9999	99.9
Footprint	Cm^2	10,000–30,000	1,500	<300
Capital cost (stack)-for min 1 MW	USD/kW	270	400	>2,000
Lifetime(stack)	Hours	60,000	50,000-80,000	< 20,000
Electrical efficiency (stack)	kWh/Kg H_2	47-66	47-66	35-50

Source: IRENA 2020[33]

[32] https://nghm.mnre.gov.in/project?cat=16&language=en, last accessed on 19th August 2025
[33] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf, last accessed on 19th August 2025

4.1.4. Key market Enablers

As outlined in previous sections, India holds significant potential for scaling up electrolyser manufacturing. This growth is being catalyzed by several key enablers:

Government Initiatives and Incentives: The SIGHT program under the NGHM is a major catalyst which promotes indigenous electrolyser manufacturing through PLI schemes, offering financial support of INR 4,440/kW in the initial year, to reduce capital costs and encourage domestic production.

Net Zero Targets: India's commitment to achieving net zero emissions by 2070 which necessitates the decarbonization of hard-to-abate sectors such as refining, ammonia, steel, and transportation. These sectors have a high demand for hydrogen as a feedstock, thereby driving the need for electrolyser deployment to produce green hydrogen.

International Partnerships and Collaborations: Initiatives like the recent SECI bid for electrolyser manufacturing have opened avenues for domestic manufacturers to collaborate with international players. These partnerships facilitate technology transfer, skill development, and experience sharing, enhancing the competitiveness of Indian manufacturers.

Export Market Potential: The introduction of the Carbon Border Adjustment Mechanism (CBAM) in European countries is creating demand for low-carbon products such as green ammonia and green steel. This presents a strategic opportunity for India to scale up electrolyser manufacturing to support exports to these markets.

Falling Renewable Energy Costs: The declining cost of solar and wind energy in India makes green hydrogen production more economically viable, which will improve the project feasibility and return on investment.

4.2. Value Chain Analysis

An electrolyser typically comprises a Single Repeating Unit (SRU), which is assembled into an electrolyser stack. The complete electrolyser system is formed by integrating this stack with the Balance of Plant (BoP).

For this report, our analysis focuses exclusively on the value chain of the electrolyser stack, as the BoP includes components such as heat exchangers, compressors, and power supply system which are already well-established and widely standardized across the industry.

4.2.1. Components of the Electrolyser stack

The Single Repeating Unit (SRU) serves as the core functional element within an electrolyser stack. Each SRU consists of several critical components that work in tandem to facilitate efficient water electrolysis. While the schematic of an electrolyser is shown in the figure[36] below. It is also important to note that the specific components and their configurations within the SRU can vary depending on the underlying electrolyser technology, but the general architecture typically includes the following elements:

a) **Ion-Conducting Separator or Electrolyte**: It serves as the medium for selective ion transport between the anode and cathode, while preventing direct electron flow. Depending on the technology, this may be a polymer membrane, liquid electrolyte, or solid ceramic.

b) **Electrodes:** These are conductive layers coated with catalytic materials to facilitate electrochemical reactions. It is positioned on either side of the separator, which forms the core reactive interface of the cell.

c) **Gas and Water Transport Layer:** A porous structure that aids in the efficient removal of generated gases (hydrogen and oxygen) and the distribution of water or steam to the reaction sites.

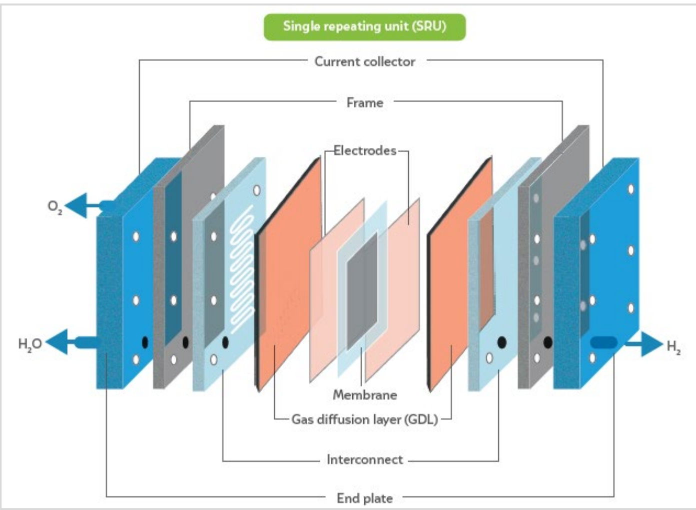


Figure 11: Schematic of SRU of a typical electrolyser

d) **Flow Field Plate / Bipolar Plate / Interconnect:** It performs multiple roles such as uniform delivery of water, steam, or electrolyte across the active area of the cell to support consistent electrochemical reactions along with helping in conducting current between adjacent cells and providing mechanical support for stack assembly.

e) **Current Collector:** A conductive component that distributes electrical current uniformly to the electrodes to ensure consistent cell performance.

f) **Frame:** Provides structural support, holding the cell components together to maintain integrity and prevent gas leakage.

4.2.2. Assessing role of critical minerals in localizing electrolyzer manufacturing value chain

The components of electrolysers outlined above vary in material requirements depending on the electrolyser technology (e.g., PEM, alkaline, SOEC). Each technology relies on specific critical minerals for performance and durability.

Alkaline electrolysers[34]

The alkaline electrolysers are the most cost-effective due to their avoidance of precious metals. Majority of the material consumption in the alkaline electrolysers are non-critical minerals such as stainless steel and Aluminium which are used in frame and end plate manufacturing.

to the larger physical footprint of these electrolysers, the material requirements can be substantial reaching up to 10 tonnes of stainless steel and 0.5 tonnes of aluminium per MW of capacity.

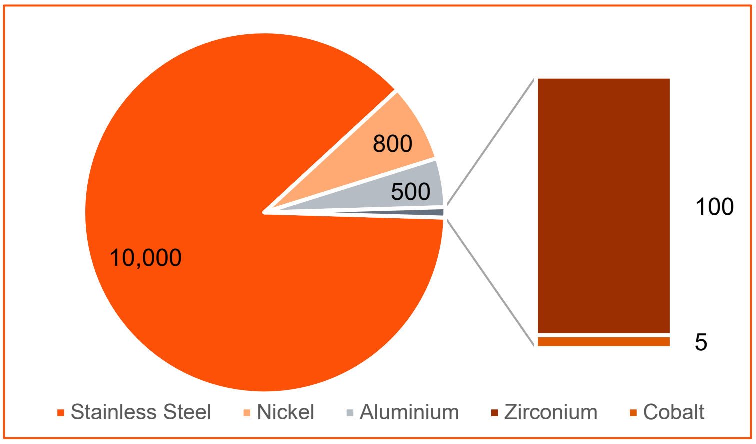


Figure 12: Material Composition of Alkaline electrolyser (kg/MW)

In addition, smaller quantities of critical materials such as cobalt (approximately 5 kg/MW) and copper catalysts are also required. The electrodes and membranes incorporate essential minerals like Nickel (Ni) and Zirconium (Zr), with consumption levels of around 800 kg/MW and 500 kg/MW respectively.

PEM electrolysers[34]

The PEM electrolyser cell exhibits a higher dependency on critical raw materials compared to alkaline electrolyser. Titanium (528 kg/MW) plays a crucial role as it is extensively used in the manufacturing of electrodes which serves as a porous substrate as well as used in the fabrication of bipolar plates and current collectors.

Additionally, precious metals such as Iridium (~0.75 kg/MW) and Platinum (~0.5 kg/MW) are employed as catalysts on the anode and cathode, respectively, to drive the electrochemical reactions. For structural components like frames and end plates, non-critical minerals such as aluminium (~27 kg/MW) and stainless steel (~100 kg/MW) are used, which provides mechanical strength and durability to the electrolyser stack.

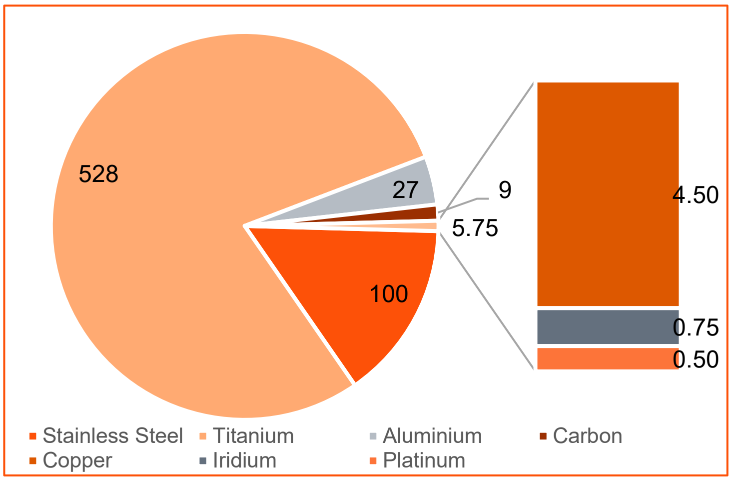


Figure 13: Material Composition of PEM electrolyser (kg/MW)

SOEC electrolysers[34]

[34] https://www.sciencedirect.com/science/article/pii/S036031992401783X

The SOEC electrolysers are high temperature electrolysers that has very high dependency on critical and rare earth metals.

A typical SOEC electrolyser requires substantial quantities of nickel (~200 kg/MW) and zirconium (~40 kg/MW). Nickel is primarily used in the cathode manufacturing in the form of Nickel oxide and Zirconium, in the form of yttria-stabilized zirconia (YSZ), is used as the solid electrolyte, offering high ionic conductivity and thermal stability.

In addition to these, SOECs also rely on rare earth elements to enhance performance and durability. Scandium (~23 kg/MW), lanthanum (~20 kg/MW), and yttrium (~5 kg/MW) are commonly used in the anode (oxygen electrode) and electrolyte materials.

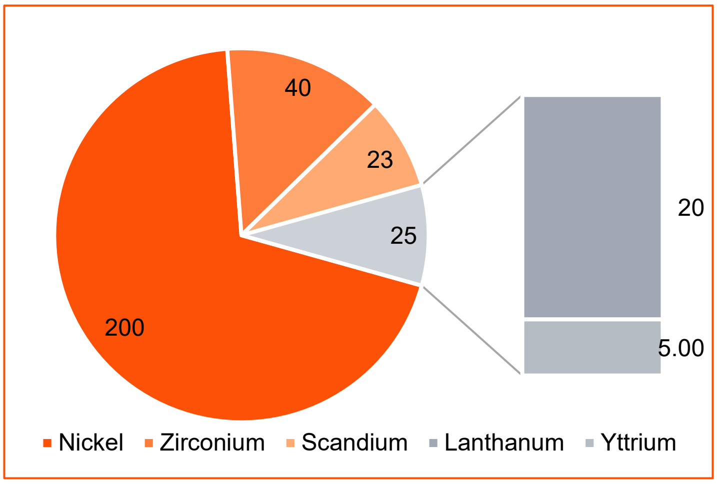


Figure 14: Material Composition of Alkaline electrolyser (kg/MW)

4.2.3. Import dependency on critical minerals

As discussed in the previous section, the raw materials required for manufacturing electrolyser stacks are significantly dependent on both critical and non-critical minerals. Non-critical minerals such as stainless steel and aluminium are predominantly used in the manufacturing of alkaline and PEM electrolysers and are generally available in sufficient quantities. As of 2022, India's Stainless steel and aluminium production is 2.77 million tonnes and 4.02 million tonnes respectively.

On the other hand, critical minerals such as nickel, titanium, zirconium, cobalt, copper, and platinum are not as easily accessible, with India lacking sufficient domestic production for several of these resources. Nevertheless, the current global supply of these minerals remains adequate, reducing the risk associated with manufacturing alkaline and PEM electrolysers in India through imports. The recent production capacities of these critical minerals in India and globally are presented in the table below.

Table 3:Annual production of critical minerals in India and the World in million tones

Critical Minerals	Nickel	Titanium*	Zirconium	Cobalt	Copper	Platinum$
World	3.2	13.8	1.44	0.17	22.2	437
India	0	0.42	0.02	0	0.55#	0

**Titanium is derived from Ilmenite and Rutile, with their respective global and Indian production capacities (in million tonnes) being: Ilmenite – 13.2 (World), 0.6 (India); Rutile – 0.4 (World), 0.01 (India).*
#Copper cathode wire
$Platinum group of metals in tonnes

However, rare earth elements such as scandium, lanthanum, and yttrium present a greater challenge due to their limited global availability of 0.3 million tonnes in 2022.

At electrolyser system level, about 30-40% of components are imported. On the materials front, in 2022–23, India imported approximately 51,625 tonnes of nickel ores and alloys from Ethiopia, the USA, and Saudi Arabia, as the country lacks domestic production capacity. Currently, nickel is primarily consumed by the stainless-steel industry, which poses a supply risk for alkaline electrolyser manufacturing, where nickel is a key material.

India also imported 82,831 tonnes of zirconium, mostly from Southeast Asia and Oceania, despite having 36.56 million tonnes of zircon resources within its borders. These reserves, largely concentrated in Andhra Pradesh, Kerala, and Odisha, remain underutilized due to policy and operational bottlenecks, reinforcing India's import dependency for this critical mineral.

For Platinum Group Metals (PGMs), especially platinum and iridium, which are essential for PEM electrolysers, India's domestic reserves are restricted to just 20.92 tonnes, mostly in Odisha.

Consequently, the country imported over 31 tonnes from the USA, South Africa, and the UK in 2022–23, highlighting a high vulnerability to global supply chains.

Similarly, In the case of titanium derived from ilmenite and rutile, remains another area of concern. Although India produced 403,000 tonnes of ilmenite and 14,000 tonnes of rutile in 2022–23, it still imported nearly 111,653 tonnes of titanium, primarily from Mozambique and Malaysia. This underscores the need to scale up domestic production through companies like TTPL, KMML, Kilburn Chemicals, and Kolmak Chemicals to reduce external dependence.

However, in contrast, the situation is more stable for cobalt and copper. The demand for cobalt in electrolyser manufacturing is relatively low and can be met through imports and recycling from scrap materials, despite the absence of primary production. For copper, India produced 112,746 tonnes of copper concentrates in 2022–23, with Madhya Pradesh and Rajasthan contributing the entire output. With Hindustan Copper Limited planning to triple ore production, domestic supply is expected to remain sufficient and reliable for supporting electrolyser manufacturing.

Beyond these, Rare Earth Elements (REEs) such as lanthanum, yttrium, and scandium—critical for SOCE electrolysers due to their catalytic and thermal properties—pose a major supply risk. While global production is dominated by China, India holds 12.73 million tonnes of monazite resources, mainly in beach and inland placer deposits. However, regulatory constraints have limited domestic extraction, making supply visibility uncertain.

Based on NITI Aayog's projections for electrolyser manufacturing capacity by 2050, the estimated requirement of critical and rare earth metals needed to support the targeted 226 GW of installed electrolyser capacity is presented in the table below.

Table 4:Projected critical mineral requirement in tones by 2050

Critical Minerals	Quantity	20 GW by 2030	112 GW by 2040	226 GW by 2050
	kg/MW	Tonnes	Tonnes	Tonnes
Alkaline electrolyser				
Nickel	800	16,000	89,600	180,800
Zirconium	100	2,000	11,200	22,600
Cobalt	5	100	560	1,130
PEM electrolyser				
Titanium	528	10,560	59,136	119,328
Copper	4.50	90	504	1,017
Iridium	0.75	15	84	170
Platinum	0.50	10	56	113
Solid Oxide electrolyser				
Nickel	200	4,000	22,400	45,200
Zirconium	40	800	4,480	9,040
Scandium	23	460	2,576	5,198
Lanthanum	20	400	2,240	4,520
Yttrium	5.00	100	560	1,130

Source: PwC Analysis

4.2.4. Significance of recycling/EoL waste management in fostering circularity

India's electrolyser manufacturing ecosystem is deeply reliant on critical minerals and REE and many of which are imported due to limited domestic availability or production constraints. As demand for green hydrogen scales up, this dependency poses strategic vulnerabilities. In this context, recycling and End of life (EoL) waste management emerge not just as sustainability measures, but as essential levers for material security and circularity.

However, India's EoL management ecosystem for electrolysers is still at a nascent stage, with most initiatives either in early pilot phases or confined to academic and industrial R&D. The preferred recycling methods along with EoL recycling rate (EOL-RR) for specific components vary and are summarized in the table below[35]:

Table 5: Summary of end-of-life waste management of electrolyser components

Electolyser	Common Material	Recycling method	Output	EOL-RR
Alkaline	Nickel mesh	Direct re-use	Nickel mesh	Nickel>50%
		Pyrometallurgical method	Nickel powder	
		Hydrometallurgical method	Nickel salt	
		Atomization method	Nickel powder	
	Zirconia stabilized PPS	Pyrometallurgical method	Zirconium powder	Zirconium <10%
		Hydrometallurgical method	Zirconium salt	
PEM	Pt/C	Pyrometallurgical method	Platinum powder	Platinum: 25% – 50%
		Hydrometallurgical method	Platinum salt	
	Iridium oxide	Pyrometallurgical method	Iridium powder	Iridium:25%–50%
		Hydrometallurgical method	Iridium salt	
	Titanium felt/ Titanium mesh	Remelting	Titanium ingot	Titanium >50%
		Molten salt electrolysis	Titanium powder	
SOEC	YSZ	Hydrometallurgical method	Zirconium salt	Zirconium <10%
		Hydrothermal method	Zirconia powder	
	Ni-YSZ	Hydrothermal +Leaching	YSZ powder	Yttrium <1%
	LSM	Hydrometallurgical method	Lanthanum salt Strontium salt	Lanthanum <1% and Strontium <1%

4.3. Economic and financial analysis

4.3.1. Electrolyser cost and investment opportunity

The electrolyser stack accounts for approximately 39% of the total cost of an electrolyser system, making it one of the most significant cost components[36]. Across all electrolyser technologies, material costs form the major component of overall expenses. These include the balance of stack, stack assembly materials, bipolar plates, frames, and electrodes. Among these, the electrode manufacturing cost is highest for SOCE due to the technology's early-stage development, followed by alkaline electrolysers, which require more material because of their larger physical footprint. Consequently, the capital cost trend for these electrolysers mirrors their material intensity, with SOCE being the most expensive, followed by alkaline systems. A detailed breakdown of cost distribution across various electrolyser technologies illustrated in Figure 15 below.

[35] https://www.nature.com/articles/s43247-025-02621-6
[36] https://www.ceew.in/publications/how-can-india-indigenise-hydrogen-electrolyser-manufacturing, last accessed on 5th September

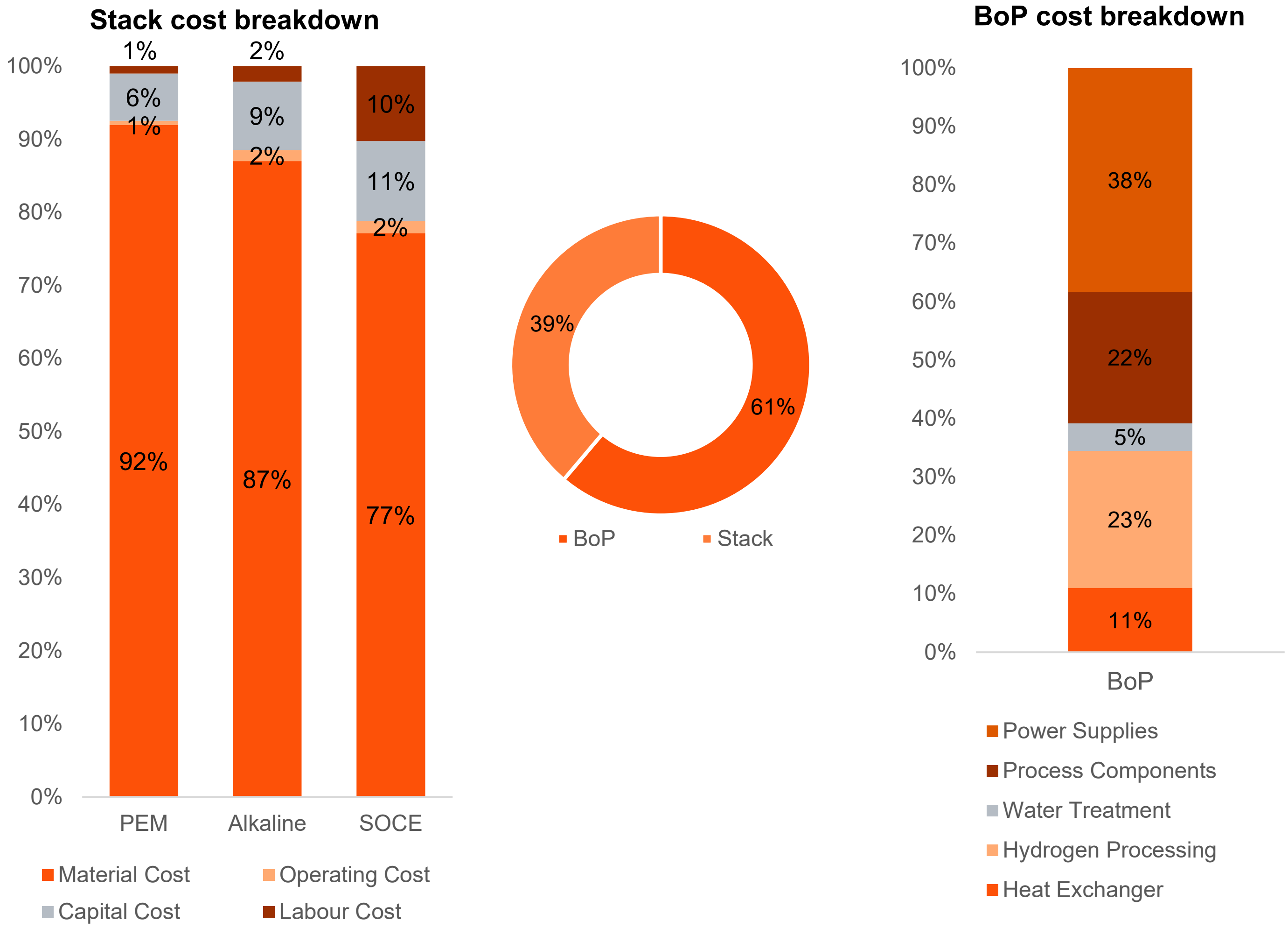


Figure 15: Cost breakdown of different electrolyser technologies

Building on the cost breakup, it's important to recognize the scale of investment required to unlock the full potential of the domestic electrolyser market. NITI Aayog has also estimated that to meet the projected demand of 226 GW electrolyser capacity by 2050, India would require an investment of approximately USD 31 billion. This underscores the vast potential of the domestic electrolyser market, as illustrated in Figure 16 below.

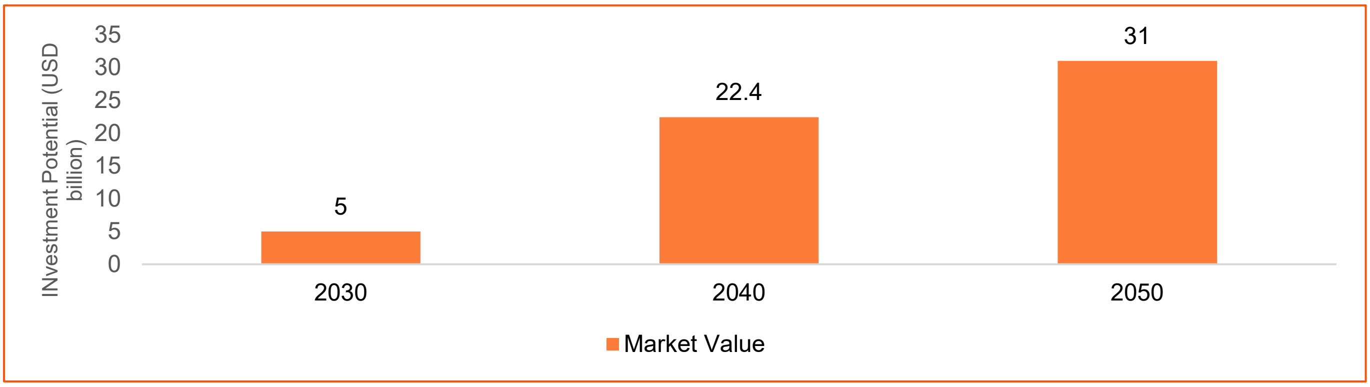


Figure 16: Domestic electrolyser capacity potential

Source: NITI Ayog

4.3.2. Export oriented opportunities

India is rapidly advancing its green hydrogen ambitions under the NGHM, targeting to produce 5 MMT of green hydrogen annually by 2030 and the potential to export up to 10 MMT by aiming to capture 10% of the global market. Backed by abundant renewable energy resources, a unified power grid, a skilled workforce, and a strategically advantageous location, India is well-positioned to become a leading exporter of green hydrogen and electrolyser technologies.

Further, key global markets like the European Union, Japan, and South Korea are actively planning large-scale imports to meet their decarbonization goals. The EU, under its RE Power EU strategy37, aims to import 10 MMT of green hydrogen by 2030, while Japan targets 3 MMT by 2030 and 20 MMT by 2050[38]. South Korea, too, has announced plans to import 1.96 MMT of green hydrogen by 2030[39]. These import commitments present a significant opportunity for India to emerge as a preferred supplier, contributing to global energy security and climate action.

4.4. Challenges in electrolyzer manufacturing

The major challenges faced in electrolyser manufacturing in India have been highlighted below.

Lack of electrolyser demand visibility

The absence of a clean technology-wise roadmap for electrolyser demand is creating significant uncertainty across the hydrogen value chain. This lack of visibility hampers effective planning for supply chains, infrastructure development, and financial investments. The situation is further complicated by the slow pace of Final Investment Decisions (FIDs) for green hydrogen and ammonia projects globally, reflecting the long gestation period and evolving economics of these projects. Without short-term (within the next 6–18 months) and long-term demand visibility, electrolyser manufacturers remain hesitant to invest in ancillary machinery and production lines for critical components such as diaphragms, membranes, and electrodes. As a result, the present and future electrolyser capacities are at risk of becoming underutilized, with assets potentially turning into non-performing assets (NPAs), further discouraging investment and localization efforts.

High Capex and Financing Challenges

Electrolyser manufacturing involves high CAPEX, which varies significantly across technologies such as Alkaline, PEM, and SOEC. This variability makes it difficult for manufacturers and investors to accurately predict costs and returns. Also, in the absence of clear demand visibility, banks and financial institutions are reluctant to fund capacity expansion, as they require evidence of market demand to justify lending.

High dependency on critical and rare earth materials in electrolyser manufacturing

Electrolyser manufacturing is highly dependent on critical and rare earth elements such as iridium, platinum, nickel, and scandium materials that have limited domestic availability in India. These elements are essential for key components like electrodes and catalysts, particularly in PEM and SOEC technologies, where performance and durability are closely tied to material quality.

This dependence on imported materials exposes the supply chain to global price volatility, market fluctuations, and geopolitical risks. All these risks significantly impact the cost competitiveness and scalability of electrolyser deployment. Further, without a clear strategy to secure, substitute, or recycle these materials through domestic initiatives, India's efforts to localize electrolyser manufacturing and drive down costs may face serious constraints.

Technology maturity over suitability

Currently, the global electrolyser market is dominated by Alkaline electrolysers due to their commercial maturity and established supply chains. In particular, they are widely adopted because of their lower capital costs and simpler design. However, they operate at low temperatures and have a larger physical footprint, which can limit their integration in space-constrained or high-efficiency applications.

In contrast, SOCE offer higher efficiency and are particularly well-suited for industrial decarbonization, especially in sectors like steel, cement, and refining, where high-temperature integration is advantageous. SOECs can utilize waste heat from industrial processes, improving overall system efficiency and reducing energy costs.

However, despite these advantages, the adoption of SOCE remains limited. This is primarily due to the market's strong preference for commercially mature technologies like Alkaline and, to some extent, PEM electrolysers, which benefit from established supply chains, lower upfront costs, and proven operational

[37] https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen_en
[38] https://gh2.org/sites/default/files/2025-04/Copy%20of%20Japanese%20Publication%20%28English%20Version%29.pdf
[39] https:// Leverage India's expertise in power electronics to identify and standardize BoP components for electrolysers. This will enhance the export potential of indigenous electrolysers by aligning with global technical benchmarks.gh2.org/countries/south-korea

reliability. As a result, SOECs face significant barriers to scaling, cost reduction, and market penetration, even though they may be the most technically suitable option for high-temperature industrial applications such as steelmaking and refining.

Lack of standards

Unlike the solar and wind sectors, electrolyser technologies currently lack harmonized standards and certification frameworks, largely due to their early stage of commercial development. This regulatory gap creates long-term uncertainty for manufacturers, project developers, and investors, making it difficult to ensure interoperability, safety, and performance benchmarks across different technologies and suppliers. Further, the absence of clear standards can slow down technology adoption, scaling, and market confidence.

Training and skill building

India faces a significant skill gap in hydrogen technologies and electrolyser manufacturing, particularly in areas such as stack design, balance-of-plant equipment, and advanced materials handling. The shortage of trained professionals with specialized knowledge, ranging from hydrogen safety and leak detection to compliance with international standards. This gap poses a challenge to building a robust domestic electrolyser ecosystem capable of meeting future demand.

A key contributor to this gap is the limited collaboration between academia and industry in R&D, curriculum development, and hands-on training. Without structured programs to align educational outcomes with industry needs, the talent pipeline remains underdeveloped. Strengthening partnerships between universities, research institutions, and manufacturers will be essential to ensure that India can build the skilled workforce required to support its green hydrogen ambitions.

4.5. Recommendations

To overcome the challenges faced in electrolyser manufacturing in India, following recommendations have been highlighted below.

Electrolyser market creation through green hydrogen mandates

Electrolyser manufacturing capacity is intrinsically linked to the scale of hydrogen production, which in turn depends on the strength of domestic demand. To catalyze this demand, India must introduce sector-wise mandates or blending quotas for green hydrogen, particularly in industries such as refining, fertilizers, steel, and transport. These mandates will help create a stable and predictable market for electrolyser deployment, encouraging manufacturers to invest in capacity expansion. Furthermore, accelerating domestic demand and enabling faster Final Investment Decisions (FIDs) for green hydrogen and ammonia projects will also build confidence among electrolyser equipment manufacturers. This, in turn, will support the development of competitive supply chains capable of meeting both domestic needs and global market opportunities.

Long-Term commitments for electrolyser capacity targets

To unlock the full potential of domestic manufacturing, it is essential to establish clear, electrolyser manufacturing targets that align with the country's green hydrogen roadmap. These targets should not only reflect volume goals but also support the scaling and commercialization of emerging technologies such as PEM and SOEC. In this regard, a technology-wise approach will help ensure that suitable solutions are promoted for different industrial applications, rather than relying solely on commercially mature options like Alkaline electrolysers. Further, to overcome the limitations of market preference and maturity bias, India may also adopt technology-neutral incentive schemes that reward performance, efficiency, and sustainability across all electrolyser types.

Secure Supply Chains & Recycling

To ensure long-term sustainability and resilience in electrolyser manufacturing, India must prioritize the development of robust and localized supply chains for critical minerals and metals. Establishing a strong domestic supply base will reduce reliance on imports and mitigate risks associated with global price fluctuations and geopolitical uncertainties. In addition, India should formulate a national strategy for electrolyser recycling to enhance resource efficiency and minimize the environmental impact of manufacturing. Furthermore, investing in research and development to identify alternative materials can significantly reduce import dependency on critical minerals and strengthen the self-reliance of India's green hydrogen ecosystem.

Skill and capacity building

India's existing workforce, particularly professionals from the chemical and petrochemical sectors, possesses foundational skills relevant to electrolyser operations and maintenance. However, to make them industry-ready for the green hydrogen economy, significant upskilling is required in areas such as electrolyser assembly, inspection, troubleshooting, and safe hydrogen handling. To ensure safety and technical competence, mandatory certification should be introduced for critical roles like Electrolyser Technicians and O&M Managers. These certifications must be made a prerequisite for participation in government tenders and PLI schemes, ensuring that manufacturing and operational facilities are staffed with qualified personnel capable of handling hydrogen technologies safely and efficiently. Additionally, regular workshops and knowledge-sharing initiatives, facilitated through government collaboration with industry platforms should be conducted to keep professionals updated on evolving technologies, safety protocols, and global best practices in hydrogen production and electrolyser operations.

Financial backing for electrolyser manufacturing

To address the high CAPEX and financing challenges in electrolyser manufacturing, India must implement a robust financial support framework. The government has already introduced VGF under the NGHM in supporting domestic manufacturing capacity. Building on this, additional instruments such as blended finance models combining public and private capital and concessional loans through dedicated green financing institutions should be introduced to improve bankability across electrolyser technologies. Furthermore, the inclusion of interest subvention schemes and Accelerated Depreciation (AD) benefits can help lower borrowing costs and improved cash flows to incentivize early investments in the sector. Moreover, inclusion of electrolyser manufacturing systems under Priority Sector Lending (PSL), will enable banks to extend credit more readily.

5. Battery Energy Storage System manufacturing in India

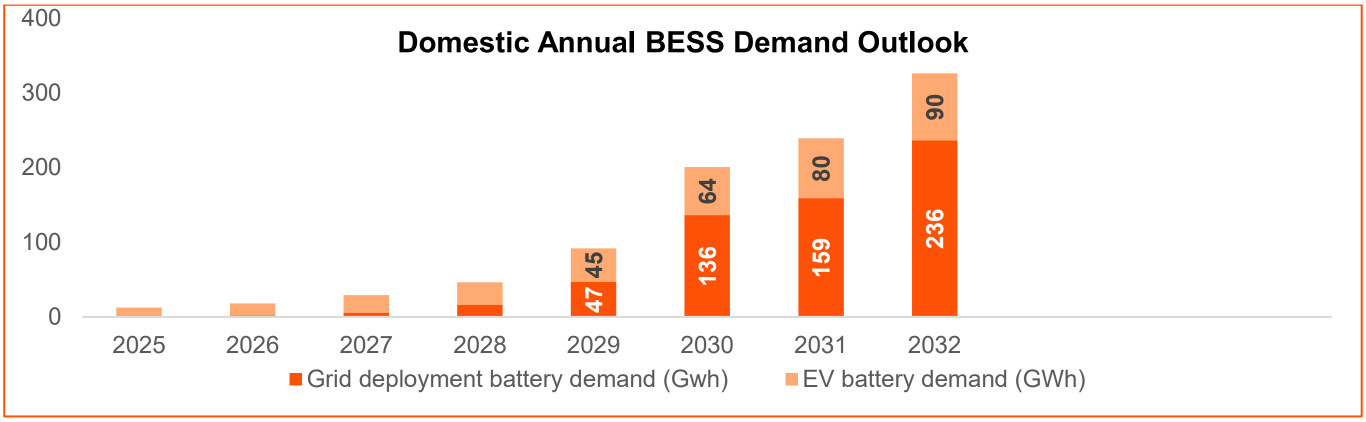
India's Battery Energy Storage Systems (BESS) manufacturing sector is rapidly becoming a cornerstone of the country's clean energy transition, driven by ambitious RE targets and robust government support. The domestic installed BESS capacity has surged, from 51 MWh in 2023 to over ~500 MWh in 2025, representing the beginning of extensive expansion plans. Government initiatives are fostering a thriving manufacturing ecosystem, with domestic production capacities expected to reach 220 GWh by 2030. Amidst this rapid growth, the sector faces significant challenges, particularly in supply chain dependencies on imported components and critical minerals. However, initiatives like eliminating BCD on essential materials and promoting local production signal an aggressive push towards reducing import reliance. The BESS sector's potential applications are vast, particularly in grid-scale deployments that integrate RE sources to provide round-the-clock capabilities, and in traction applications (Electric Vehicles). This section will delve deep into the BESS value chain and highlight key issues that the industry should tackle, and KPIs that should be prioritized to capitalize on its growth.

5.1. Current BESS manufacturing landscape in India

5.1.1. Demand Size Assessment: Market Sizing and Key Demand Avenues

The momentum in India's BESS market is unparalleled, fuelled by ambitious RE objectives and supportive governmental policies. In 2025, the market witnessed an extraordinary 10x growth, with new capacity additions on the stationary BESS side reaching 510 MWh, up from just 51 MWh in 2023. Nevertheless, this impressive growth trajectory falls significantly short of the scale required to fulfil national energy storage commitments.

According to projections by the Central Electricity Authority (CEA), India must expand its **BESS capacity to 236.22 GWh by 2031-32**, necessitating a staggering 573-fold increase from the current installed capacity of 510 MWh, (expected installation of 1 GWh by end of year 2025 owing to an additional 500 MWh anticipated to come online by Q3/ Q4). Achieving this enormous expansion demands sustained annual growth rates exceeding 120%—a formidable target highlighting critical infrastructure shortcomings. From the electric vehicle side, the demand for batteries is expected to reach ~71 GWh in 2030, owing to the Government of India's (GoI) target of 30% EV penetration by 2030.



Source: CEA

Figure 17: Domestic Annual BESS Demand Outlook

BESS demand is growing across both Front-of-The-Meter (FTM) and Behind-The-Meter (BTM) applications, driven by several key factors. For FTM applications, BESS facilitates renewable integration and firming by absorbing surplus solar and wind energy and delivering firm power, crucial for decarbonization goals and supporting India's structural energy transformation. It also addresses ramping requirements during peak hours and provides critical services like frequency regulation and congestion management, enhancing grid stability and delaying costly infrastructure upgrades.

In BTM applications, particularly within key industries such as commercial and industrial sectors, telecom, and residential, BESS plays a pivotal role. The C&I sector, one of India's largest electricity consumers, is experiencing growth with anticipated demand reaching around 1,245 billion units by 2032. This growth is complemented by corporate decarbonization goals and the shift towards captive renewable power consumption to mitigate rising grid tariffs. In the telecom sector, the rapid expansion of infrastructure, driven by 5G network deployment, necessitates reliable, green energy solutions, positioning BESS as an alternative to diesel generators for backup power. Lastly, the residential sector's rapid adoption of rooftop solar, underpinned by government incentives and a shift toward smart homes, is driving the need for energy storage solutions like BESS to manage intermittency and provide reliable backup during outages. As these industries evolve towards greater efficiency, sustainability, and energy independence, BESS integration becomes crucial.

5.1.2. Evolving BESS manufacturing landscape

The BESS manufacturing in India is witnessing swift evolution, driven by a combination of government incentives, private sector investments, and the pressing need to reduce dependency on imported components. One of India's most significant challenges is its limited domestic manufacturing capacity. ~75-80% of Li-ion cells, which constitute ~50%-60% of BESS container costs, are imported. Although with key players announcing their Li-ion cell manufacturing plans, focus is now on curbing imports and being self-reliant. Projections (announced capacity of domestic Li-ion producers) suggest that by 2032, >200 GWh of Li-ion cell manufacturing capacity is expected to come online, supporting the targeted BESS deployment by that year (~236 GWh).

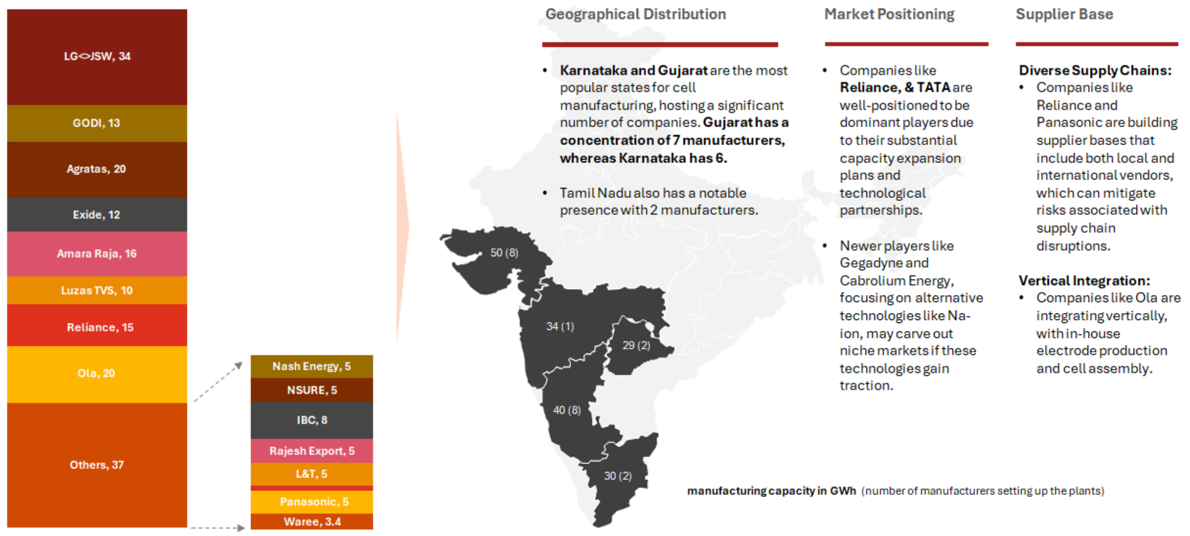


Figure 18: Announced Li-ion cell manufacturing capacity by key players (non-exhaustive list)

To support this growth, the Indian government has implemented the Production Linked Incentive (PLI) scheme for Advanced Chemistry Cell battery storage, allocating a manufacturing capacity of 50 GWh. Notable allocations include 30 GWh awarded to companies such as Reliance Energy, Ola Electric, and Rajesh Exports Limited (Rel), Bangalore. However, progress towards establishing large-scale production facilities remains sluggish. The focus of many companies continues to be on battery pack assembly rather than cell manufacturing, which limits the capacity to fully satisfy domestic demand. Recent developments in the manufacturing sector indicate a promising trajectory, although at a pace insufficient to meet imminent demand surges. Players like Pace Digitek's 5 GWh annual capacity plant in Bengaluru and Cygni Energy's 4.8 GWh assembly plant in Hyderabad are steps in the right direction but need to be complemented by larger-scale initiatives.

5.1.3. Technology scan and emerging cell chemistries

The screening of 14 battery technologies utilized Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) to identify market-ready BESS solutions. A balanced approach prioritized technologies that excelled in grid-side applications like peak load management and renewable energy integration. The six most promising technologies- Lithium-ion Phosphate (LFP), Nickel Manganese Cobalt (NMC), Vanadium Redox Flow Battery (VRFB), Sodium Sulphur Battery (NaSB), Sodium-ion Battery, Solid-State Battery selected for their strong performance and stakeholder interest, aimed to bolster infrastructure for stationary storage, ensuring technological and commercial viability.

The table below highlights how favourable is the corresponding chemistry is with respect to the selected parameters:

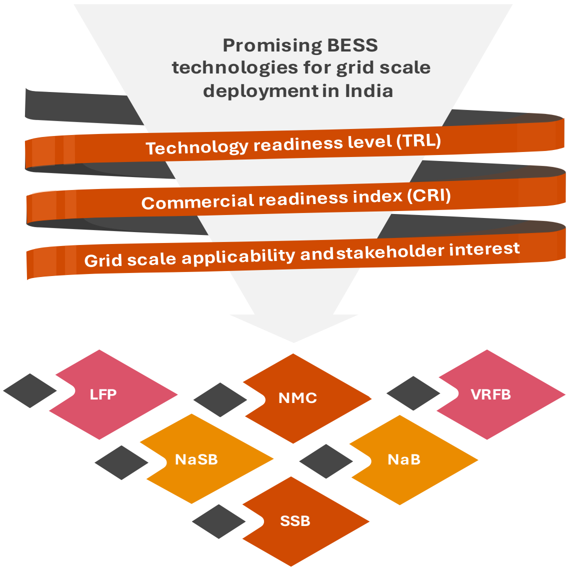
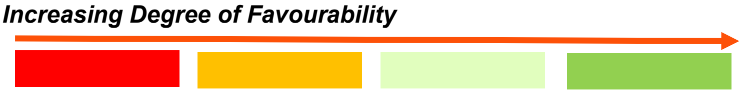


Figure 19: BESS technologies for grid-scale deployment in India

Table 6: Comparative assessment of BESS Technologies

BESS technologies	**LFP**	**NMC**	**VRFB**	**Na-B**	**NaS**	**Solid State**
Energy Density (Wh/kg) (average)						
Cycle Life (no. of cycles) (max)						
RTE (%) (average)						
Annual capacity retention (opposite of annual degradation)						
Safety (qualitative)						
Cell cost (USD/kWh)						X
System cost (USD/kWh)						X
Market deployment (GWh)						
Applicability in LDES						
Economic value of recycling						

Increasing Degree of Favourability



LFP and NMC batteries have an edge when it comes to key technical performance and commercial parameters but do lag in terms of safety and overall project life. Whereas Na-ion batteries and VRFB stand out for their excellent cycle life, making them promising technologies for LDES in the long run (next 5 years).

5.1.4. Key market enablers

Robust Government Policy Support

India's central government has laid a strong foundation for the domestic battery manufacturing ecosystem through a series of strategic policy interventions. The Production-Linked Incentive (PLI) scheme for Advanced Chemistry Cell (ACC) batteries, with an outlay of ₹18,100 crore, is a cornerstone initiative that incentivizes large-scale manufacturing and technology adoption. Additionally, the Viability Gap Funding (VGF) scheme for standalone BESS projects—amounting to ₹5,400 crore—further supports infrastructure development. The extension of the Inter-State Transmission System (ISTS) waiver until June 2028 significantly reduces transmission costs for renewable energy and storage projects. Complementing these are customs duty exemptions on capital goods and raw materials, which lower the cost of setting up manufacturing units. Schemes like FAME-II also indirectly boost battery demand by promoting electric vehicle (EV) adoption.

Strategic Industrial Investments

India's private sector is responding robustly to policy signals with substantial investments in gigafactories and integrated battery supply chains. Ola Electric, Reliance Industries, and Rajesh Exports are among the major players setting up giga-scale battery manufacturing facilities. Ola Electric, for instance, plans to scale its capacity from 1 GWh to 50 GWh by 2027. Reliance is building a fully integrated ACC battery ecosystem, including proprietary technologies like LFP and sodium-ion batteries. Tata Group's Agratas Energy Storage Solutions and Exide Industries are also investing heavily in cell manufacturing and energy storage solutions. These investments are not only increasing domestic capacity but also fostering innovation and reducing reliance on imports.

State-Level and Infrastructure Support

State governments are playing a pivotal role by offering land, infrastructure, and policy support to attract battery manufacturing investments. Several states are developing dedicated industrial parks and clusters for clean energy technologies. Large-scale BESS tenders—such as the 3625 MW / 8100 MWh tender floated in 2024—are creating predictable demand pipelines, encouraging private sector participation. These initiatives are helping build a robust ecosystem that supports both manufacturing and deployment of energy storage solutions across the country.

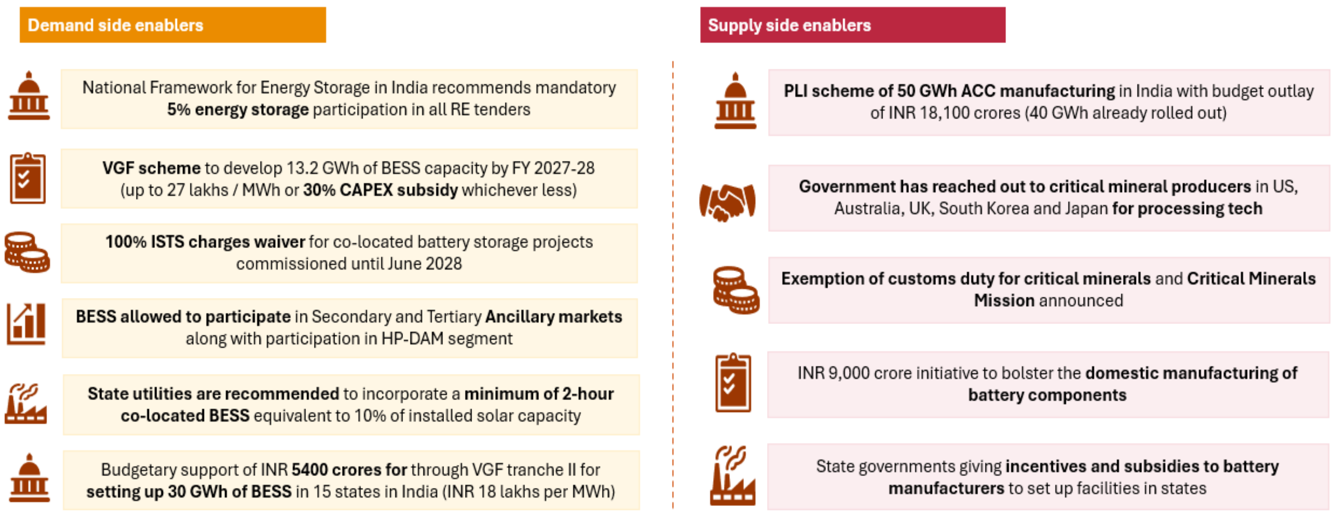


Figure 20: Key demand and supply side enablers

5.2. Value chain analysis

In the dynamic global shift towards electrification and clean energy, batteries have emerged as the pivotal force driving the transition. From the electric Vehicle and grid-scale energy storage to portable electronics and smart infrastructure, the reliance on high-performance sustainable battery technologies has never been more pronounced, for a rapidly developing nation like India- with one of the world's largest and fastest growing energy needs- building a resilient and localized battery value chain is both a critical challenge and an enormous opportunity.

Over the past few years, India's battery space has journeyed from being a mayor consumer of pre-assembled imports to talking substantial steps toward becoming a serious contributor in the global value network, though the road to self-reliance is still evolving, marked by technological, infrastructural, and geopolitical complexities.

On the contrary India has been heavily reliant on imports not only for battery cells but even for fundamental materials and technology. Over 80% of India's lithium-ion battery cells were being sourced from China and Hongkong as of 2024. These imports still have a very staggering rate of more than 60% annually, exacerbating trade dependencies. The core issue lies in the domestic value chain structure, where most of the action has so been limited to assembly and packaging of battery pack- a low value addition activity that captures minimal economic and technological rent.

5.2.1. National Drivers: Manufacturing Push and Domestic initiatives

Recognizing the risks of import dependence potential of a homegrown battery ecosystem, the Government of India has been steadily rolling out policies and incentives structures to catalyze indigenous manufacturing. The Cornerstone of this initiative is ACC PLI scheme which carried a financial outlay of 18,100 crore. Launched with the aim of establishing 50 GWh of domestic capacity by 2026 with localization requirement of 60% of raw materials/ components, the scheme has attracted interest from both established conglomerates and emerging technology ventures. Several major Indian firms – Reliance, Ola, Tata group, Exide and some other players have stepped into this with aggressive plans to setup gigafactories boasting capacities ranging from 5 to 20 GWh.

Apart from this the Government's e-mobility ambitions target a reduction of transportation emission by 33-35% (from 2005 levels) and 30% market penetration of EVs by 2030. Over 3.66 million EVs have already been registered as of March 2025 aided by key policies such as FAME and the Production-linked Incentive (PLI Scheme). The initiative is crucial in encouraging manufacturing and establishing India as a hub for EVs and battery Production.

5.2.2. The Critical mineral conundrum

The battery value chain is typically divided into three key segments:

- Upstream: Extraction and processing of critical battery minerals (Bauxite, nickel, manganese, cobalt, lithium, phosphate, graphite, copper, and aluminum
- Midstream: Manufacturing battery components (Cathodes, anodes, separators, electrolytes) using processed minerals
- Downstream: Cell manufacturing, battery pack assembly, integration into EVs, and recycling

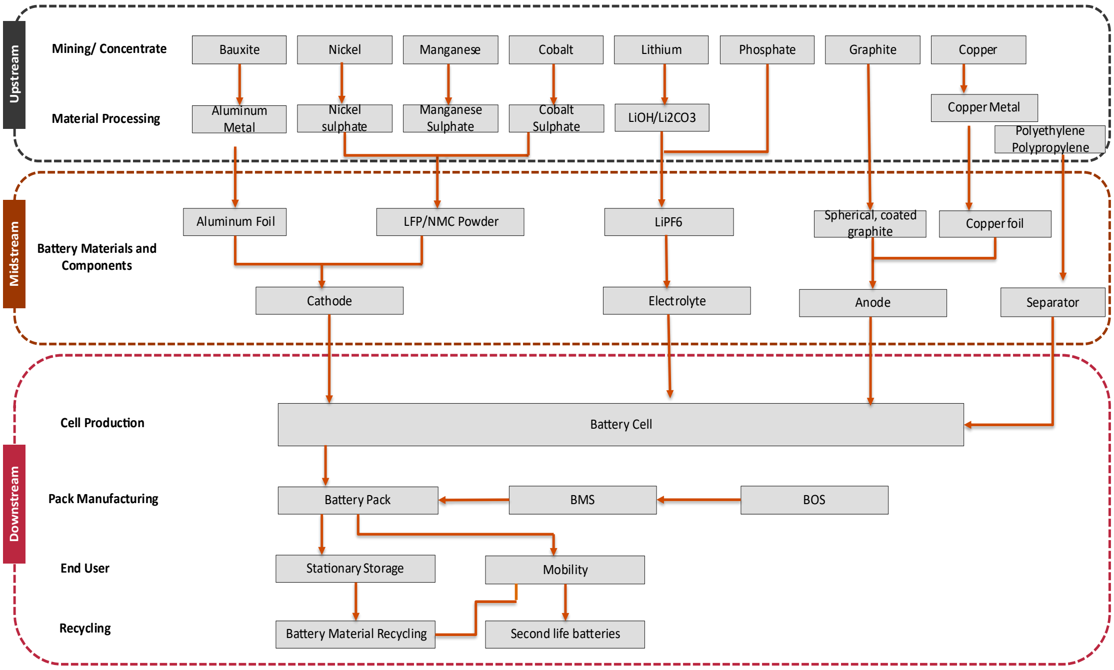


Figure 21: BESS value chain

Despite the policy momentum and industrial participation, India's biggest challenge in battery localization lies upstream- in the availability and processing of critical minerals such as lithium, nickel, cobalt, and graphite. These minerals are like building block of rechargeable battery chemistries, and their extraction, refining, and market control remains overwhelmingly concentrated in a few global regions, primarily Asia-pacific and Africa region.

China dominates nearly every layer of this value chain: Over 60% of the world's lithium is processed there, cobalt and graphite refining stand at over 75% and 100%, respectively. Even where raw mining occurs in Australia, Chile, or Democratic Republic of Congo, the material is often shipped to China for downstream refining and conversion in battery grade chemicals. For a country like India, without substantial known reserves of these resources, the imbalance poses a severe threat to long-term self-reliance

Now taking India Upstream, midstream, downstream into consideration these are the overview on all three sides:

Upstream Segment Overview

There are five critical minerals (and their compounds) – cobalt, copper, graphite, lithium and nickel – integral to the clean energy transition. Currently India imports most of the battery grade minerals. The upstream primarily involves mining and sourcing raw minerals. India currently imports most battery-grade minerals, through domestic firms like Hindalco, Vedanta- Nicomet, and NMDC are exploring extraction and processing opportunities. While some minerals (Aluminium, copper, iron, the domestic ability to process battery-grade materials is limited).

Table 7: Critical minerals used in BESS

Critical Mineral	Clean Energy Technology requirement by 2030	Import/ Concentrates in India	Key Supplier Country
Cobalt	177 kt	44 million tonnes (Resource in India)	Belgium, Italy, Germany, Netherlands, and China
Copper	12000 kt	1.1 million tonnes (imported copper ores and concentrates)	Norway (accounting for India 50% of import in recent years)

Graphite	6013 kt	8.56 million tonnes (in reserves) 203.6 million tonnes (in remaining resources)	China (accounts for 50% of the graphite import in India used in EV and ESS batteries)
Lithium	442 kt	Lithium Carbonate – 945 tonnes (Imported) Lithium oxide and Hydroxide – 990 tonnes (Imported)	Ireland, Belgium, the Netherlands, Argentina and China Belgium, Singapore, UAE, and China
Nickel	665,000 tons (by 2025)	189 million tonnes (estimated reserves)	China, Sweden, the US, France, Japan, Singapore, Malaysia, the Philippines and Belgium.

Challenges and Trajectory:

- Heavy Import Dependence for key minerals such as lithium, cobalt, and graphite anode
- Initiatives to localize extraction are in development, but large-scale processing technology is lacking
- Increased upstream activity from Indian mining companies will reduce supply-chain vulnerabilities but will take time to realize major impacts by 2030

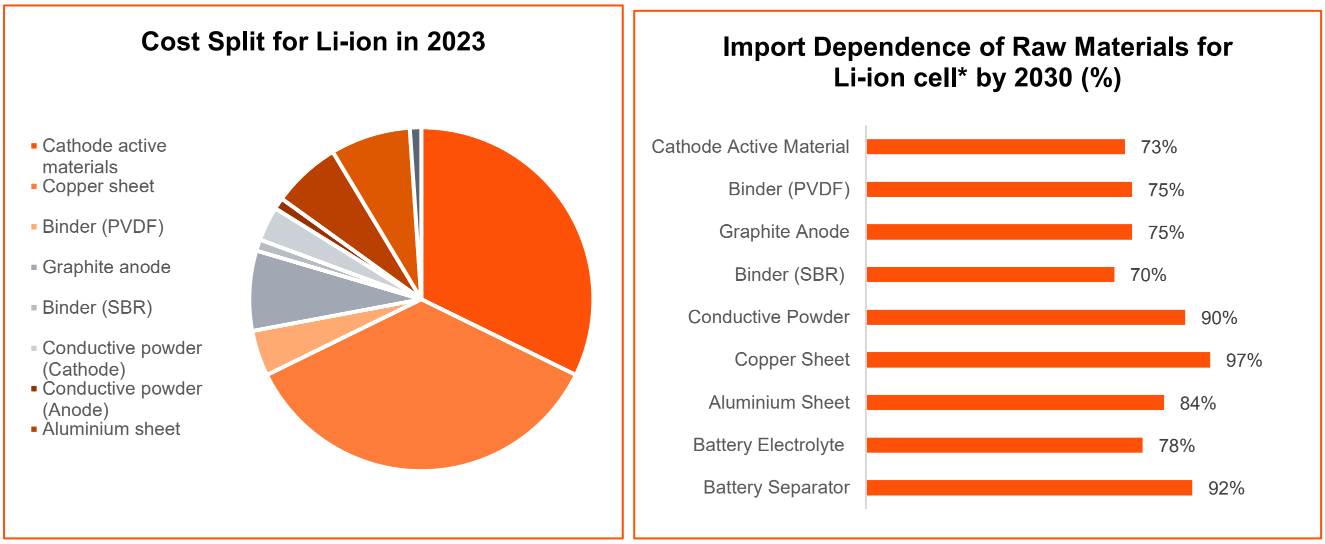


Figure 22: Cost split and import dependence for Li-ion

Note:
1) The percentage cost split of each raw material is based on raw material cost in US $/kWh
2)Import dependence (%) of components is calculated considering absolute value in Kilotonne (kt)
3) here the Li-ion cell considered is LFP*

Midstream segment Overview:

The Midstream segment covers the production of the critical battery components: cathode and anode active materials, battery electrolytes, separators, and binders. Indian Chemical firms are stepping up efforts to supply battery grade chemicals and active materials. Currently domestic supply meets only a fraction of projected 2030 demand or many components, with demand supply gaps particularly severe for LFP powder, electrolyte, synthetic graphite, and copper sheet.

Challenges and Trajectories:

- High Import dependency expected to persist for key battery materials
- Local production incentives are boosting domestic capabilities but will not close supply gaps by 2030

- New players and international collaboration (e.g. Reliance-Lithium Werks, Exide-SVOLT/24M) are helping in accelerating the development

Downstream Segment Overview:

Downstream includes cell manufacturing, battery pack assembly, integration into vehicles and stationary energy storage systems, as well end-of-life recycling, India hosts several major players making strategic investments:

- Gigafactory Investments: OLA electric, Reliance Industries, Exide Technologie, Tata Group, Amara Raja, and others have committed to establishing large-scale cell manufacturing through partnership and technology transfers.

Table 8: Project manufacturing capacities by 2030

Company	Capacity
Ola Electric	20 GWh
Reliance	20 GWh
Tata	20 GWh
Amara Raja	14 GWh
Exide	12 GWh
Lucas TVS, Rajesh Exports, Godi Energy, and Others	Remaining Capacity

To combat above mentioned vulnerabilities India has launched the National Critical Mineral Mission which targets the acquisition of overseas mining assets, foreign strategic partnership, and domestic investment in refining facilities. The objective of NCMM is to secure India’s critical mineral supply chain by ensuring mineral availability from domestic and foreign sources. India has also entered mineral cooperation talks with countries like Australia, Argentina, Zambia, and Bolivia.

Recycling Closing the loop in the battery chain

The rapid expansion of industries reliant on battery technologies, particularly within electric vehicles (EVs) and renewable energy storage, has led to a surge in demand for batteries. However, this growth has also raised concerns about the environmental impact and sustainability of battery manufacturing processes. Addressing these challenges has become increasingly urgent.

In parallel with mining efforts, India expects approximately 128 GWh end-of-life (EoL) LIBs to be available for recycling by 2030, offering significant potential for mineral recycling India is also looking inwards to bolster battery recycling, which could provide a secondary, but increasingly vital sources of critical materials. The idea is simple- extract valuable elements from used batteries and loop them back into production.

Companies such as Attero Recycling, Lohum are spearheading this, investing in efficient, low-emission technologies to recover lithium, cobalt, nickel, and manganese. These materials can then be reused in producing cathodes and other mesh components, offering both economic circularity and environmental benefits. By 2030-35, recycling could meet up to 20% of India’s raw materials demand, provided the ecosystem matures technologically and policy-support scale-up.

5.2.3. Supply chain

One of the very foremost challenges are import of the battery grade chemical to India. Currently India is 100% import-reliant for five important green-technology minerals- Lithium, Cobalt, Nickel, REEs, and silicon. The reliance on imports not only inflates costs but also exposes manufacturers to geopolitical and trade-related risks. Although recently discovered lithium resource highlights geological potential. Similarly large resources of cobalt and Nickel has been discovered but there has been no action in converting them into mineral reserves.

Table 9: Critical mineral reserves in India

Minerals	Reserves	Remaining resources	Import Dependence
Lithium	163,892 kt	1496979 kt	57%

Cobalt	NIL	45 mt	100%
Copper	NIL	5.9 mt	100%
Rare earth elements	NIL	459727 kt	100%
Nickel	NIL	189 mt	100%
Silicon	NIL	NA	100%

5.3. Economic and financial analysis

5.3.1. Key Cost Considerations

Cell Capex breakdown

Before we delve into the BESS capex, it's essential to understand the capex split of a Li-ion cell, which accounts for ~60% share of the BESS container cost. The figure 23 below details the capex breakdown of Li-ion cell manufacturing

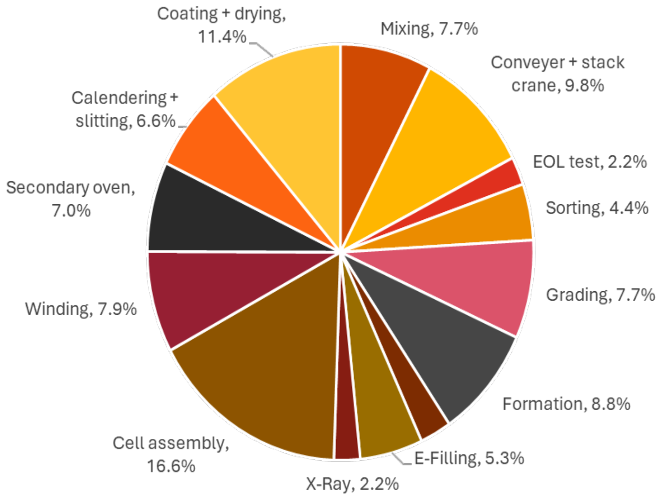


Figure 23: Capex breakdown for Li-ion cell manufacturing

The CAPEX breakdown of Li-ion cell manufacturing reveals a complex and multi-stage process, each contributing significantly to the overall cost structure. Based on the pie chart and supported by industry data, the largest capex share is attributed to **cell assembly (16.6%)**, followed by **coating and drying (11.4%)** reflecting the complexity and precision required in electrode preparation, and **conveyer and stack crane systems (9.8%)**, which reflect the importance of automation and precision in handling and assembling components. **Formation (8.8%)**, a critical step for activating the electrochemical properties of the cell, also commands a substantial portion of the investment.

Industry sources further validate this breakdown, noting that **electrode manufacturing accounts for 45%**, **cell finishing for 30%**, and **cell assembly for 25%** of manufacturing costs. Additionally, formation and aging alone can represent up to one-third of the total capex per GWh. Understanding this breakdown is crucial for identifying cost optimization opportunities, especially as Li-ion cells constitute nearly 60% of the total cost of a BESS container**.**

OPEX, on the other hand, include ongoing costs such as those related to energy, labor, water, chemicals, and raw materials

BESS capex breakdown

The CAPEX breakdown of a BESS project, as illustrated in the pie chart, reveals that the DC side cost dominates the overall setup, accounting for approximately 86.11% of the total investment. This includes key components such as the BESS container, Power Conversion System (PCS), and DC cabling, which are essential for storing and managing energy within the system.

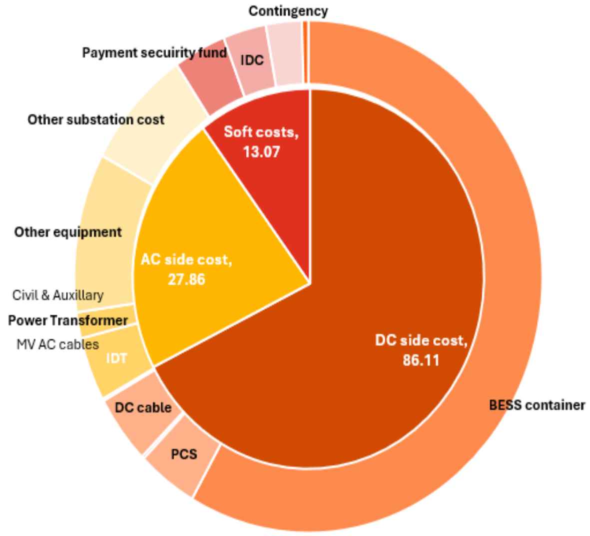


Figure 24: Capex breakdown for BESS manufacturing

The AC side cost, comprising 27.86%, covers infrastructure like interconnecting distribution transformers (IDT), medium-voltage AC cables, power transformers, civil and auxiliary works, and other equipment necessary for grid integration and energy dispatch. Meanwhile, soft costs make up 13.07%, encompassing expenditures such as substation costs, payment security funds, Interest During Construction (IDC), and contingency provisions.

Given that the DC block alone contributes 60–70% of the total BESS cost, and the BESS container itself is a major cost driver, there are clear opportunities for capex optimization. Strategies such as in-house manufacturing, bulk procurement, and reuse of existing equipment can significantly reduce container costs and improve project economics. With the total cost of setting up an LFP-based BESS project in India estimated at USD 115–120 per kWh, understanding this breakdown is crucial for stakeholders aiming to enhance cost-efficiency and scalability in energy storage deployments.

5.3.2. Opportunity size: Investment required to meet demand

To reach a BESS capacity of 236 GWh by 2032, an estimated investment of INR 4.79 lakh crore[40] is required[41]. This investment will be vital for developing and upgrading infrastructure, advancing battery technologies, and integrating modern grid systems. Key areas of focus include the construction of efficient storage facilities, fostering innovation in battery performance and cost-effectiveness, and establishing a robust manufacturing and supply chain.

5.4. Challenges in BESS manufacturing

Integration Complexity

Successfully integrating BESS remains highly complex and risky, primarily due to manual processes involving third-party contractors. This complexity has contributed to a significant increase in system-level defects, amplifying safety risks and necessitating enhanced quality control and advanced component monitoring.

Manufacturing Defects

Persistent defects at cell and module levels are rooted in electrode manufacturing inconsistencies and contamination. Challenges such as seal failures further compromise system reliability, emphasizing the urgent need for robust quality assurance practices throughout the manufacturing process.

Thermal Runaway

[40] Cost considered by CEA (higher than the current existing market cost)
[41] PIB Article, 2025, last accessed on 2nd September 2025

As energy densities surge from legacy levels to modern standards, sophisticated cooling systems become essential to prevent thermal runaway. Inadequate thermal management poses severe safety hazards, including fires and explosions, necessitating fail-safe cooling and rigorous safety protocols.

Grid Integration Challenges

Integrating BESS with the electrical grid requires advanced control algorithms and seamless communication with energy management systems. Sustained performance monitoring and real-time operations ensure alignment with fluctuating market prices and grid conditions, safeguarding project viability.

Lack of Standardization

The absence of industry-wide standardization exacerbates manufacturing and operational complexities. Harmonized safety codes, quality benchmarks, and data communication protocols are crucial for ensuring compatibility across global deployments and maximizing investment returns.

High Capital Costs

The substantial upfront investment required for BESS manufacturing is a significant barrier, largely driven by rare earth material needs and complex integration processes. Traditional financial institutions struggle to accommodate this unique risk profile due to a lack of tailored loan products.

Investor Concerns

Technological risks, such as battery degradation and ambiguous manufacturer warranties, deter investors and increase capital costs. The paucity of historical benchmark data limits institutional participation, leaving emerging economies reliant on insufficient innovative finance models.

Revenue Uncertainty

Market revenue uncertainties complicate the BESS business case, as formerly lucrative ancillary services face saturation and price deflation. Operators must navigate new markets, like energy arbitrage and capacity reserves, to stabilize cash flows and ensure long-term project bankability.

Environmental Risks

BESS manufacturing encompasses environmental risks spanning the entire lifecycle, from harmful mining practices to insufficient recycling capabilities. Improper handling can lead to direct chemical contamination, fires, and hazardous waste leakage, necessitating comprehensive environmental management strategies.

Cybersecurity Threats

As BESS systems become increasingly digital, vulnerabilities such as outdated software and foreign supply chain dependencies emerge. Investing in cyber-informed engineering and resilient network architectures is critical to safeguarding data and ensuring system reliability against sophisticated threats.

Regulatory Volatility

Regulatory inconsistencies, shifting compliance requirements, and regional standards create unpredictable landscapes for BESS deployment. Manufacturers must navigate these complexities to mitigate risks associated with delayed permitting and ensure legal conformity and project stability.

Rapid Scaling Challenges

Meeting the projected 15-fold industry growth by 2030 requires expanding global production capacity and developing a skilled workforce. Geographic disparities in manufacturing hubs complicate logistics and innovation, demanding a delicate balance between quality, cost, and speed amidst fierce market competition.

5.5. Recommendations

Manufacturing Acceleration

To accelerate domestic manufacturing of battery cells, it is essential to provide targeted financial incentives that make investments more attractive and economically viable for manufacturers. Streamlining the approval processes is equally important to reduce bureaucratic delays, enabling companies to establish and expand production facilities more swiftly. The government should prioritize the timely implementation of the PLI scheme to ensure that manufacturers receive the promised support without disruption. Additionally, extending policy and financial support to the localization of equipment manufacturing and component supply will strengthen the entire battery production ecosystem. These measures collectively will drive self-reliance, enhance competitiveness, and position the domestic industry for sustained growth.

Supply Chain Expansion

To secure a sustainable supply of critical minerals essential for clean energy technologies, it is imperative to establish strategic alliances with countries rich in these resources. These partnerships will facilitate access to vital raw materials, ensuring a steady and reliable supply chain. Concurrently, India must focus on enhancing domestic refining and processing capabilities to add value locally and reduce dependence on imports of refined minerals. Investing in state-of-the-art refining infrastructure and technology will enable the country to efficiently convert raw materials into high-purity inputs for manufacturing. Together, these efforts will strengthen India's resource security, support the scaling of domestic industries, and bolster the nation’s position in the global clean energy market.

Innovative Financing Solutions

Develop tailored financial products specifically designed for BESS projects, incorporating concessional financing options and risk-sharing mechanisms to mitigate investment uncertainties. Such instruments would lower the cost of capital and encourage broader participation from private sector players. Additionally, issuing green bonds dedicated to energy storage initiatives can provide a sustainable and attractive funding source, appealing to environmentally conscious investors. Infrastructure investment trusts focused on BESS can further mobilize capital by pooling resources and distributing risks among diversified investors. Combined, these financial innovations will catalyze the expansion of BESS deployment, accelerating India's transition towards a resilient and clean energy future.

GST reduction

Reducing the GST on battery components from the current 18% to 5% would significantly lower the upfront capital costs associated with battery manufacturing and deployment. This tax reduction aligns with similar concessions provided to other renewable energy components, thereby promoting a more uniform and supportive tax environment for clean energy technologies. Lower GST rates would encourage manufacturers to increase production capacity, making batteries more affordable and accessible across various applications. Additionally, this measure would attract both domestic and foreign investment by improving the profitability of battery-related businesses. Ultimately, a reduced GST would accelerate the growth of the battery industry, boosting India’s clean energy transition and contributing to energy security and sustainability goals.

Grid Infrastructure Growth

Investing in the modernization and expansion of transmission networks is crucial to support the large-scale deployment of energy storage systems, ensuring efficient integration of stored energy into the grid.

Enhancing grid infrastructure will address capacity constraints, reduce transmission losses, and improve overall reliability, enabling seamless energy flow from diverse sources. Incorporating smart grid technologies will allow for real-time monitoring, demand response, and adaptive control, optimizing grid performance amid increasing renewable penetration. Advanced grid management systems will facilitate better forecasting, automation, and fault management, minimizing outages and enhancing stability. Collectively, these upgrades will create a resilient, flexible, and future-ready grid, capable of supporting India's ambitious clean energy goals.

Regulatory Framework Development

Developing comprehensive regulatory frameworks for energy storage systems is essential to create a transparent and conducive environment for investment and operation. These guidelines should clearly define revenue streams, including mechanisms for compensation through various ancillary services, capacity payments, and energy arbitrage, ensuring financial viability for storage operators. Additionally, establishing clear rules for market participation will facilitate fair competition and integration of storage assets across different market segments, including wholesale, retail, and ancillary service markets. It is equally important to incorporate climate-specific safety standards that address unique challenges posed by different geographic and environmental conditions, ensuring the safe deployment and operation of energy storage facilities. Moreover, defining stringent performance criteria will guarantee reliability, efficiency, and longevity of storage systems, promoting trust among stakeholders and supporting the overall stability of the energy grid.

Technology Advancement

Promoting research and development in alternative energy storage technologies tailored to India's unique climatic and economic conditions is vital for building a resilient and sustainable energy ecosystem. Technologies like sodium-ion batteries, which offer advantages in terms of cost-effectiveness and local material availability, should be prioritized to address specific challenges faced by the Indian market. Investing in such innovative solutions can accelerate the diversification of energy storage options, reducing reliance on traditional lithium-ion batteries that are more dependent on imported raw materials. By fostering domestic technological advancements, India can enhance its self-reliance, create new industrial opportunities, and strengthen supply chain security. Ultimately, these efforts will contribute to cost reductions, improved energy access, and the overall scalability of clean energy storage across the country.

Skills Development Initiative

To meet the growing demand for skilled professionals in the energy storage sector, it is essential to initiate specialized training programs designed to equip workers with the technical expertise and practical knowledge required for this rapidly evolving industry. Complementing these programs, educational campaigns should be launched to raise awareness about career opportunities in energy storage, highlighting the sector's importance for sustainable development and economic growth. Establishing strong partnerships with technical institutes and industry organizations will foster collaboration, ensuring that curriculum and training content remain aligned with industry needs and technological advancements. These collaborations can facilitate internships, apprenticeships, and hands-on workshops, providing learners with valuable real-world experience.

Innovation Hubs Creation

Establishing dedicated R&D centers focused on energy storage technologies tailored to India's unique tropical climate is crucial for creating solutions that address local environmental challenges such as high temperatures and humidity. These centers would facilitate targeted innovation, enabling the development of storage systems optimized for performance, reliability, and safety under tropical conditions. By fostering collaboration among scientists, engineers, and industry experts, these hubs can accelerate the commercialization of homegrown technologies that are both cost-effective and scalable. Indigenous innovation will also help mitigate dependency on foreign technologies, reducing supply chain vulnerabilities and enhancing self-reliance.

6. Transmission Equipment Manufacturing in India

India's transmission network is rapidly growing to keep pace with rising power demand and the expanding generation capacity. This growth has not only involved extending the physical reach of the network but also incorporating higher transmission voltages and advanced technologies to enhance bulk power transfer efficiency. Additionally, increasing focus is being placed on transmission network planning and operations to improve grid resilience and flexibility. Expanding the transmission system is essential to meet the country's rising electricity demand and support the integration of RE sources. A strong transmission infrastructure is vital for efficiently delivering power across long distances, maintaining grid stability, and ensuring a reliable and continuous electricity supply.

As of July 2025, the total length of transmission lines at the 220 kV and above levels stood at 496,069 circuit kilometer (ckt km), comprising 57,240 ckt km at the 765 kV level, 207,036 ckt km at the 400 kV level and 212,418 ckt km at the 230/220 kV level. At the high voltage direct current (HVDC) level, line length stood at 9,655 ckt km at the ±800 kV level, 9,432 ckt km at the ±500 kV level and 288 ckt km at the ± 320 kV level[42]. Similarly, as of July 2025, the transformation capacity at the 220 kV and above levels stood at 1,369,568 MVA comprising 335,200 MVA at the 765 kV level, 504,873 MVA at the 400 kV level and 495,995 MVA at the 220 kV level. At the HVDC level, transformation capacity stood at 18,000 MVA at the ±800 kV level, 13,500 MVA at the ±500 kV level and 2,000 MVA at the ± 320 kV level[43]. The below figure shows the growth of total transmission line and transformation capacities over the last 5 years in India.

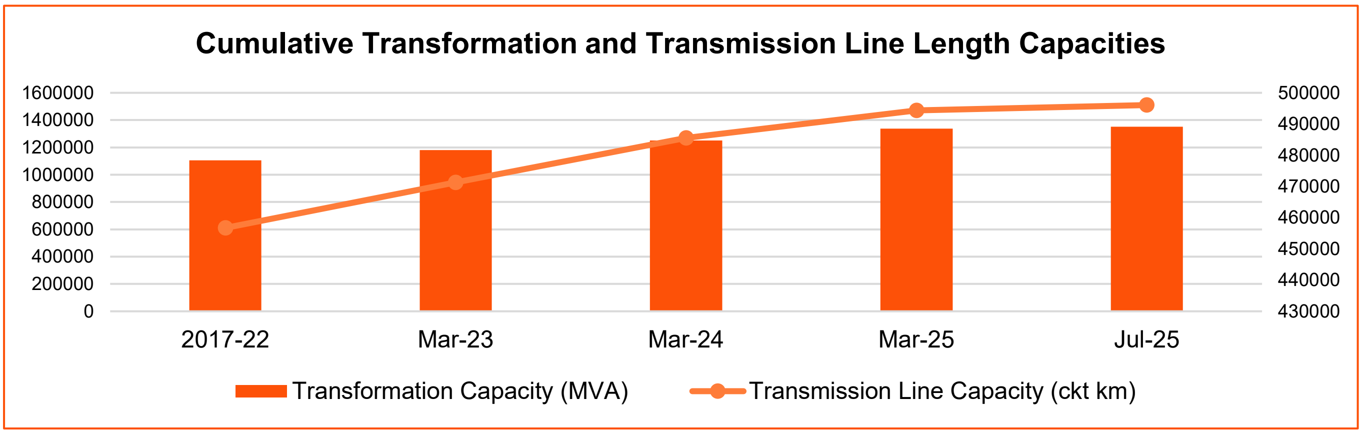


Figure 25: Cumulative transformation and transmission line length capacities in India *Source: CEA*

Transmission expansion plans

In October 2024, the Central Electricity Authority published the National Electricity Plan (NEP) – Transmission, detailing the transmission network needs through 2031-32. The plan estimates an investment exceeding INR 9 trillion between 2022 and 2032 for both inter-state and intra-state transmission infrastructure. This projection aligns with the updated (draft) Electric Power Survey, which forecasts a peak electricity demand of 296 GW by 2026-27 and 388 GW by 2031-32.

According to the NEP, between 2022 and 2027, approximately 114,687 ckt km of transmission lines and 776,330 MVA of transformation capacity will be added, requiring an investment of INR 4,252.22 billion. In the following period from 2027 to 2032, an additional 76,787 ckt km of transmission lines and 497,855 MVA of transformation capacity are projected, with investments totaling INR 4,909.2 billion.

During 2022-27, 1,000 MW of HVDC bipole capacity is expected to be installed, which will increase substantially to nearly 32,250 MW between 2027 and 2032. By the end of 2031-32, the total transmission

[42] https://cea.nic.in/wp-content/uploads/transmission/2025/07/TL_GS_July__2025.pdf, last accessed on 5th September 2025
[43] https://cea.nic.in/wp-content/uploads/transmission/2025/07/SS_GS_July___2025.pdf, last accessed on 5th September 2025

line length is anticipated to reach 648,190 ckt km, with a transformation capacity of 2,345,135 MVA. HVDC bipole capacity, including back-to-back systems, is also forecasted to rise to 66,750 MW by 2031-32. The plan includes an interregional transmission capacity increase of 30,690 MW during 2022-27, with several interregional corridors under development adding 24,600 MW of capacity. This expansion is expected to boost the total interregional transmission capacity to around 167,540 MW by the end of 2031-32.

Significant efforts are underway to facilitate green power evacuation. Under the Green Energy Corridor (GEC) scheme, Phase I of the Inter-State Transmission System (ISTS) was completed in 2020, enabling the evacuation of 6 GW of RE. Intra-state transmission systems (InSTS) are being implemented across eight renewable-rich states—Andhra Pradesh, Gujarat, Himachal Pradesh, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Tamil Nadu—connecting 18.72 GW of renewable capacity to the grid. While most projects are nearing completion, some states have received extensions until 2024-25 due to delays in land acquisition and clearances. The InSTS GEC-II scheme plans to add 10,750 ckt km of intra-state transmission lines and 27,500 MVA of substations, with an estimated investment of INR 120.31 billion. This phase will be executed by seven states—Gujarat, Himachal Pradesh, Karnataka, Kerala, Rajasthan, Tamil Nadu, and Uttar Pradesh—to evacuate around 20 GW of RE. Currently, state transmission utilities are preparing project packages and issuing tenders, with a scheduled commissioning date of March 2026 for Phase II.

6.1. Key policy enablers for transmission sector in India

India's power transmission equipment manufacturing ecosystem has evolved into a highly advanced and competitive industry, capable of meeting both domestic and international demand. Over the years, this sector has developed extensive expertise and infrastructure, enabling Original Equipment Manufacturers (OEMs) to produce a wide range of transmission components such as transformers, switchgear, cables, insulators, and towers at world-class standards. A key driver behind this growth is India's investor-friendly and supportive regulatory framework, which has encouraged OEMs to invest in localizing their production capabilities. This localization has not only reduced dependency on imports but also enhanced cost competitiveness and supply chain resilience. As a result, India now hosts a significant portion of global manufacturing capacity for power transmission equipment, making it a crucial hub in the international energy equipment market. This robust manufacturing landscape supports India's ambitious power infrastructure expansion plans and its broader goals of energy security and sustainable development.

The growth of India's transmission and distribution (T&D) sector is driven by three key pillars: the ongoing energy transition toward renewable sources, the rising potential for increased per capita energy consumption, and growing demand from emerging sectors such as electric vehicles, green hydrogen, data centers. These factors collectively create a sustainable ecosystem poised for long-term expansion.

Public-private partnerships (PPPs) and increased private sector investments play a critical role in meeting national T&D targets by expanding T&D networks in tandem with the growth of RE. The government has launched extensive transmission projects to evacuate power from renewable sources while adding substantial thermal capacity to meet base load demand. These initiatives require significant investments—estimated at around INR 4.9 lakh crore—to add 77,000 ckt km of transmission lines and 500 GVA of transformation capacity. Similar investments are planned for the distribution segment, primarily driven by state governments.

The clear prioritization and visibility of these schemes have encouraged equipment manufacturers and EPC companies to enhance their production capacities and increase capital expenditure. This momentum is expected to continue, supported by the government's strong commitment to climate change mitigation. Together, these factors highlight a dynamic and rapidly expanding T&D sector that is essential for supporting India's evolving energy needs and achieving sustainable growth.

6.2. Key trends and emerging technologies in T&D sector in India

India's T&D sector is undergoing a significant transformation, driven by government initiatives such as 'One Nation-One Grid-One Frequency' and the ambitious goal of achieving 500 GW of RE capacity by 2030. These efforts have evolved the previously fragmented transmission network into a well-integrated and interconnected grid. Key growth drivers include green energy corridors, decentralized systems, smart grids, and increasing private sector investments. Emerging trends in the sector also focus on energy storage solutions, global collaborations, electric vehicle infrastructure, and regional grid integration.

Market sentiment remains optimistic, bolstered by initiatives like the revamped distribution sector scheme (RDSS) and expanded public-private partnerships in transmission. Transmission assets are attracting considerable interest from infrastructure funds and foreign investors due to their stable, long-term returns and transparent regulatory frameworks. However, the distribution segment continues to face challenges such as high aggregate technical and commercial (AT&C) losses and financial stress among distribution companies, though ongoing reforms are yielding positive results. Government of India's commitment is demonstrated through the allocation of US$36.74 billion to RDSS, aiming to improve power supply reliability and efficiency nationwide, with AT&C losses reduced to around 15.98% by FY23.

The sector's evolution is further propelled by strengthening interregional transmission corridors to manage regional supply-demand mismatches, expanding green corridors for renewable energy evacuation, and integrating offshore wind power. Digital transformation technologies like artificial intelligence, the Internet of Things, and blockchain are increasingly being adopted to enhance grid management and facilitate energy trading. Additionally, consumer-centric innovations such as prosumer models, net metering, and peer-to-peer energy trading are gaining momentum as distribution utilities shift toward more customer-focused approaches, signalling a more dynamic and responsive energy sector.

High Voltage Direct Current (HVDC) technology is anticipated to play a pivotal role, with the government considering options to transmit large amounts of power even at ultra-high voltages like 1,200 kV. HVDC systems, including line-commutated converter (LCC) and voltage source converter (VSC) technologies, will be crucial for managing long-distance and cross-border power flows. Additionally, static synchronous compensator (STATCOM) technology is gaining importance for reactive power management and maintaining voltage stability amid rising renewable penetration. Digital transformation forms a core part of this evolution, with grid orchestration becoming essential to manage the increasingly complex energy ecosystem. On the operational front, technologies like drones, robots, and artificial intelligence are enhancing predictive maintenance and asset management, improving the productivity and reliability of power infrastructure such as extra-high-voltage (EHV) transmission lines. The adoption of smart grids, advanced metering infrastructure (AMI), energy storage systems (ESS), and hybrid switchgear is expected to further elevate grid performance, resilience, and sustainability.

Artificial intelligence (AI) and machine learning (ML) are emerging as critical tools for optimizing grid operations, enabling real-time monitoring, control, and efficient energy flow management. These technologies support grid automation, improve demand-supply balance, and reduce outages, while enhancing policy development. Other notable advancements include microgrids, wide-area monitoring, cybersecurity, and digital twins for operations and maintenance. As distributed energy resources like rooftop solar, electric vehicles (EVs), and small-scale renewables grow, there will be a vital shift towards decentralized grid architectures, with particular emphasis on integrating EV charging infrastructure to meet India's ambitious EV adoption goals. Together, these technologies signal a future-ready, flexible, and robust T&D network that will underpin India's clean energy ambitions and energy security objectives.

6.3. Challenges affecting the transmission sector

The major challenges faced by the T&D projects in India have been highlighted below.

Right of Way (RoW) Issues

Delays in land acquisition for transmission lines and substations pose a significant challenge to the timely expansion and modernization of power infrastructure. One of the primary causes of these delays is landowner resistance, which often stems from concerns over displacement, inadequate compensation, environmental impact, and loss of livelihood. Many landowners may be hesitant or outright opposed to parting with their land, especially in cases where awareness about the project benefits is limited or where trust deficits exist between stakeholders. Additionally, the land acquisition process is complicated by multiple layers of regulatory requirements, including approvals from local, state, and central authorities.

These bureaucratic hurdles can prolong negotiations and approvals, further slowing down project timelines. In some cases, legal disputes and protests exacerbate delays, affecting not only project costs but also disrupting the overall power supply planning. Overcoming these challenges requires transparent communication, fair compensation policies, community engagement, and streamlined regulatory frameworks to balance development goals with social and environmental considerations effectively.

Financial Constraints

High initial costs and delayed payments from financially stressed state-owned DISCOMs pose significant challenges to the expansion and sustainability of the T&D sector. Setting up transmission lines, substations, and associated infrastructure demands substantial upfront capital investment, including costs related to land acquisition, equipment procurement, and construction. These high initial expenditures can deter private investors and slow project implementation due to the long gestation periods before returns are realized. Compounding this issue, many state DISCOMs suffer from poor financial health driven largely by high AT&C losses — including energy theft, transmission inefficiencies, and billing gaps — which strain their ability to pay power producers and equipment suppliers promptly. Delays in payments not only disrupt cash flows for manufacturers, contractors, and service providers but also increase financing risks and discourage further investment in the sector. Addressing these financial challenges requires comprehensive reforms aimed at reducing AT&C losses, improving operational efficiency, and strengthening the financial viability of DISCOMs to ensure timely payments and foster a healthier investment climate.

Transmission Congestion

Power congestion in transmission corridors occurs when the capacity of transmission lines is insufficient to handle the volume of electricity being generated and dispatched through the grid. This bottleneck situation can lead to the phenomenon of stranded resources, where available generation assets—such as RE plants or thermal power stations—are unable to transmit their full output to consumers or the grid, despite having the capacity to produce electricity. Congestion not only wastes valuable energy but also results in financial losses for power generators, as they may have to curtail production or sell electricity at lower prices due to grid limitations. Additionally, persistent transmission congestion undermines grid reliability and flexibility, leading to inefficiencies in power delivery and increased operational costs. It also discourages further investments in new generation capacity, especially renewables, if developers anticipate difficulties in evacuating power. Addressing transmission congestion effectively ensures optimal utilization of energy resources, supports grid stability, and contributes to India's broader energy security and sustainability goals.

RE Integration

Grid stability issues arise primarily due to the intermittent and variable nature of solar and wind energy, which are heavily influenced by weather conditions and time of day. Unlike traditional power sources that provide a steady and controllable supply, solar and wind power generation can fluctuate rapidly, leading to unpredictable changes in electricity output. These fluctuations pose significant challenges for maintaining the balance between electricity supply and demand—a critical aspect of grid stability. Sudden drops or spikes in renewable generation can cause frequency and voltage variations, potentially leading to power quality problems, equipment damage, or even widespread outages if not properly managed. Integrating large shares of variable renewables requires advanced grid management solutions such as real-time monitoring, energy storage systems, demand response mechanisms, and flexible backup power plants. Additionally, upgrading grid infrastructure and deploying smart grid technologies enable better forecasting, adaptive control, and seamless integration of renewable resources.

Inadequate skilled manpower

The rapid growth and evolving complexity of the T&D sector in India have led to a significant increase in demand for skilled professionals. However, this surge has exposed a critical skilling gap, with an acute shortage of industry-ready talent available to meet the sector's needs. A major contributing factor is the inadequate training infrastructure, which lacks sufficient capacity, modern facilities, and updated curricula tailored to the specific requirements of the power sector. Additionally, there are limited specialized institutions focusing on advanced technologies, emerging trends, and practical hands-on training essential for preparing a proficient workforce. This shortage hampers the industry's ability to effectively design, operate, and maintain increasingly sophisticated grid systems, potentially slowing project execution and innovation adoption. To bridge this gap, significant investments are needed in expanding educational and vocational training centers, upgrading course content to align with industry standards, and fostering partnerships between industry and academia for apprenticeships and continuous skill development. Strengthening the talent pipeline is essential for sustaining the sector's growth and ensuring the reliable and efficient operation of India’s power transmission infrastructure.

Lack of visibility of tenders and delay in signing LoA

There is a clear understanding of the upcoming transmission projects aligned with the NEP, indicating a well-defined pipeline of initiatives intended to expand and strengthen India’s power infrastructure. However, despite this clarity on project plans, there remains a significant lack of transparency and predictability regarding the tendering process. Specifically, there is insufficient visibility into the timeline and pace at which Requests for Qualification (RfQs) are issued, Letters of Award (LoAs) are granted, and Special Purpose Vehicles (SPVs) are formally transferred or established. This ambiguity creates uncertainties for developers, investors, and other stakeholders, making it difficult to plan resource allocation, mobilize capital, and manage project execution effectively. Moreover, the absence of strict, sacrosanct timelines for each stage of the tendering and project award process can lead to delays, increased costs, and potential loss of investor confidence. To improve efficiency and attract sustained investment, it is crucial to establish clear, transparent, and enforceable timelines from the issuance of RfQs through to the finalization of SPVs, ensuring that projects proceed promptly and predictably in alignment with the NEP’s objectives.

6.4. Recommendations

Improve grid reliability through standardization

It is essential to establish uniform standards across all voltage levels, including lower intra-state levels, to streamline design, procurement, and interoperability within the transmission network. This standardization will reduce inefficiencies, lower project costs, and enable economies of scale for manufacturers, fostering a competitive and scalable market aligned with the “One Nation, One Grid” vision. Additionally, removing regulatory barriers such as the BIS Quality Control Order on CRGO steel will enhance the availability and affordability of critical transformer materials, supporting timely infrastructure development. Standardizing technical specifications for key components like Voltage Source Converters (VSC) in HVDC systems will ensure consistency across projects, simplify manufacturing and procurement, and attract sustained investment by providing a stable and predictable market environment. Together, these measures will enhance operational efficiency, reduce delays, and strengthen the overall reliability of India’s power grid.

Use emerging technologies and BESS integration to reduce the RE intermittency

To effectively integrate intermittent RE into the grid, it is essential to implement advanced automation and AI/ML-driven strategies for optimizing load balancing and capacity utilization. Additionally, promoting the widespread adoption of BESS will help provide a reliable, RTC power supply by smoothing out fluctuations and ensuring grid stability as RE penetration increases.

Streamline tendering process

To effectively increase capacity and efficiency in India’s power transmission sector, implementing early tendering processes is essential to avoid project bunching and the associated delays. Project bunching occurs when multiple transmission projects are launched simultaneously, leading to intense competition for resources such as skilled labor, equipment, and financing. This congestion can cause cost escalations, extended timelines, and strained supply chains, ultimately slowing down the overall progress of infrastructure development. By initiating tenders well in advance and staggering project timelines strategically, the sector can ensure smoother resource allocation, better project management, and timely execution. Early tendering also provides manufacturers and contractors with sufficient lead time to scale up production capabilities, optimize workflows, and coordinate supply chains efficiently. Moreover, it helps investors and stakeholders plan better, reducing uncertainties and enhancing confidence in the power transmission market. Overall, adopting an early and phased tendering approach will facilitate balanced growth, improve cost-effectiveness, and accelerate the expansion of India's transmission network, supporting the country's broader energy goals.

Adopt a program-based approach rather than a project-based one

To strengthen India's power transmission sector, adopting a program-based approach with long-term framework agreements and capacity bookings of at least five years, as practiced by entities like TenneT, RTE, SSE, and Grid United, is recommended. This method provides greater predictability, enabling manufacturers, contractors, and investors to plan and scale operations efficiently. It facilitates coordinated grid expansion, reduces project redundancies, and supports seamless integration of renewable energy. The approach encourages public-private collaboration, fostering innovation and faster project execution. Ultimately, it aligns infrastructure development with national energy goals, enhancing grid resilience and supporting India's clean energy transition.

Policy support would be required to overcome C-BAM in EU

India's power transmission sector must prepare for the European Union's Carbon Border Adjustment Mechanism (CBAM), which imposes tariffs based on carbon emissions to promote cleaner manufacturing globally. Policymakers need to provide support through financial incentives, cleaner technologies, and access to RE for manufacturers to meet these requirements. Establishing clear carbon measurement and reporting standards will help compliance with CBAM regulations. Capacity-building and technical aid are crucial, especially for small and medium enterprises, to manage the transition without excessive costs. Proactive policy measures and international engagement will protect India's manufacturers and enhance competitiveness.

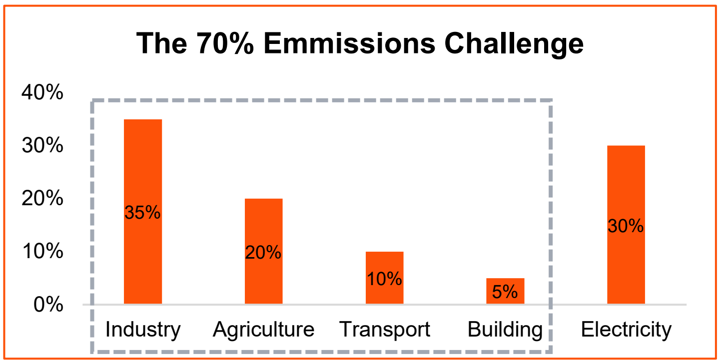
Dedicated RoW framework

The Bid Process Coordinator (BPC) should offer consistent baseline estimates for RoW compensation by utilizing state government notifications or historical data to minimize uncertainty for bidders. Implementing a standardized compensation framework will guarantee fair remuneration for landowners while giving developers clear financial expectations. A specific RoW framework under the Electricity Act should be introduced to replace reliance on the Telegraph Act, ensuring a thorough and transparent compensation and approval process. This new framework should clearly define compensation norms, simplify approval procedures, and help reduce delays in project execution.

7. Manufacturing Landscape for Emerging Technologies

The following section provides a brief overview of emerging technologies related to this field that are currently in the very early stages of development in India. It is important to note that manufacturing for these technologies has not yet commenced domestically, and significant research and development efforts are still required before they can be commercially deployed. This summary aims to highlight the potential of these nascent technologies, and the opportunities and challenges associated with their future advancement.

7.1. Carbon Capture Utilization and Storage (CCUS)



Source: IEA

Worldwide, the power and industrial sectors account for nearly 50% of all greenhouse gas (GHG) emissions, making emission reductions in these areas essential to global climate change mitigation. India ranks as the third-largest emitter of carbon dioxide (CO2) after China and the United States, releasing an estimated 2.6 gigatonnes annually. The Indian government has pledged to cut CO2 emissions by 50% by 2050 and achieve net-zero emissions by 2070. While the expansion of renewable energy capacity is a major success in India's clean energy transition, the power sector currently represents only about one-third of total CO2 emissions. These emissions are projected to decline further as renewable sources increasingly replace fossil fuels. However, the industrial sector, which contributes another one-third of emissions, remains challenging to decarbonize and may continue to grow unless advanced technologies and carbon reduction strategies are implemented.

Despite efforts to reduce coal dependency, India will likely continue relying on fossil fuels—especially coal—for affordable and dependable baseload electricity and industrial energy needs for the foreseeable future. Thus, India’s carbon reduction pathway must incorporate technologies that address emissions from difficult-to-electrify industrial sectors and residual fossil fuel-based power generation. In this context, Carbon Capture, Utilization, and Storage (CCUS) has become a crucial technology, enabling the capture of CO2 emissions from industrial activities and the atmosphere, followed by carbon reuse and secure storage to lessen environmental harm.

CCUS plays a vital role in decarbonizing industrial sectors where fossil fuels are not only energy sources but also integral to manufacturing processes, making these emissions hard to abate. It is equally important for the power sector, as coal currently supplies over 70% of India's electricity. Even with India’s ambitious goal to install 500 GW of RE capacity by 2030, there is a continuing need for fossil-fuel-based or other dispatchable power sources to ensure grid stability due to the intermittent nature of solar and wind energy.

Another emerging technology is Direct Air Capture (DAC), which removes dilute CO2 directly from the atmosphere irrespective of emission source or concentration. While DAC holds broad potential, it remains in early development stages with costs currently estimated between US$400-800 per tonne of CO2, and its economic viability and scalability are yet to be proven.

7.1.1. CCUS Technology and Applications

CCUS involves a suite of technologies designed to chemically capture CO2 at its emission points, such as chimneys, using processes like chemical oxidation. Once captured, this CO2 can be upcycled and reused in various industries including fuel production (such as methane and methanol), plastics manufacturing, pharmaceuticals, fire safety equipment, food and beverage carbonation, soda ash production, building materials, and agriculture. Innovative advancements include artificial photosynthesis methods, such as bio-solar leaves and phytoplankton-based solutions, mimicking nature’s photosynthesis process to transform CO_2 efficiently. Captured carbon is often stored deep underground in geological formations, including depleted oil and gas wells, ensuring safe, long-term sequestration. Various categories and types of commercial-scale carbon capture technologies exist, and their suitability for specific applications or sectors depends largely on the typical composition of the CO_2 gas stream involved.

Chemical solvent-based CO_2 capture technologies

This approach is favoured for handling gas streams with low CO_2 concentrations and relatively low pressures, such as flue gases from power plants, blast furnace gases in steel manufacturing, and gas streams from refineries or chemical plants. Additionally, the cost and availability of steam play a crucial role, as solvent regeneration demands substantial amounts of steam.

Physical solvent-based CO_2 capture technologies

These technologies are effective for gas streams that have relatively higher CO_2 concentrations and pressures, such as those encountered in pre-combustion capture processes during gasification projects.

Adsorption based CO_2 capture

Well-suited for gas streams exhibiting moderate to high pressure and moderate CO_2 concentrations, such as flue gas from steam methane reforming (SMR) or blast furnace (BF) gas.

Cryogenic CO_2 capture

This technology is favoured when power costs are low and is particularly applicable for capturing carbon from the PSA tail gas of Steam Methane Reforming units used in hydrogen production. It offers the distinct advantage of enhancing hydrogen yield and recovery from the same amount of natural gas feedstock.

A comparative analysis of various CO_2 capture technologies have been shown in the table below.

Table 10: Comparative analysis between CO_2 capture technologies

Process	Working Principle	Advantages	Limitations
Chemical Solvent	• Chemical reaction between CO_2 and solvent. • Governed by rate kinetics & thermodynamics	• High absorption at low partial pressure of CO_2 • Selective capture and high purity CO_2 product	High energy (steam) requirements for solvent regeneration
Physical Solvent	• Absorption due to CO_2 solubility in the solvent • Governed by Henry's Law	• Suitable for gas streams with high partial pressure of CO_2 • Regeneration through low temperature flashing or pressure reduction • High absorption capacity & lower solvent recirculation rates	• Low energy efficiency for low partial pressure of CO_2 • High compression requirement for low pressure feed gas • H_2S often absorbed more effectively than CO_2
Adsorption	• Selective adsorption due to difference in diffusivity & heat of adsorption • Governed by pressure change	• Selective capture • Can be performed at normal temperatures	• Batch process • Complex pressure balancing management system • High electrical energy consumption

Cryogenic Separation	• Low-temperature separation through liquefaction • Governed by temperature change	• Selective capture and high purity CO_2 • Liquefied CO_2 product • No steam consumption • Low area footprint	• High energy requirement • High operating pressure

CCUS is a fundamental technology for achieving decarbonization and ensuring the sustainable growth of key industries and sectors that form the backbone of the Indian economy. By effectively reducing carbon emissions, CCUS supports the continued operation and competitiveness of these vital sectors, enabling them to meet environmental targets without compromising productivity or economic contribution. Its adoption is essential not only for minimizing the carbon footprint of energy-intensive industries but also for safeguarding jobs, promoting innovation, and driving long-term economic resilience across India's most critical growth areas. Key sectors where CCUS technologies can be

Steel

India's steel industry is expected to continue relying heavily on fossil fuels and the CO_2-intensive blast furnace-basic oxygen furnace process due to limited availability of scrap metal and natural gas. To ensure the sustainability of this vital sector and maintain its global export competitiveness, the adoption of CCUS is essential. Additionally, CCUS offers the potential to convert waste gases from blast furnaces, coke ovens, and basic oxygen furnaces in integrated steel plants into blue hydrogen at a competitive cash cost of under INR 100/kg. This blue hydrogen can be utilized within the steel plants as a clean energy source or for producing direct reduced iron (DRI). Furthermore, surplus blue hydrogen can be marketed to external customers, thereby driving the growth of India's clean hydrogen economy.

Cement

The cement industry is a significant source of CO_2 emissions, with fossil fuels playing an irreplaceable role in the cement production process. Capturing, storing, and converting CO_2 into aggregates and other chemical products offers valuable synergies for this sector. CCUS technology is acknowledged as a crucial tool for achieving net-zero carbon emissions while enabling continued industrial growth. Moreover, it supports multiple United Nations Sustainable Development Goals (SDGs), such as climate action, clean energy, industrial innovation and infrastructure, responsible consumption, and fostering global partnerships.

Oil and gas refineries

This is another hard-to-abate sector, where CCUS is essential for ensuring sustainability. Carbon capture is inbuilt in many of the processes, which makes CCUS costs competitive for this sector.

Hydrogen production

Cost-effective blue hydrogen production leveraging India's abundant coal resources is essential for advancing the future hydrogen economy. Since carbon capture is integrated into the hydrogen production process, it results in economically viable CCUS solutions.

Coal gasification

Coal gasification is a sunrise sector and key to ensuring the materials and energy security of India, based on India's rich endowments of coal. CCUS is critical to enabling the coal gasification economy in India and the production of clean products.

Thermal power

Even with the expected growth in RE capacities, coal-based power will continue to meet more than 50% of electricity demand in India in the foreseeable future. As the largest emitter of CO2, CCUS of the power sector is essential for meaningful decarbonization and ensuring energy security in India.

7.1.2. India's CO2 Storage Potential

The captured CO2 can either be utilized or permanently stored. Utilization options include its use in urea production, conversion into chemicals such as methane, methanol, and ethanol, as well as emerging applications like producing aggregates. Alternatively, CO2 can be permanently stored in deep underground geological formations, including depleted oil and gas reservoirs (often used for enhanced oil recovery), deep saline aquifers, and basaltic rock formations. These methods for CO2 storage capacity assessment and their potential have been discussed below.

Enhanced Oil Recovery Storage Capacity Assessment

The injection of CO2 for Enhanced Oil Recovery (EOR) has been extensively studied and implemented, particularly in North America. CO2 is miscible with crude oil, enabling the extraction of oil that cannot be recovered through secondary methods. Additionally, this process facilitates the permanent storage of CO2 within oil reservoirs, making CO2 EOR a sustainable approach for reducing carbon emissions. In CO2 EOR, compressed CO2 is injected into the reservoir. At high densities, CO2 is readily miscible with oil. It swells the oil and reduces its viscosity, thereby driving it away from rock formations and towards the production wells. A minimum pressure is required for CO2 and oil to be miscible. To prevent lower viscosity CO2 from escaping the reservoir, water and CO2 are injected alternatively.

India has a total of 26 sedimentary basins. According to the Directorate General of Hydrocarbons' (DGH) 2020 India Hydrocarbon Outlook report, these basins are classified into three groups: category I, category II, and category III basins. Category I basins are the ones where commercial oil & gas exploration and production activities are ongoing. There are 7 basins in category I. The theoretical capacity estimates of the seven category I basins have been listed in the table below.

Table 11: India's CO2 storage capacity

Basin	Storage Capacity (mt CO2)
Krishna-Godavri	658.69
Mumbai	1597.24
Assam shelf	667.48
Rajasthan	312.52
Cauvery	99.50
Assam-Arakan	67.01
Cambay	657.25
Total	**3402.43**

Thus, a total of 3.4 Gt of theoretical storage capacity is estimated to be available for EOR. The CO2 EOR capacities are expected to increase as more basins are explored for hydrocarbon production.

Enhanced Coal Bed Methane Recovery (ECBMR) Storage Capacity Assessment

Coal bed methane (CBM) is produced from coal seams and can play a significant role in enhancing India's energy security. In ECBMR, CO2 is injected into un-mineable coal seams under supercritical conditions, where it accumulates in the coal cleats as a dense gas. The CO2 is both adsorbed and absorbed by the coal, and since it has a stronger affinity for coal than methane, it displaces the coal bed methane toward production wells, thereby increasing methane recovery. Similar to CO2-enhanced oil recovery, ECBMR not only facilitates permanent CO2 storage but also generates methane that can help offset carbon capture costs. This approach is particularly viable for thermal power plants, many of which are located near coalfields.

Indian coal reserves mostly comprise anthracite and bituminous coal, spread across the Gondwana basin and scattered in some parts of north-eastern India. These coalfields are rich in CBM, and the CH_4 to CO_2 ratio may vary in the range of 1:2 to 1:3. Since several large-scale thermal power plants are located near coal fields, ECBMR presents a promising opportunity for CO_2 utilization and storage. Information about several parameters is required for a high-level estimation of the CO_2 storage capacity in coal reserves, which are difficult to get. Based on high-level calculations, the CO_2 storge capacity has been estimated to be between 3.5 to 3.7 Gt of CO_2. More pilot testing is needed to gather data specific to the Indian context for ECBMR, which will help pave the way for its commercial implementation.

Deep Saline Aquifer Storage Capacity Assessment

Captured CO_2 can be permanently stored in deep saline aquifers. Unlike EOR or ECBMR, injecting CO_2 into these aquifers does not provide any direct economic benefit. However, deep saline aquifers cover vast areas and hold the capacity to store large volumes of CO_2. These aquifers are composed of porous rock formations saturated with highly saline, unusable water known as formation brine. This brine is confined beneath an impermeable rock layer called the caprock, which prevents CO_2 from escaping. Supercritical CO_2 can be injected into deep saline aquifers, where the denser brine water causes the lighter CO_2 to rise and become trapped beneath the impermeable caprock, a mechanism known as structural or stratigraphic trapping. During injection, some CO_2 occupies pore spaces by displacing existing fluids, referred to as residual trapping. Additionally, a portion of the CO_2 dissolves into the brine, forming a denser mixture that settles downward, known as solubility trapping. Over time, dissolved CO_2 reacts with minerals in the formation to create solid carbonate compounds, a process called mineral trapping.

India's deep saline aquifers are spread across 26 sedimentary basins, which are classified into three categories: I, II, and III. Category I basins possess the most comprehensive lithological data, while further exploration is required to acquire high-quality data for the basins in categories II and III. The total theoretical storage capacity is estimated to be 291.1 Gt CO_2 for deep saline aquifers. This estimation will increase based upon the availability of more data on category III basins. Deep saline aquifers offer immense storage potential, and thus more studies and pilot tests are required to generate the baseline data for CO_2 sequestration operations in India.

Basalt Rock Storage Capacity Assessment

Recent studies have focused on the CO_2 storage potential of basaltic rocks, which contain divalent cations such as calcium, magnesium, and iron. These minerals can react with CO_2 dissolved in water to form stable carbonate minerals, providing a secure method for long-term CO_2 sequestration. Compared to mineralization in saline aquifers, basalt rocks enable faster reaction rates due to their high content of iron, calcium, and magnesium oxides. The widespread presence of basalt on the Earth's surface has further driven interest in researching and developing CO_2 storage technologies involving basalts. Researchers estimate the global CO_2 storage capacity of basalt formations to be between 8,000 and 41,000 Gt.

Basalt formations in India are found primarily in the Deccan Volcanic Province (DVP) and the Rajmahal trap. The DVP basalts extend across the northwestern region, covering an area of nearly 500,000 km^2, with an estimated volume of approximately 512,000 km^3. In contrast, the Rajmahal trap in eastern India is a smaller formation, consisting of basalt layers 450 to 600 meters thick, spread over an area of about 18,000 km^2. The CO_2 storage capacity of these Indian basalt formations is estimated to range between 97 and 315 Gt.

The overall CO_2 storage capacity assessment for the four options discussed have been summarised in the table below.

Table 12: Storage pathway wise CO_2 storage capacities

Storage Pathways	Theoretical Storage Capacity (Gt)
EOR	3.4
ECBMR	3.5-3.7

Storage Pathways	Theoretical Storage Capacity (Gt)
Deep Saline Aquifer	291
Basalts	97-315
Total	**395-614**

7.1.3. Government Initiatives to Promote CCUS

As part of its commitment to international climate agreements like the Paris Accord—which seeks to limit global warming to below 2°C, preferably 1.5°C above pre-industrial levels—India has initiated policies supporting CCUS uptake, positioning the country on its path toward a green, technology-driven energy economy. To accelerate CCUS research and innovation, the Indian government has established two national Centers of Excellence namely, National Centre of Excellence in Carbon Capture and Utilization (NCoE-CCU) at IIT Bombay, Mumbai and National Centre in Carbon Capture and Utilization (NCCCU) at Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bengaluru.

These centers will serve as multi-disciplinary hubs driving R&D, fostering collaboration between researchers, industries, and stakeholders, and facilitating knowledge sharing and capacity building in cutting-edge CCUS technologies. The National Centre of Excellence in Carbon Capture and Utilization (NCoE-CCU) at IIT Bombay will establish key milestones and lead science and technology initiatives focused on industry-driven CCU innovation in India. It will develop advanced methodologies to enhance the technology readiness levels of CCU processes and accelerate research and development in carbon capture and utilization techniques. The center's work will encompass the conversion of captured CO2 into chemicals, as well as aspects of CO2 transport, compression, and utilization, including enhanced hydrocarbon recovery as a complementary benefit. Additionally, NCoE-CCU will focus on efficient CO2 capture from representative flue gases originating from power and biogas plants.

Meanwhile, the National Centre in Carbon Capture and Utilization (NCCCU) at JNCASR, Bengaluru, aims to develop and demonstrate carbon capture and conversion technologies by creating relevant materials and processes. These technologies will be scaled up to pilot-level operations for producing hydrocarbons, olefins, and other value-added chemicals and fuels. The center will work to achieve technology readiness levels appropriate for industrial commercialization and promote CCU research through training, consultancy, and translation of its research outcomes into globally impactful solutions.

Together, these centers will harness India's collective expertise to develop a robust and practical R&D and innovation roadmap for CCUS. They will also monitor international trends and recommend potential collaborations to strengthen India's position in the global CCUS landscape.

Another such measure is Mission Innovation Challenge. The Mission Innovation Challenge on CCUS focuses on enabling near-zero emissions from power plants and carbon-intensive industries. The DST, in partnership with the Department of Biotechnology (DBT), launched a national research program that supports CO2 storage and carbon capture projects. Started in 2018, this joint effort with 24 member countries prioritizes breakthrough technologies in CO2 capture, separation, storage, and utilization. Out of numerous proposals, 20 projects across DST and DBT have been recommended for funding, showcasing international cooperation for technological development.

Another major step includes Accelerating CCS Technologies (ACT) Initiative. This initiative aims to catalyze R&D innovations targeting the development of safe, cost-effective CCUS technologies. By financing cutting-edge research, it supports overcoming technological, environmental, social, and economic challenges associated with CCUS deployment. India has collaborated with various countries—including France, Germany, Norway, and the United States—to advance these objectives. To date, four rounds of ACT funding have supported numerous projects to mature and accelerate CCUS technology readiness.

7.1.4. Challenges faced by CCUS in India

The development of CCUS projects in India faces several challenges, reflecting the complex nature of integrating such technologies into the country's industrial and energy landscape. Despite its promise, India's CCUS sector faces several challenges detailed below.

Cost and Financing

The upfront capital investment required to deploy CCUS technologies is often substantial, reflecting the complexity and scale of these systems. Securing adequate financing for such projects can be challenging, especially in economic environments where cost efficiency and return on investment are closely scrutinized. The high initial costs may deter potential investors and stakeholders, necessitating innovative financing mechanisms, policy support, and risk mitigation strategies to make CCUS projects more financially attractive and viable in the long term.

Lack of Regulatory Framework

The establishment of a strong and well-defined regulatory framework tailored specifically for CCUS projects is crucial for their successful development and deployment. Such a framework should include clear guidelines and technical standards that outline best practices for project design, operation, safety, and environmental compliance. Additionally, incorporating targeted incentives—such as tax breaks, subsidies, or carbon credits—can significantly motivate industry stakeholders to invest in CCUS technologies. Together, these regulatory measures create a predictable and supportive environment that fosters industry participation, ensures adherence to safety and environmental protocols, and accelerates the scaling of CCUS initiatives.

Infrastructure Development

Developing the infrastructure necessary for transporting and securely storing captured CO2 presents significant logistical challenges. Establishing extensive pipeline networks to move CO2 from capture sites to storage locations, alongside constructing reliable and safe geological storage facilities, demands considerable capital investment and meticulous planning. Moreover, this process requires effective coordination and collaboration among multiple stakeholders, including government agencies, private sector players, local communities, and environmental regulators, to address technical, regulatory, and social considerations. Overcoming these complexities is essential to ensure the efficient and safe implementation of large-scale CCUS projects.

Technology Readiness

The current level of technological maturity within the CCUS sector can pose significant limitations to its broader implementation. While some carbon capture and utilization technologies have been proven at commercial scales, several others remain in nascent stages of development and pilot testing. These emerging technologies require further validation to demonstrate their scalability, operational reliability, and economic feasibility. Until these aspects are thoroughly proven, widespread adoption will be constrained, underscoring the need for continued research, development, and demonstration projects to advance these innovative solutions toward commercial readiness.

Awareness and Capacity Building

A significant barrier to the advancement of CCUS technologies is the limited awareness and understanding among key stakeholders, including policymakers, industry executives, and the general public. Without a clear comprehension of the benefits, operational mechanisms, and potential impact of CCUS, decision-makers may hesitate to prioritize or invest in these technologies. Similarly, industry leaders may be reluctant to adopt CCUS solutions without sufficient knowledge of their feasibility and advantages. Public scepticism or lack of information can also hinder acceptance and support for projects involving carbon capture and storage. Addressing this gap through targeted education, transparent communication, and stakeholder engagement is essential to build confidence, foster informed decision-making, and accelerate the deployment of CCUS initiatives.

To address the challenges CCUS faces in India, there is a need to develop and evolve an ecosystem supporting CCUS facilities in the Indian market. Success of CCUS is not only impeded by technology which will be advancing in coming years but also by the lack of a policy ecosystem. The ecosystem should be built and strengthened around the essential pillars, namely, R&D, policy, finance, and governance. However, an India-specific comprehensive analysis needs to be undertaken to understand the challenges and the local solutions that are possible. The next section highlights some of the key strategic recommendations which can be taken up to aid the CCUS sector in India.

7.1.5. Recommendations

The Government of India needs to adopt a multi-pronged approach to promote the adoption of CCUS technologies in India. The key elements of the approach need to incentivize the following:

Promoting R&D

The Government of India should actively support and cultivate an ecosystem that encourages research and innovation in the development of CO2 utilization technologies, as well as the creation of new products and applications derived from captured CO2. Emerging technology areas that warrant support include relatively nascent methods such as oxy-fuel combustion, membrane separation, microbial and algae-based CO2 capture, and calcium looping, all of which could contribute significantly to India's net-zero goals and clean energy transition. Additionally, government policies should provide incentives to promote R&D in Direct Air Capture (DAC) technologies as a promising future solution.

Increasing private sector participation

Private sector involvement is essential for facilitating the transfer and commercialization of established CCUS technologies, as well as driving innovation in emerging capture and utilization methods. To attract and maximize private investment, early government funding, clear long-term policies that provide incentives and reduce risks, and the establishment of sustainable CCUS business models and value chains are crucial. These measures will help create a conducive environment for private participation in advancing CCUS technologies and projects.

Focus on technology transfer

Carbon capture technologies have been successfully demonstrated at commercial scale worldwide, especially in the United States, where they have been in use for nearly five decades. Therefore, India's focus should be on transferring, assimilating, and adopting these established technologies rather than developing new ones from scratch. This approach will help minimize technological and operational risks, while also reducing costs associated with CCUS projects. Both pre-combustion and post-combustion carbon capture technologies—including solvent-based, adsorption, and cryogenic methods—are commercially proven and offered by numerous technology providers.

National research collaborations and knowledge-sharing initiatives are creating promising opportunities to transform India's energy landscape. CCUS serves as a crucial bridging technology, enabling decarbonization in line with India's climate commitments. With its substantial geological storage capacity and ongoing innovation support, India can develop economically scalable CCUS solutions, positioning itself as a global leader in sustainable energy generation and consumption. Given the vast market potential for CCUS, the manufacturing of CCUS technologies is poised to become a significant industry in India. As demand for these solutions grows to support the country's climate goals and industrial decarbonization efforts, domestic production of CCUS equipment and components will play a crucial role in driving cost efficiencies, fostering innovation, and creating economic opportunities across the manufacturing sector.

7.2. Pumped Hydro Storage

As India rapidly expands its renewable energy capacity to achieve the ambitious target of 500 GW by 2030, ensuring grid reliability and stability becomes critically important. RE sources such as solar and wind are inherently variable and intermittent, leading to fluctuations in power generation. To effectively manage these variations and maintain a steady and reliable supply of electricity, adequate energy storage solutions are essential. Among the available options, pumped hydro storage (PHS) power plants have demonstrated themselves as the most sustainable and efficient form of large-scale energy storage. They play a key role in balancing supply and demand, providing grid stability, and facilitating the integration of increasing shares of RE, thereby contributing significantly to a clean and sustainable energy future.

In the Indian context, PHS technology is poised to be a vital component of the country's energy infrastructure. Recognizing its importance, India has already commenced the construction of several large-scale pumped storage power stations. These projects are expected to not only support the growing renewable installations but also enhance the overall resilience of the power grid, ensuring that the nation can meet future energy demands reliably while advancing towards its climate and sustainability goals.

7.2.1. Need for PHS

PHS plays a crucial role in supporting grid operations by providing a range of valuable services. It enables peak load shaving by storing excess energy during low-demand periods and releasing it during peak demand, helping to balance supply and demand efficiently. PHS facilitates energy arbitrage, allowing operators to buy electricity at lower prices, store it, and then supply power when prices are higher, thereby optimizing economic returns. Additionally, PHS offers load following capabilities, adjusting its output to match real-time fluctuations in grid demand and maintaining system stability. It provides round-the-clock grid support, ensuring continuous power availability and enhancing overall reliability. Moreover, PHES smooths out the intermittent and variable output from renewable energy sources, such as solar and wind, by absorbing excess generation and supplying power when renewable output dips. Beyond these functions, PHES contributes to various ancillary services, including frequency regulation, voltage control, and spinning reserves, all of which are essential for maintaining the stability and resilience of the power grid. The below illustration offers an insight into the different roles that PHS can play in offering grid support to the Indian grid.

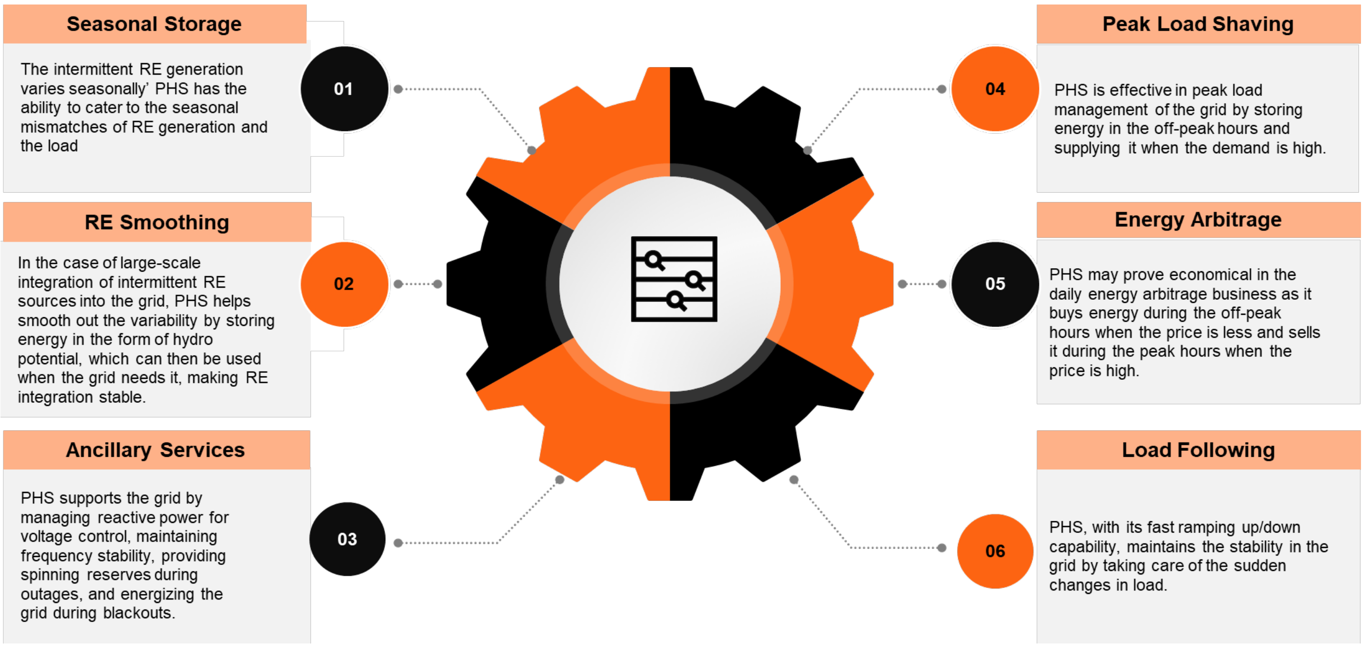


Figure 26: Use-cases of PHS

7.2.2. Operational Structure of PHS

PHS functions both as an electricity generator and as an energy storage system by converting electrical energy into the potential energy of water. It consists of two water reservoirs situated at different elevations, connected by a penstock—a water conduit—with a reversible turbine positioned between them. During power generation, water flows from the upper reservoir down through the penstock and turbine, producing electricity as it moves to the lower reservoir. To store energy, excess electricity from the grid is used to pump water back up to the upper reservoir, thereby storing energy in the form of gravitational potential for future use.

The energy storage capacity of a PHS system depends on the size and elevation difference between the two reservoirs, while the power output is determined by the turbine size. Using reversible turbines, these plants switch between pumping water uphill and generating power as needed.

There are two types of pumped storage hydropower systems: open-loop pumped storage and closed-loop pumped storage. These categories are based on whether the system has a continuous connection to a natural water source. Each type, open-loop and closed-loop, plays a key role in energy storage and grid stability, with different designs suited for various environmental and operational conditions. PHS plants are classified into on-stream and off-stream systems, which can be either open-loop or closed-loop. Open-loop (or on-river) PHS link a reservoir with a natural flowing water body through a tunnel, utilizing a turbine/pump and generator/motor setup to transfer water and produce electricity. Closed-loop (off-river) PHS connects two reservoirs without flowing water features via a tunnel, using a turbine/pump and generator/motor to move water and generate electricity.

A comparison between the open-loop and closed-loop control system for PHS is depicted in the table below.

Table 13: Comparative analysis between open-loop and closed-loop PHS

Feature	Open-loop	Closed-loop
Water source	Continuous connection to a natural water source	No connection to external water bodies
Reservoir connection	Either upper or lower reservoir connected to flowing water	Both reservoirs isolated, water cycles only between them
Natural inflow contribution	More than 5% of water volume passing through turbines annually	Less than 5% of water volume passing through turbines annually
Environmental impact	Potential impact on natural water ecosystems	Reduced ecological disruption due to isolated system
Water quality concerns	Possible mixing with natural water affecting quality	Better control over water quality within closed system
Site selection flexibility	Limited by proximity to natural water bodies	More flexible; can be sited where natural water sources aren't available
Operational flexibility	Can be more complex due to variable natural inflow	Generally simpler operation with controlled water volumes
Dependence on seasonal variation	More affected by seasonal water availability	Less affected by seasonal changes, offering consistent operation

As the world shifts toward cleaner energy, PSH offers multiple benefits that enhance grid stability, reduce emissions, and provide cost-effective long-duration storage on a large scale. The details of flexibility capabilities of typical thermal and PHS plants are shown in the table below.

Table 14: Flexibility comparison between PHS and thermal plants

Parameter	PHS	Hydro	Open-cycle gas turbine	Combined-cycle gas turbine	Coal-fired plant
Start-up time (cold start)	75-120 sec	0-5 min	5-10 min	120-240 min	300-600 min
Minimum load (% of Power Output)	35-45%	35-45%	40-50%	40-50%	25-40%
Average ramp rate (% of Power Output/min)	80-100%	80-100%	8-12%	2-4%	1-4%

Source: TERI

7.2.3. PHS Scenario in India

With an estimated on-river potential of about 103 GW of PHS and an overall identified PHS potential of 176.2 GW[44], India has huge potential for developing PHS projects. According to the latest CEA report as of July 2025, there are currently 74 PHS projects in various stages of development across India, with a combined installed capacity of 92.51 GW. Of these 17 are on-river with a total installed capacity of about 12.75 GW, and 57 are off-river sites, accounting for about 79.77 GW[45]. In total, there 10 PHS projects which are currently operational, out of which 2 are not working in pumping mode. The below table shows the status of PHS projects in India.

Table 15: Current status of PHS projects in Inia as on 31st July 2025

Status	On-river		Off-river		Total	
	No. of schemes	Installed capacity (MW)	No. of schemes	Installed capacity (MW)	No. of schemes	Installed capacity (MW)
In operation	7	3,805.6	1	1,200	8	5,005.6
Not working in pumping mode	2	1,440	-	-	2	1,440
Under construction	4	4,350	7	8,000	11	12,350
Under examination	1	640	1	1,800	2	2,440
Concurred by CEA	1	1,000	2	2,280	3	3,280
Under survey and investigation	2	1,500	46	66,490	48	67,990
Total	**17**	**12,735.60**	**57**	**79,770**	**74**	**92,505.60**

7.2.4. Existing PHS Technologies

Fixed Speed PHS

Most of the currently operational PHS employ traditional fixed-speed (or single-speed) technology. They utilize a motor-generator known as a synchronous machine that operates in synchronization with the grid frequency. While synchronous machines are typically used solely as generators in other technologies, in PHS systems, they function as both motors and generators. During pumping mode, the synchronous machine acts as a motor, consuming power from the grid to pump water into the upper reservoir. When water is released from the upper reservoir, the machine reverses its rotation and operates as a generator, supplying power back to the grid.

A fixed-speed PHS unit equipped with a reversible pump-turbine can vary the power output during generating mode, but when pumping at a specific head, it consistently consumes the same amount of power from the grid. While fixed-speed PHS units can provide regulation and spinning reserve services to the grid during generation, they cannot offer regulation services while pumping because their pumping power cannot be adjusted. Nonetheless, by completely stopping pumping—which effectively adds an equivalent amount of generating capacity to the power system—they can still provide spinning reserve services.

Variable Speed PHS

Variable speed PHS technology was first introduced at Japan's Yagisawa facility in the early 1990s using semiconductor-based power converters to increase nighttime grid flexibility. Since demand is lower at night but baseload generation continues, variable speed PHS help by pumping more during low demand, allowing baseload plants to run steadily. Unlike fixed-speed units, they can adjust pumping power and provide regulation services while pumping. This flexibility makes them valuable for grids dominated by

[44] PIB Press Release
[45] https://cea.nic.in/wp-content/uploads/hpi/2025/07/Status_of_development_of_PSPs.pdf

baseload or high renewable penetration. Consequently, adjustable-speed PHS have been built in Japan, Europe, and elsewhere. Today, new PHS developments also focus on providing ancillary services alongside energy and capacity markets. The latest fixed-speed PHS feature faster response times and broader operating ranges, making them highly flexible in generating mode. However, adjustable-speed PHS offer key operational advantages, including:

- Ability to regulate pumping power by varying consumption, typically operating between 70% and 100% of rated capacity.
- Improved generating efficiency at partial loads by adjusting rotor speed to match head and flow.
- Reduced or eliminated rough zones due to flexible rotor speed adjustment.
- Wider operating range with minimum loads as low as 20–30% of rated capacity.
- Less wear and tear from running near optimal speeds, leading to longer equipment life.
- Enhanced voltage support via decoupled active and reactive power through frequency converters.
- Faster, more dynamic response to grid disturbances, boosting system reliability and reducing frequency drops.

However, since adjustable-speed units need more power electronics and other equipment, the cost is significantly more than fixed-speed units of the same size.

Ternary PHS

Ternary technology consists of three separate components: a motor-generator, a turbine, and a pump. This setup was standard before the invention of the reversible pump-turbine. Modern ternary systems often include “hydraulic short circuit” capabilities, providing greater operational flexibility. A clutch allows the pump and turbine to be mechanically separated, but when engaged, both operate simultaneously, rotating in the same direction. This simultaneous operation in hydraulic short-circuit mode enhances flexibility, as the pump and turbine, sharing the same shaft, don’t need to stop or reverse direction when switching between pumping and generating. Depending on site conditions, ternary units may use Francis turbines or other types instead of the more common Pelton turbines.

The below table shows a comparison of the existing PHS technologies[46].

Table 16: Comparison between different PHS technologies

Parameters	Fixed speed	Variable speed	Ternary
	Pumping mode		
Power consumption (% of rated capacity)	100%	60-100%	60-100%
Standstill to pumping mode (seconds)	160-340	160-230	80
Pumping to generation mode (seconds)	90-190	90-190	25
Frequency regulation	No	Yes	Yes
Spinning reserve	No	Yes	Yes
Ramping/load following	No	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Load shedding	Yes	Yes	Yes
	Generating mode		
Power output (% of rated capacity)	30-100%	20-100%	0-100%
Standstill to generating mode (seconds)	70	75-85	65
Generating to pumping mode (seconds)	240-420	240-415	25

[46] https://publications.anl.gov/anlpubs/2022/05/175341.pdf

Frequency regulation	Yes	Yes	Yes
Spinning reserve	Yes	Yes	Yes
Ramping/load following	Yes	Yes	Yes
Reactive power/voltage support	Yes	Yes	Yes
Generator dropping	Yes	Yes	Yes

7.2.5. Policy framework and government initiatives

Over the years, the Indian Government has introduced several policy measures to promote the growth of the hydropower sector, including the National Electricity Policy 2005, Tariff Policy 2016, National Rehabilitation & Resettlement Policy 2007, and the Right to Fair Compensation & Transparency in Land Acquisition, Rehabilitation and Resettlement Act 2013. The following are key initiatives undertaken to accelerate development and enhance infrastructure in the hydropower sector.

MoP guidelines for PHS projects

In April 2023, the Ministry of Power (MoP) released guidelines for PHS projects[47], recognizing their vital role in grid stabilization and meeting peak power demands. The guidelines offer recommendations on the PHS market, policies, and safe development practices. Key aspects include monetizing ancillary PHS services to address critical electricity market needs, reimbursing State GST taxes, waiving land acquisition fees for off-river PSPs, eliminating upfront premiums for project allocation, and identifying exhausted mines as potential safe sites for future PSP development.

National hydropower policy

In December 2024, the MoP internally circulated the draft National Hydro Power Policy 2024. This policy covers all large hydropower projects, including those with capacities over 25 MW and PHS. It highlights the vital role of hydropower in fulfilling the country's energy needs, maintaining grid stability, and advancing regional development goals. Additionally, the policy stresses the importance of assessing project viability by taking into account the various value attributes linked to hydropower.

ISTS charges waiver

In May 2023, a waiver of ISTS charges was granted, among other benefits, to PHS projects whose construction contracts are awarded by June 30, 2025, subject to certain conditions. Following this, a phased partial waiver of ISTS charges—reducing by 25% increments—has been extended from July 1, 2025, to July 1, 2028, for PHS with construction contracts awarded by June 30, 2028.

Guidelines for procurement of storage capacity from PHS

On August 22, 2024, the MoP released draft guidelines for procuring storage capacity and stored energy from PHS through competitive bidding. These guidelines seek to facilitate PHS development and establish a transparent framework for their integration into the national power grid, while also promoting risk-sharing among the stakeholders involved.

The draft outlines a single-stage, two-part bidding process for procuring storage capacity from PHS projects, comprising technical and financial evaluation stages. For on-river PHS, operations are required to commence within 66 months of signing the power purchase agreement (PPA), while off-river PHS must be completed within 48 months. Developers may begin operations early with a 15-day notice, and the initial phase of partial commissioning must achieve at least 50% of the total project capacity or 50 MW, whichever is less. According to the draft, the government proposes two methods for procuring storage capacity from PHS. The first involves PHS located at government-designated sites, where the procurer can select a project site listed in the bidding documents. If the site is owned by the government or a government entity, the project will be developed under a build-own-operate-transfer (BOOT) model for 25 to 40 years. The

[47] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2023/08/20230828720675911.pdf

second method allows bidders to provide storage capacity from PHS developed on self-identified sites or from existing commissioned PHS, with projects operating on a finance-own-operate basis for 15 to 25 years.

Guidelines for formulation of DPRs

In March 2023, the CEA released updated guidelines for the preparation and approval of DPRs for PHS[48]. These guidelines shorten the approval timeline from 90 days to 50 days for PSPs awarded under Section 63 of the Electricity Act, 2003 (where tariffs are determined through bidding). The guidelines also apply to PHS integrated with renewable energy projects such as wind and solar, as well as those developed as captive or merchant plants. In June 2023, the timeline for the approval of DPRs for other PHS were reduced from 125 days to 90 days to expedite the process.

Policy thrust on CPSUs

With robust project management expertise, extensive experience in large-scale project development, and access to competitive capital costs, CPSUs are well-positioned to lead the development of hydropower projects, including pumped storage schemes. In line with this, the Ministry of Power (MoP) has identified project sites totalling 73 GW in capacity and allocated them to CPSUs to accelerate capacity rollout.

7.2.6. Challenges faced by PHS in India

The key issues and challenges faced by PHS projects in India are multifaceted and include technical, environmental, financial, and regulatory aspects. These challenges affect the planning, development, and operation phases of PHS projects and must be addressed to fully harness the potential of this technology to support India’s growing and increasingly renewable-based power system. Some of the key challenges are highlighted below.

Timeline and cost overruns

The development timeline for PHS projects—from securing clearances and approvals to construction and commissioning—is a significant barrier to the timely completion of plants. Delays in obtaining these necessary approvals and clearances often lead to major cost overruns beyond the original project budget.

Long process of approvals, permits and clearances

Large PHS projects must undergo an extensive approval, permitting, and clearance process involving central and state governments as well as other authorities. The development of PHS facilities can take several years to complete. In India, this permitting and licensing process for new PHS projects typically spans 3 to 6 years, depending on the project's geographic location, making it considerably longer than the timelines for most other energy storage technologies.

Land acquisition issues

Land acquisition poses a significant challenge for PHS construction in India. The process often involves lengthy negotiations with local governments and communities, which can lead to delays and conflicts. Key issues include the absence of a clear legal framework for land acquisition, resistance from affected communities due to displacement and loss of livelihoods, and difficulties in obtaining the required permits and approvals from government bodies. Additionally, the high costs associated with land acquisition and compensation can increase the overall project expenses, potentially rendering the project unprofitable.

Geological issues

[48] https://cea.nic.in/wp-content/uploads/hpa/2024/07/Guidelines_for_Formulation_of_Detailed_Project_Reports_for_Pumped_Storage_Schemes_July_2024_version_3.0.pdf

Geological uncertainties present significant challenges for pumped hydro storage projects in India. Unexpected geohazards—such as landslides, earthquakes, unstable rock formations, poor soil quality, water scarcity, altered water flow patterns, erosion, and impacts on local ecosystems—can all disrupt construction and operation. A recent example is the crisis in Joshimath, Uttarakhand, where land subsidence, possibly triggered by hydro power projects and other development activities, has made the area vulnerable to landslides, earthquakes, and erosion. The underlying cause of this land subsidence is still under investigation.

Rehabilitation and resettlement issues

Rehabilitation and Resettlement (R&R) concerns are crucial while building PHS in India. These project' development may result in the uprooting of local people and the loss of their means of subsistence, which may cause social and economic disruptions as well as resistance and opposition from the impacted communities. Inadequate compensation, lack of job prospects post rehabilitation, and the loss of cultural and natural legacy are few of the major R&R concerns.

Capital investments

Most PSPs are large-scale projects, with capacities spanning from several hundred to over a thousand megawatts. Such projects require significant financial investment and often involve collaboration among multiple owners or off-takers. The high upfront capital expenditure (CAPEX) lengthens the payback period, increases development risks, and complicates financing arrangements. Consequently, many developers—including utilities and independent power producers (IPPs)—as well as financial institutions tend to be risk-averse, favouring projects with lower investment demands and faster returns.

Environmental issues

Many PHS projects worldwide, especially open-loop systems that involve building dams on rivers or lakes and impacting aquatic and other ecosystems, have faced public opposition. Unlike open-loop systems, closed-loop PHS use primarily artificial reservoirs, avoid damming natural water bodies, and have no direct connection to rivers or lakes. These man-made reservoirs, often created anew or repurposed from abandoned mines or brownfield sites, typically lack fish and aquatic life, minimizing their impact on local ecosystems. As a result, environmental groups have become more receptive to developing new closed-loop PHS projects.

7.2.7. Recommendations

Promote closed-loop PHS

Most cost overruns in PHS projects result from delays in obtaining environmental and forest clearances. These approvals take considerable time due to the sensitive nature of environmental concerns, as previously mentioned. To address this, promoting closed-loop PHS is advisable, given their reduced impact on forests, the environment, and rehabilitation and resettlement requirements.

Timely execution of projects and tender timelines

The commissioning timeline of PHS projects is crucial for meeting the ambitious targets set by the Government of India. Recent tenders for stationary storage, aimed at assured peak power or Round-the-Clock (RTC) supply, have commissioning deadlines of 18 to 24 months. However, many PHS projects are either under construction or still in the survey and investigation phase, with full operation expected to take 4 to 5 years. Such delays in commissioning risk undermining the objectives of these tenders and may prevent achieving the desired outcomes. Future tenders should take these timelines into account to ensure the targets are met.

Conduct techno-commercial assessment

Given the key factors involved in evaluating PHS projects and the lengthy timelines needed for execution, it is important to set realistic targets. PHS development demands substantial investment, and as noted earlier, many projects experience significant cost overruns due to reasons such as prolonged environmental and forest clearance processes, challenging geology, and local opposition. Therefore, a thorough techno-commercial assessment with full due diligence is essential to minimize the risk of cost overruns.

Considerations of technological advancements of future projects

PHS can be used for varied range of application such as peak shaving, ancillary service application, black start reserve, etc. Considering the huge potential in India and with the technological advancement, PHS can be developed for small capacity (1-10 MW or 200 MW) which will have lesser execution timelines and can play important role in supporting energy storage applications which will suffice the intended requirements.

7.3. Offshore Wind

Wind energy is a vital component of India's renewable energy sector, with the country being a global leader in onshore wind power generation. India boasts abundant wind resources, particularly in the states of Gujarat, Maharashtra, Karnataka, Rajasthan, and Tamil Nadu. With over three decades of experience, India has demonstrated significant expertise in utilizing wind technology for power generation. The nation currently has an installed onshore wind capacity of nearly 52 GW[49], ranking it as the fourth-largest wind energy market worldwide. Despite this impressive growth, the onshore wind sector faces challenges such as land availability, grid integration, and intermittency.

With a coastline of approximately 7,600 km and water on three sides, holds significant potential for offshore wind energy. Recognizing this, the Government of India notified the National Offshore Wind Energy Policy in 2015[50]. According to the policy, the MNRE serves as the nodal ministry responsible for the development of offshore wind energy in India, coordinating closely with other government agencies to manage maritime space within the country's Exclusive Economic Zone (EEZ) and oversee the overall progress of offshore wind projects. The National Institute of Wind Energy (NIWE) in Chennai is to act as the nodal agency for resource assessment, surveys, and studies within the EEZ, block demarcation, and facilitating developers in establishing offshore wind farms.

NIWE has estimated offshore wind energy potential in Gujarat (36 GW) and Tamil Nadu (35 GW), totaling 71 GW in these two states. No capacity has been deployed in India to date although numerous studies and research activities have been conducted to develop the offshore wind sector.

7.3.1. Key Developments in the offshore wind sector in India

Since the first National Offshore Wind Energy Policy was published in 2015, the Government of India has subsequently published various reports to support the sector and attract investor interest. MNRE notified a strategy paper dated August 2023, titled "Strategy for Establishment of Offshore Wind Energy Projects"[51] that proposed a target to auction 37 GW by 2030 for a holistic development of offshore wind in the country. The strategy paper proposed three models to fast track the process and ensure a comprehensive growth of the offshore wind industry as discussed in the table below.

Model A	This model would be applicable to those demarcated offshore wind zones, where MNRE/NIWE has conducted or plans to conduct detailed studies. Central financial assistance in the form of Viability Gap funding (VGF) would be provided to achieve a predetermined power tariff.

[49] https://mnre.gov.in/en/physical-progress/
[50] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2024/12/202412201344723115.pdf
[51] https://mnre.gov.in/en/document/strategy-paper-for-establishment-of-offshore-wind-energy-projects/ last accessed on 30th May 2025

Model B	This model would be applicable for the sites identified by NIWE which focuses on offshore wind project development for sale of power under open access, captive use, third party sale, bilateral power purchase agreement or through power exchanges without any financial assistance from the government. Allocation of offshore wind sites under a lease with site exclusivity over seabed during the survey period would be provided to the developers.
Model C	This model would be applicable for the sites identified by the developers within the EEZ, excluding those sites identified under Model A and B. Allocation of offshore wind sites would be provided for carrying out the surveys without exclusivity over seabed without any VGF support. Under this model, offshore wind developers may select any site(s) within the country's Exclusive Economic Zone (EEZ), excluding those already designated under Model-A and Model-B. Developers must submit a proposal for conducting wind power assessment studies or surveys to the NIWE, in accordance with the relevant guidelines. Further, multiple developers may carry out studies or surveys at the same site, with a maximum duration of three years. Additionally, developers are prohibited from sharing the collected data with any third party, except for their own affiliates, subsidiaries, or parent/holding companies.

Further, GoI also introduced the Offshore Wind Energy Lease Rules in 2023 to regulate the leasing of offshore areas for streamlining the allocation process.[52] In addition, a Viability Gap Funding (VGF) scheme was approved in September 2024, with a total outlay of INR 7,453 crore for the initial 1 GW of offshore wind capacity—500 MW each for Gujarat and Tamil Nadu.[53]

Additionally, Solar Energy Corporation of India (SECI) issued a tender for 500 MW ISTS connected offshore wind project in Gujarat dated 17th March 2025[54] and a request for selection for allocation of sea-bed lease rights for 4 GW offshore wind capacity in Tamil Nadu dated 2nd February 2024[55] to mark a significant milestone in the sector.

[52] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2023/12/202312208216880.pdf last accessed on 30th May 2025
[53] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2024/09/20240912108998 7626.pdf last accessed on 30th May 2025
[54] https://www.seci.co.in/tender-details/ZjkwZTQxMGVhNjczOGQxMTc5N2Q1YjRhNmU1YjY0YTk3YzY4NjI2ZDkxOWVhZTI0N2IwN2I0NGU0ZDEyMWU3NGQ0NTgzN2EwZmIwZmJhZWViMDA3NDBmNWYyMWE0M2Q4NzhlOWRhZGI4NGMwODYzMWIyMjU2ZDQzZTQyOTMyMWFRYVJvaTg5cG9tdFNUWThvSWg2MFB5R1NVZnA2ejl3VnRrZ0JvZUJjR1VnPQ, last accessed on 30th May 2025
[55] https://www.seci.co.in/tender-details/ODI0ZDgwNWEwOWY0YWU2MWU2NTg1NzA5ZTRmMWIzYTM0ZmVlZmMzNDRmMTYzOTdhZDQwNTI4ZTc3NmNiMTIyNDVjZmJmMmZiMzJmZGEwYzk5NzdiOTZjZDk2YzUzOWNlNmIyODE2YjNkODUzMDNjYmM5ZjI4YzYzMTgyN2QxMTRDVlEwYXVzanEvUzNzNzJzZ2VoMGlEdUdUMnFrMXE5bDZJVG5RQ3Jkc2RjPQ last accessed on 30th May 2025

The key recent advancements in India's offshore wind sector are illustrated in the figure below.

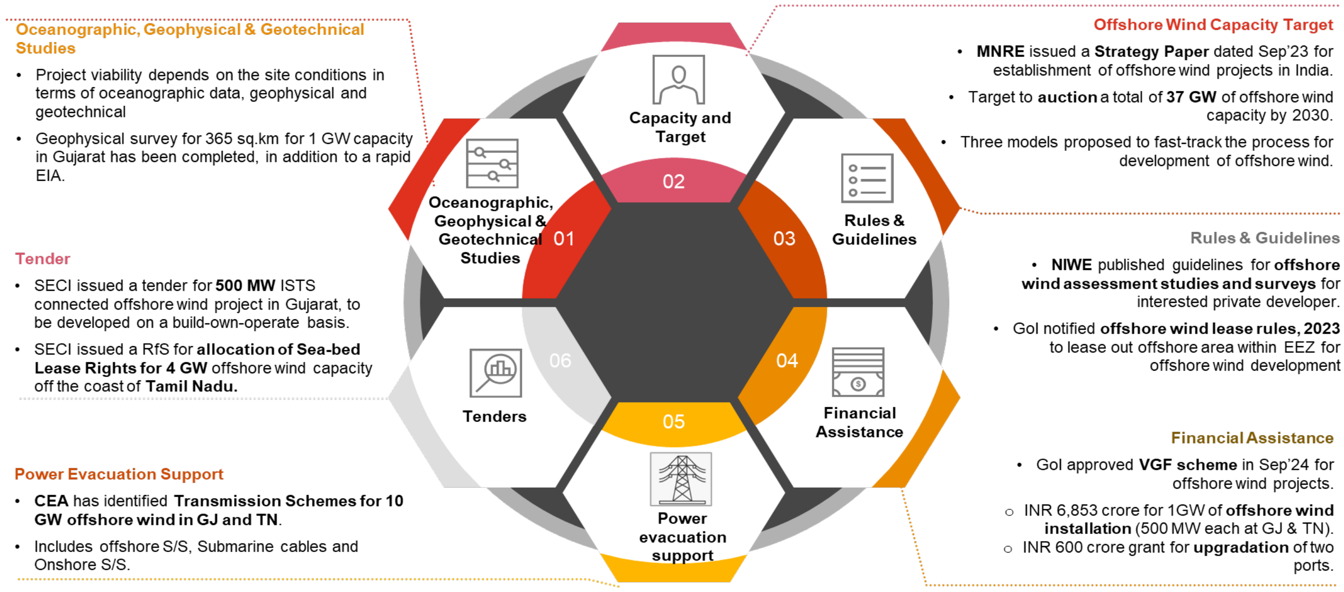


Figure 27: Recent development of offshore wind sector in India

Apart from various policy and regulatory developments, various studies and assessments have also been undertaken to support the development of the offshore wind sector in India. Some of the key activities completed so far include, but are not limited to, the following:

- Pre-feasibility and feasibility assessments for development of offshore wind in Gujarat and Tamil Nadu
- Maritime Spatial Planning for offshore wind farms in Gujarat
- Financial Modelling of Offshore wind in India
- Offshore wind infrastructure study for India
- Supply chain study for offshore wind in India
- Supply chain, port infrastructure and logistics study
- Tamil Nadu Offshore Wind Manufacturing Supply Chain Investment Study
- Grid integration study for offshore wind development in Gujarat

Recently, in August 2025, SECI cancelled the two major offshore wind tenders because of severe lack of developer interest, despite the government offering VGF and extending the bid deadlines multiple times. These cancellations are attributed to the high costs and technical complexities of offshore wind in India's price-sensitive market, where solar power is significantly cheaper. The move has dashed hopes for India's first large-scale offshore wind projects to be operational before 2030.

7.3.2. Offshore Wind Supply Chain Analysis

Building an offshore wind farm is a major endeavour and the supply chain required to deliver the material and workforce for such task is immense. The procurement list for an offshore wind farm is extensive, making use of both, elements from the onshore and the marine industry. It applies highly specialized technologies like underwater high voltage cablings, as well as simpler engineering elements such as concrete structures and steel frames. The supply chain contains components for the wind turbine itself like the generator, control systems, blades or main bearings to items for marine foundations like scour protection, navigation lights, marine coatings or vessel docking interfaces as well as electrical equipment for high and low voltage application. The development of such a vast local supply chain is a long-term effort and will occur simultaneously with skill building, and knowledge transfer over many years.

This section explores the key elements and components required for developing a future offshore industry in India. The current market state-of-play is described along with expected upcoming developments. While project development tasks and survey activities are paramount for establishing a robust wind farm design and realizing a low LCOE, development costs account for only around 2% of the total project costs. Hence, capturing most of the project value in India relies on capturing other aspects of the project, e.g., manufacturing and installation. Developing the Indian supply chain must therefore consider the breakdown of capital costs such as wind turbine, foundations, electrical infrastructure and installation vessels and ports.

Wind Turbine

Early offshore wind projects used onshore turbines adapted for marine conditions. However, the industry has since evolved into a distinct sector with rapidly advancing technologies. Modern offshore turbines are specifically designed to withstand harsh marine environments, including strong waves, salt corrosion, and typhoons. Built for reliability over 25+ years, new maintenance approaches aim to reduce costs and enhance durability. In recent years, offshore turbines have grown significantly in size, and this trend is expected to continue. Due to higher initial costs and recent market consolidation, the number of offshore turbine OEMs is much smaller than for onshore turbines. Currently, three major Western companies dominate the global market: MHI-Vestas, SiemensGamesa , and GE Renewable Energy. In China, four key suppliers—Goldwind, SEwind, MingYang, and Envision—control over 90% of the offshore market.

While none of the aforementioned offshore wind turbines have yet been manufactured or installed in India, the country has already built a strong production market for onshore wind turbines with almost 90% of the supply chain being available in the country. However, while the production for onshore wind turbines is already well established in the country, it is not straight forward to apply these manufacturing facilities for offshore purposes.

Most of the current onshore wind turbine manufacturing facilities are inland and only a few located closer to the sea, the development of offshore WTG, blade and nacelle manufacturing in India will most likely require the establishment of new coastal facilities specially close to the waterfront, as the large components can hardly be transported overland from a cost and logistical point of view. While OEMs are fully in charge of design, the actual supply and assembly of the whole wind turbine is done by numerous sub-suppliers who integrate the different components locally into a complete system.

A further challenge for the advent of the Indian offshore turbine supply is the fact that current generation offshore WTGs are designed for high average, high extreme wind speed regimes. However, India presents wind regimes with low average winds coupled with high extreme wind speeds. The combination of general operation during low average winds coupled with a design capable of withstanding harsh extreme events is not a product that exists in the market yet and is only slowly in developing markets such as Japan. Developing such low wind speed offshore wind turbines, which can also withstand typhoons will be connected with higher initial prices and investment in technology R&D.

Offshore foundations

Offshore wind turbines have traditionally been installed on fixed seabed foundations. Recently, floating foundations have emerged, but this technology is still in early development, with only a few pilot projects worldwide. Among fixed foundations, three main types are common: gravity-based concrete foundations for shallow waters, steel monopiles for depths of 20-50 meters, and steel jackets for deeper sites up to 60 meters. Due to their lower cost, simple design, and favourable seabed conditions, most European offshore wind projects use steel monopiles, followed by gravity-based foundations. Jackets account for a smaller share but are gaining interest as projects move to deeper waters and larger turbines. Foundation choice depends on site conditions—such as water depth, seabed type, and wave loads—as well as turbine size and local fabrication and installation capabilities.

Electrical infrastructure

Besides foundations, a key component of offshore wind projects is the electrical infrastructure that transmits power from turbines to the onshore grid. Individual turbines are linked by medium-voltage subsea cables called inner array cabling, which connect to a local offshore substation. Here, the power is stepped up to high voltage and sent to shore via high-voltage export cables. The electrical design depends largely on the distance from shore and the wind farm's size. For distances over 80-100 km or centralized power hubs (power islands), high voltage direct current (HVDC) systems are an option, offering reduced electrical losses but requiring significant investment and a lengthy 5 to 7 year lead time. So far, only a few German sites have implemented HVDC, while in India, shorter-range HVAC cable systems are the more likely near-term solution.

Installation vessels and ports

The installation of a wind farm requires a wide variety of vessels, each of them with a specific design and purpose. Broadly speaking, the technical design can be split into the following vessel types: heavy-lift vessels combined with working barges, jack-up barges without propulsion and self-propelled jack-up vessels. From the point of view of construction, these vessels serve the purpose of installing the turbine foundations, subsequently the turbines, the inner array cabling and export cabling and the offshore substation. After completion of construction and commissioning, further vessels are involved, which help with the operation and maintenance of the offshore wind farm. The ports involved in the construction need to comply with specific requirements in order to accommodate the type of vessels.

7.3.3. Challenges faced by the offshore wind sector in India

India is still in the early stages of developing the offshore wind sector and faces numerous challenges that need to be addressed. The key challenges faced by the offshore wind sector currently in India have been listed below.

Infrastructure development

Infrastructure development is a major challenge for India's offshore wind sector due to the complexity of building and maintaining transmission lines, offshore substations, and maintenance facilities in harsh marine environments. Specialized equipment, skilled labour, and significant investment are needed to navigate difficult ocean conditions and ensure reliable operations. Limited domestic experience, supply chain gaps, and inadequate coastal infrastructure further increase costs and project timelines. Effective coordination among stakeholders and supportive policies are essential to overcome these hurdles and enable the sector's growth.

Economic feasibility

Offshore wind projects incur about 80% more capital costs than an onshore wind project affecting the profitability and payback period for investors. Government incentives like VGF, subsidies and tax credits play a key role in improving financial viability. Financing conditions and project planning, including site selection, also impact profitability.

Lack of demonstration projects

The absence of demonstration projects in offshore wind slows the validation and showcase of new technologies, making stakeholders hesitant to adopt innovations. Without proven models, developers and investors face increased uncertainties regarding performance, costs, and environmental impacts. This hesitancy can delay the scaling of offshore wind deployment and limit experience gained in local conditions. Higher perceived risks may also lead to increased financing costs and reduced investor confidence. Consequently, the lack of demonstration projects impedes technology advancement and the overall growth of the offshore wind sector.

Higher levelized cost of electricity

A higher Levelized Cost of Energy (LCOE) in offshore wind leads to increased electricity costs for consumers and utilities, making it less competitive compared to other energy sources. Elevated LCOE often arises from higher capital expenses, complex installation processes, and maintenance challenges in harsh marine environments. When offshore wind electricity is more expensive, it may struggle to secure power purchase agreements or government support. This reduced competitiveness can limit investment and slow the sector's growth. Addressing factors that drive up LCOE is essential to making offshore wind a viable and attractive energy solution.

Lack of implementation support

The absence of a single window clearance system for offshore wind projects results in developers having to navigate multiple regulatory agencies and approval processes separately. This fragmented approach leads to prolonged delays in obtaining necessary permits and clearances, slowing down project timelines. Extended approval processes increase administrative and financial burdens, contributing to higher project costs. Delays can also affect investor confidence and disrupt project financing arrangements.

7.3.4. Recommendations

The offshore wind sector in India holds immense potential to contribute significantly to the country's renewable energy goals and energy security. However, several challenges related to policy, infrastructure, technology, and financing need to be addressed to unlock this potential effectively. The following recommendations outline strategic actions aimed at overcoming these barriers, fostering a conducive environment for sustainable growth, and positioning India as a competitive player in the global offshore wind market. By implementing these measures, India can accelerate the development of its offshore wind industry and maximize its benefits for the economy and the environment.

Focus on Model A to lower capital costs for developers

India should consider adopting Model-A incentives for offshore wind development, similar to successful approaches in the Netherlands and Denmark, rather than pursuing Model-B. In Denmark, offshore wind projects benefit from subsidies through a Contract for Difference (CfD) mechanism, which guarantees a fixed price per kilowatt-hour for a specified number of full-load hours, typically over a period of 11 to 12 years. This model provides revenue stability and reduces investment risk, encouraging greater private sector participation. By securing predictable returns, developers can more confidently plan and finance offshore wind projects. Emulating this approach could accelerate India's offshore wind deployment by attracting more investment and fostering long-term market confidence.

Prioritise investments in demonstration projects

Prioritizing investment in offshore wind demonstration projects is essential to accelerate technology adoption and build industry confidence in India. Examples like China's 102 MW Shanghai Donghai Bridge Offshore Farm and Denmark's 10 MW pilot initiatives have showcased the viability and benefits of offshore wind technology. These projects help identify technical challenges, validate new solutions, and provide valuable operational experience. Furthermore, early demonstration projects play a key role in reducing overall costs by driving innovation and creating supply chain efficiencies. By focusing on such pilot projects, India can establish a strong foundation for scaling its offshore wind sector sustainably and cost-effectively.

Single window clearance mechanism

Implementing a single-window clearance mechanism through the NIWE could significantly accelerate offshore wind energy development in India. This streamlined system would centralize all approvals and permits, reducing bureaucratic delays and eliminating the need to navigate multiple regulatory agencies separately. By simplifying the approval process, it would provide developers with greater clarity and predictability, encouraging investment and project initiation. Additionally, a single-window approach would facilitate better coordination among various government departments, ensuring faster resolution of issues. Overall, this mechanism could enhance efficiency, reduce costs, and support the timely deployment of offshore wind projects.

Publish a long-term vision for offshore wind

The MNRE should outline medium- and long-term visions for offshore wind development through 2070, positioning it as a key element of India's decarbonized energy mix alongside other renewable technologies. These plans would highlight the cost advantages and long-term contributions of offshore wind to the energy sector, emphasizing its critical role in achieving India's net-zero goals. The vision should focus on maximizing the value offshore wind brings to the energy system and identify the measures that both the government and industry need to implement to drive continuous cost reductions over time.

7.4. Small Modular Reactor

Nuclear power promises a viable solution for diversification of the clean energy portfolio. Apart from being one of the lowest greenhouse gas emitters in life-cycle analysis, nuclear power also has the ability to provide baseload power and contribute to a stable and resilient electrical grid by providing a constant energy source. Innovation in nuclear reactor technologies, both in Large Reactors (LRs) and in the newer concept of Small Modular Reactors (SMRs) will be important for nuclear to remain a competitive option and to give access to more countries to clean and plentiful energy. Cogeneration SMR systems not only meet electricity and process heat demands but also have the flexibility to complement variable RE sources. Their ability to be installed in remote, off-grid areas further enhances their utility. As a result, SMRs can play a vital role in facilitating an effective energy transition.

SMRs are designed so that their Systems, Structures, and Components (SSCs) are manufactured in controlled factory settings and then transported to the project site for installation, optimizing both time and cost. They offer deployment advantages such as a smaller Emergency Planning Zone (EPZ) and passive safety systems. SMRs can also be considered for repurposing decommissioned fossil-fuel power plants. While some SMR models require refuelling every three to seven years, others provide up to 30 years of operation without refuelling. Additional benefits include a smaller plant footprint, the ability to site SMRs in locations unsuitable for large reactors, and the flexibility to expand capacity by adding modules incrementally. Although the initial capital investment per reactor is lower than that of large reactors, the capital cost per MW may be higher initially but is expected to decrease as more units are built.

Currently, the SMR industry is in an evolution stage. India is taking steps to develop SMRs, with up to 300 MWe capacity, to fulfil its commitment to the clean energy transition. The government is exploring the options of collaborating with other countries and taking up indigenous development of SMRs. The provisions of the Atomic Energy Act of 1962 are being examined to allow the participation of the private sector and start-ups to promote SMR technology in the country. It is imperative to note here that technology sharing and availability of funding are the two crucial links for ensuring commercial availability of SMR technology.

7.4.1. SMR Technology and Types

SMRs are nuclear reactors with power outputs up to 300 MW, designed using modular technology that allows for factory fabrication of components, enabling economies of scale and shorter construction periods. The term "SMR" highlights their key features:

Small: SMRs are significantly smaller than traditional nuclear reactors, requiring much less land, which provides a competitive edge in site selection.

Modular: Their systems and components are manufactured in controlled factory settings and then transported to the site, making them more cost-effective compared to large reactors that often need site-specific customization.

Reactors: These devices use nuclear fission to produce heat, which is then converted into electricity.

Unlike large reactors, SMRs' modular design enables installation in remote or off-grid areas, offers faster construction timelines, and involves lower upfront capital costs, making nuclear energy more accessible and affordable. SMR designs can be categorized into 6 types based on the basic nuclear technology employed in the design.

Land based water-cooled SMRs

These include various water-cooled SMR designs based on Light Water Reactor (LWR) and Pressurized Heavy Water Reactor (PHWR) technologies, leveraging the proven technology used in most large reactors currently in operation. There are around 25 water-cooled SMR designs, encompassing integral PWRs, PHWRs, compact PWRs, loop-type PWRs, BWRs, and pool-type PWRs. The Central Argentina de Elementos Modulares (CAREM) is an integral PWR featuring natural coolant circulation, currently under construction in Argentina, with first criticality expected in 2026. China's ACP100, another integral PWR with design simplifications, began construction in 2021 and aims for commercial operation by 2026. Additional designs are underway for early deployment domestically or for export, including NuScale VOYGR and GEH BWRX-300 in the USA, Rolls-Royce SMR in the UK, and EDF's NUWARD in France. Meanwhile, a land-based SMR pilot project based on the RITM-200N design is progressing, with first criticality planned for 2027.

Marine based water-cooled SMRs

These include SMR designs for deployment in marine environment. This can be achieved in the form of floating units installed on barge or ships. Many flexible SMR deployment options are available in this category. Some marine based water-cooled SMR designs are deployed for nuclear ice-breaker ships. SMR KLT-40S which is deployed as floating SMR in Russia is from this sub-category and is the first SMR design connected to the grid. Floating small-scale NPPs based on RITM-200M and RITM-200S are under construction.

High temperature gas-cooled SMRs

SMRs in this category are capable of producing very high-temperature heat exceeding 750°C, enabling electricity generation at high efficiency levels. These reactors are also suitable for various industrial applications and cogeneration purposes. According to an IAEA publication, there are 14 SMRs utilizing High-Temperature Gas-Cooled Reactor (HTGR) technology, including China's HTR-PM, which was connected to the grid in December 2021. This group also includes three test reactors, two of which have been operational for over twenty years in Japan and China, respectively.

Liquid metal-cooled fast neutron spectrum SMRs

These include eight designs that adopt fast neutron technology and liquid metal coolants, including sodium, pure lead and lead-bismuth eutectic. Substantial progress has been made in technology development as well as deployment on these SMRs. Lead-cooled fast reactor BREST OD 300, which is under construction in Russia, has a target of 2026 as a demonstration project. SVBR-100 is an innovative lead-bismuth fast modular reactor for multi-purpose applications with natural safety features.

Molten salt reactor SMRs

This category encompasses 13 SMR designs classified as Generation IV (GEN IV) nuclear reactors. These designs offer several advantages, including inherent safety from the unique properties of molten salt, low coolant pressure that removes the need for large containment structures, high operating temperatures that improve power generation efficiency, and a flexible fuel cycle. Several MSR designs have begun preliminary licensing processes in countries such as Canada, Denmark, the Netherlands, the UK, and the USA.

Microreactors

This category includes 12 micro-reactor designs, featuring very small reactors that produce up to 10 MW. These microreactors utilize various coolant options such as light water, helium, molten salt, and liquid metal, with heat pipes also proposed as an alternative cooling method. Several designs are currently pursuing licensing in the USA and Canada. For instance, Global First Power (GFP) has submitted an initial site application to the Canadian Nuclear Safety Commission (CNSC) for a microreactor based on USNC's Micro Modular Reactor technology. Microreactors are well-suited for specialized applications such as powering microgrids and remote off-grid locations, rapidly restoring electricity in disaster-affected areas, and supporting seawater desalination.

7.4.2. Benefits of SMR Against Large Nuclear Reactors

The table below compares SMRs and Large Nuclear Power reactors with respect to underlying economics of scale approach adopted to drive down costs with a view to bring out technological benefits and challenges of SMRs.

Table 17: Comparison between large reactors and SMRs

Parameter	Large Reactors	SMRs
Mode of execution	Project mode with partial modularity	Product mode (completely modularized and standardized)
Benefits of learning curve	One unit can be built every 5-7 years on average	Modularization can help in increasing the number of units
Mobilization of workforce	Mobilization based on project life cycle, highly variable, tied with stages of construction and commissioning	Mobilization is permanent in factory. Skilled workforce for installation deployed for short duration on site
Supply chain management	Discrete and project based	Continuous ongoing commercial relationships for ecosystem of multiple SMR units
Engineering and component production	Very large size equipment	Standard components with high TRL in supply chains
Civil design	Large reactor size; Aspects of geology, geography and environment may lead to site specific variations in design	Developed as standard designs, with seismic isolation, use seismic design parameters for multiple possible sites
Manufacturing	Partly modularised, stickbuilt and large-scale on-site construction	Fully modularized, more than 90% of components are prefabricated in controlled factory environment and SMRs are assembled on site
Investment	Requires large scale national infrastructure investment and long gestation periods (on average 5 to 10 years) before realization of revenue generation streams	Requires relatively smaller investment per reactor; relatively short period to revenue generation (on average 5 years or lesser) with possibility to reduce this time by means of learning by doing and factory standardization
In-situ work component	Large projects often with large site specificity requiring project execution in design and build mode driven by project location. In-situ work component is higher in LRs	Potentially a very high degree of replicability due to streamlined quality control in factory environment and standardized on site assembly. In-situ work component is relatively lower in SMRs

7.4.3. Regulatory Framework for SMRs in India

India is targeting nuclear power capacity of 100 GW by 2047 with new nuclear plants to be planned across greenfield and brownfield sites and SMRs rolled out for off-grid locations in remote areas. The Union Budget 2025-26 outlined a significant push towards nuclear energy as part of India's long-term energy transition strategy, the government has set a bold target of achieving 100 GW of nuclear power capacity by 2047, establishing nuclear energy as a key component of the country's energy mix. This initiative supports the broader vision of Viksit Bharat by promoting energy security and reducing reliance on fossil fuels. To realize this objective, the government is implementing strategic policy measures and investing in infrastructure, with a strong focus on indigenous nuclear technology and fostering public-private partnerships. Acknowledging nuclear power as vital for energy security and sustainability, the government launched the Nuclear Energy Mission for Viksit Bharat. This mission focuses on strengthening domestic nuclear capabilities, encouraging private sector involvement, and speeding up the adoption of advanced nuclear technologies like SMRs.

Nuclear Energy Mission for Viksit Bharat

To facilitate the implementation of the Nuclear Energy Mission, amendments to the Atomic Energy Act and Civil Liability for Nuclear Damage Act will be taken up by the parliament. These amendments are expected to encourage private sector investments in nuclear power projects. These legislative reforms aim to foster a more favourable climate for investment and innovation within the nuclear sector. The mission supports India's goal of reaching 100 GW of nuclear energy capacity by 2047, a critical step toward lowering carbon emissions and addressing future energy needs. As of July 31, 2025, India's nuclear capacity stands at 8,780 MW.

Bharat Small Reactors

The government is vigorously advancing its nuclear energy sector by developing Bharat Small Reactors (BSRs) and fostering collaborations with the private sector. BSRs are 220 MW Pressurized Heavy Water Reactors (PHWRs) known for their proven safety and reliability. These reactors are being enhanced to reduce land requirements, making them ideal for installation near energy-intensive industries such as steel, aluminum, and metals. By serving as captive power plants, BSRs are expected to support industrial decarbonization efforts and contribute to lowering carbon emissions.

Under this initiative, private entities are expected to provide critical resources such as land, cooling water, and capital investment, while the Nuclear Power Corporation of India Limited (NPCIL) will be responsible for reactor design, quality assurance, as well as operation and maintenance—all within the existing regulatory framework. This collaborative model aligns with India's ambitious targets of achieving 500 GW of non-fossil fuel energy capacity by 2030 and securing 50% of the country's energy needs from renewable sources, as committed during the COP26 Summit in Glasgow in 2021. Beyond BSRs, the Bhabha Atomic Research Centre (BARC) is actively developing SMRs designed to repurpose retiring coal-fired power plants and to supply power to remote or off-grid areas. The Department of Atomic Energy (DAE) is also planning to introduce next-generation reactors, including high-temperature gas-cooled reactors for hydrogen co-generation and molten salt reactors that aim to harness India's vast thorium reserves.

This comprehensive strategy underscores India's commitment to reducing carbon emissions and strengthening its civilian nuclear energy program. The involvement of the private sector is poised to play a pivotal role in accelerating deployment and innovation, all while adhering to India's legal and regulatory frameworks.

Bharat SMRs

India is actively pursuing SMRs as a key component of its energy transition strategy, aiming to achieve net-zero emissions while maintaining energy security. SMRs are advanced nuclear reactors with power outputs ranging from under 30 MW to over 300 MW, offering a flexible, scalable, and cost-effective alternative to traditional large nuclear reactors. As India's energy demand grows and the need for reliable, low-carbon power intensifies, SMRs have the potential to play a transformative role by complementing RE sources and enhancing grid stability. Their modular, factory-based manufacturing approach shortens construction timelines and lowers costs, making SMRs well-suited for a variety of applications, including remote and off-grid locations.

Leveraging India's established expertise in Pressurized Heavy Water Reactor (PHWR) technology provides a solid foundation for the design and deployment of homegrown SMRs. Incorporating SMRs into the national energy portfolio can help address land availability challenges, reduce reliance on fossil fuels, and support India's commitment to the Paris Agreement, which the country ratified in October 2016. Through SMRs, India aims to build a resilient, sustainable energy system capable of meeting future demands while significantly lowering carbon emissions.

India is actively expanding its nuclear power capacity to address increasing energy demands and support its environmental objectives. The government has set an ambitious target to raise nuclear capacity from the current 8,180 MW to 22,480 MW by 2031-32. This growth plan involves constructing and commissioning ten new reactors totaling 8,000 MW across several states, including Gujarat, Rajasthan, Tamil Nadu, Haryana, Karnataka, and Madhya Pradesh. Additionally, pre-project activities are underway for another ten reactors, with a scheduled phased completion by 2031-32. Furthermore, the government has granted in-principle approval for the establishment of a 6 x 1,208 MW nuclear power plant in collaboration with the USA, located at Kovvada in Srikakulam district, Andhra Pradesh.

A landmark achievement occurred on September 19, 2024, when Unit-7 of the Rajasthan Atomic Power Project (RAPP-7), one of India's largest and the third fully indigenous nuclear reactors, reached criticality, initiating a controlled fission chain reaction. This milestone highlights India's growing proficiency in developing and operating homegrown nuclear technology, paving the way for greater energy self-reliance.

Safety is a fundamental pillar of India's nuclear energy policy. The country's nuclear power plants operate under strict safety regulations and are subject to international oversight. Radiation levels at Indian nuclear facilities consistently remain well below global safety standards, reflecting a strong commitment to secure, sustainable nuclear energy generation. These initiatives support India's broader goals of ensuring clean, reliable energy supply while advancing long-term energy security and environmental sustainability.

7.4.4. Challenges Faced by SMR in India

SMRs offer promising opportunities to enhance and grow nuclear power generation, but they also face several challenges. These include perceived investment risks, difficulties in securing financing, competition from lower-cost electricity sources, and regulatory and licensing hurdles. Additionally, public concerns about safety, supply chain limitations, limited operational experience, scarcity of suitable sites, issues related to nuclear waste management, and safeguarding requirements present further obstacles to their widespread adoption.

Technology choice

Currently, there are numerous SMR technology options available, each with distinct demands related to supply chains, regulatory compliance, operational procedures, and more. To enable large-scale commercial deployment of SMRs, it is essential to prioritize and select the most viable technologies. Many SMR designs still require advancements in their Technology Readiness Levels (TRLs) to gain acceptance and confidence from utilities, investors, and government stakeholders. Achieving this will necessitate extensive further research, along with the establishment and enhancement of experimental facilities to test and validate new technological innovations. Additionally, the development of sophisticated analytical tools is critical to support design optimization, safety assessments, and performance evaluation, thereby facilitating the transition of SMR technologies from the research phase to practical, widespread deployment.

Supply chain

Similar to large Light Water Reactors (LWRs), the competitiveness of SMRs heavily depends on a robust and efficient supply chain. Recent significant construction projects worldwide have contributed to the development of initial global supply chains for nuclear technologies. However, to fully realize the potential of SMRs and achieve cost-effectiveness, greater efforts are required to build resilient and well-integrated global supply chains that can handle the unique demands of SMR production and deployment. Furthermore, the SMR industry may benefit from supply chain consolidation, enabling the sector to harness economies of scale much like the aviation industry has successfully done. By streamlining suppliers and standardizing components, consolidation can reduce costs, improve quality, and enhance reliability, ultimately strengthening the overall competitiveness and scalability of SMR technologies on a global level.

Licensing challenges

Newly developed SMR technologies often face significant challenges when navigating the existing nuclear licensing and regulatory frameworks. These processes were primarily designed for traditional, large-scale reactors and may not be well-suited to accommodate the unique features and modular nature of SMRs. Regulatory bodies frequently lack sufficient experience and expertise with these innovative designs, which complicates the thorough evaluation and approval of their safety standards. This gap can lead to prolonged review times, increased uncertainty for developers, and potential delays in deployment. To address these issues, regulatory organizations need to evolve by developing specialized guidelines, investing in training, and engaging in early collaboration with technology developers, ensuring that safety assessments are both rigorous and efficient while facilitating the advancement of next-generation nuclear technologies.

Safeguard challenges

In many countries, the deployment of innovative SMR technologies necessitates adherence to international nuclear safeguards aimed at preventing the diversion of nuclear materials for non-peaceful purposes. Given the unique designs and operational characteristics of SMRs, existing safeguard measures may not be fully applicable or sufficient. As a result, there is often a need to develop new or customized technical safeguard protocols tailored specifically to these advanced systems. This process requires considerable time, expertise, and resources, and typically involves close collaboration between national governments, international regulatory bodies, and industry stakeholders. Establishing effective and customized safeguards is essential to ensure compliance with global non-proliferation standards while enabling the safe and secure deployment of SMRs worldwide.

Public perception and engagement

Nuclear power has historically encountered significant public opposition rooted in concerns over the potential consequences of nuclear accidents, despite the fact that such events are extremely rare. The fear of catastrophic incidents, often amplified by high-profile accidents in the past, continues to influence public perception and fuel skepticism about the safety of nuclear energy. One of the key challenges lies in raising awareness and educating the broader population about the stringent safety measures, technological advancements, and regulatory frameworks that make modern nuclear power plants highly secure. Successfully integrating the general public into the mainstream acceptance of nuclear energy requires transparent communication, effective outreach programs, and engagement initiatives that build trust and demystify the technology. Overcoming these societal barriers is essential to fostering broader support for nuclear power as a reliable and clean energy source vital to meeting future energy needs.

7.4.5. Recommendations

Accelerate development of Thorium reactors

India’s vast thorium reserves offer a distinctive opportunity to lead the global shift towards clean nuclear energy. Thorium-based reactors, such as Advanced Heavy Water Reactors (AHWRs), provide notable benefits over traditional uranium reactors, including reduced nuclear waste production, enhanced inherent safety, and suitability for smaller-scale operations—making them well-suited to India’s varied energy needs.

With estimated reserves exceeding 846,000 tonnes, among the largest worldwide, thorium gives India a strategic edge by decreasing dependence on imported uranium and lowering challenges associated with long-term nuclear waste management. These advanced thorium technologies align with India’s commitments under the Paris Agreement, offering a practical pathway to substantial carbon emission reductions.

Strengthen regulatory frameworks

To promote SMR development in India, it is crucial to establish strong, SMR-specific safety standards aligned with international best practices and ensure thorough regulatory oversight. Transparent communication and public engagement should be prioritized to address concerns, educate communities, and build trust. Regular updates and open dialogue will enhance accountability and dispel misconceptions. Involving local stakeholders early fosters ownership and support. Together, these efforts will ease regulatory processes, attract investment, and accelerate SMR deployment for India's clean energy goals.

Promote public-private partnerships

Encouraging collaboration between government agencies and private companies is essential to effectively fund and manage nuclear projects, combining public oversight with private sector innovation and efficiency. Recent initiatives to involve the private sector in projects such as BSRs have shown promise and should be further expanded to harness greater expertise and resources. Providing targeted incentives, streamlined approval processes, and clear regulatory frameworks can attract more private investment and participation. Enhanced public-private partnerships can accelerate project timelines, reduce costs, and improve operational performance. Expanding such collaborations will be key to scaling up India's nuclear capacity while fostering technological advancement and energy security.

Integrate nuclear with renewables

Developing hybrid energy systems that integrate the consistent reliability of nuclear power with the flexibility and scalability of solar and wind energy can create a more resilient and balanced energy grid. Such systems can leverage nuclear's steady baseload output to complement the variable nature of renewables, ensuring uninterrupted power supply even during periods of low solar or wind generation. By combining these technologies, India can optimize resource use, reduce carbon emissions, and enhance grid stability. Integrating hybrid solutions also allows for more efficient infrastructure utilization and energy storage management. This approach supports a sustainable, cost-effective transition to a low-carbon energy future while meeting growing electricity demand.

Enhance public awareness

Launching comprehensive educational campaigns is vital to address widespread misconceptions and fears surrounding nuclear energy. These campaigns should provide clear, accurate information about the safety measures, environmental benefits, and technological advancements in the nuclear sector. By using accessible language and diverse media channels, they can reach a broad audience, including students, communities near nuclear projects, and policymakers. Highlighting success stories and real-world examples can help build trust and counteract misinformation. Ultimately, informed public understanding is essential for gaining widespread acceptance and support for nuclear energy development.

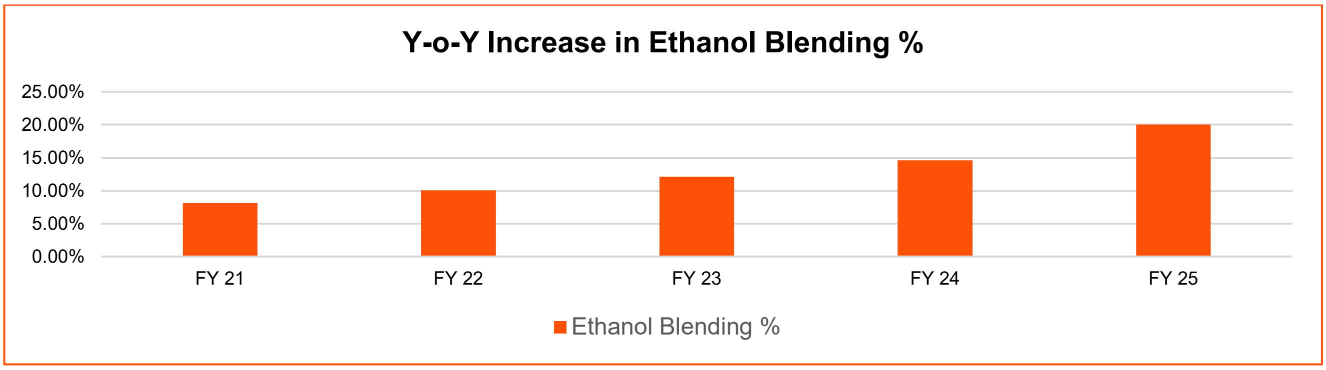
Re-engage financial institutions

Positioning nuclear energy as a stable and scalable investment is crucial to attract banks and financial consortiums to finance clean energy projects. Emphasizing nuclear power's long-term reliability, consistent returns, and low-carbon credentials can boost investor confidence. Clear policy frameworks, risk mitigation measures, and favourable financing terms will further enhance its appeal to financial institutions. Demonstrating successful project implementations and robust safety records helps reduce perceived risks and uncertainties. By establishing nuclear energy as a sound investment, India can mobilize significant capital to support its clean energy transition and infrastructure expansion.

7.5. Biofuels

Biofuels are becoming a key pathway for reducing reliance on fossil fuels and represent one of the most accessible options for addressing climate change. They provide a promising solution for both developing and developed nations to accelerate the energy transition while maintaining energy security and lowering emissions. This is especially important as emerging renewable technologies continue to face challenges related to resource availability, intermittency, and broader commercial feasibility.

India's biofuels sector is undergoing rapid transformation, driven by strong government policies, increasing energy demand, and the country's commitment to reducing carbon emissions. With a focus on ethanol, biodiesel, compressed biogas (CBG), and advanced biofuels, the sector plays a vital role in diversifying India's energy portfolio to enhance its energy security strategy. The Government of India has been actively promoting biofuels to improve farmer incomes by utilizing agricultural waste and surplus crops for biofuel production. India's National Policy on Biofuels 2018 is a major driver for biofuels, setting clear targets and financial incentives to develop the sector. A key initiative under this policy is India's Ethanol Blending Program, which aims to achieve 20% ethanol blending by the end of 2025, which it has already achieved. This success was made possible through sustained policy reforms such as guaranteed pricing for ethanol, allowing multiple feedstocks, and rapidly expanding distillation capacity across the country. The below figure shows the growth of ethanol blending in India.



Source: CEA

Figure 28: Y-o-y ethanol blending %

7.5.1. Compressed Biogas (CBG)

Compressed biogas (CBG) is a highly effective alternative energy source that can substitute natural gas and crude oil, particularly as a cleaner transport fuel. Recognizing its potential to enhance energy security and reduce reliance on costly imports of fossil fuels, the Indian government has taken significant steps to promote its development. As part of this effort, the government allocated a substantial budget of INR 10,000 crores for the Galvanizing Organic Bio-Agro Resources Dhan (GOBARdhan) scheme. This ambitious program aims to establish 500 new bio-CNG plants across the country, which will convert organic waste from agricultural residues, animal manure, and other biodegradable materials into CBG. By promoting the widespread adoption of CBG, the scheme not only provides a sustainable energy solution but also addresses environmental concerns related to waste disposal, supports rural livelihoods, and contributes to India's broader goals of clean energy transition and carbon emission reduction.

The CBG sector in India has gained strong policy support in recent years. In 2018, the Ministry of Petroleum and Natural Gas (MoPNG) introduced the Sustainable Alternative Towards Affordable Transportation (SATAT) scheme to encourage the production and use of CBG as an eco-friendly fuel alternative for the transportation sector. The scheme aims to reduce India's reliance on imported oil and gas by generating CBG from agricultural residues, cattle dung, sugarcane press mud, municipal solid waste (MSW), and sewage treatment plant waste. MoPNG has set an ambitious goal to establish 5,000 CBG plants with a combined capacity of 15 million metric tonnes per year by 2024. As of August 2025, 113 CBG plants have been commissioned under the SATAT program, marking significant progress towards this target.

7.5.2. Government initiatives to support biofuel production

The Government of India has implemented multiple programs to accelerate biofuel adoption, focusing on ethanol, biodiesel, and advanced biofuels. Some of the key policies introduced to encourage biofuel in India include:

Ethanol blending target

The policy sets an ambitious goal to blend 20% ethanol in petrol by 2030, which was later revised to be achieved by 2025. This measure is aimed at reducing India’s reliance on imported fossil fuels, thus enhancing energy security. Increased ethanol blending also helps lower greenhouse gas emissions, supporting India’s climate commitments. The target encourages the growth of the domestic ethanol industry, benefiting farmers and agro-industries. Achieving this target will require scaling up ethanol production infrastructure and creating demand through policy incentives.

Focus on advanced fuels

India’s policy strongly emphasizes development of advanced biofuels, particularly second-generation ethanol produced from non-food biomass like agricultural residues, woody biomass, and municipal solid waste. These biofuels address concerns related to food security and land use competition by utilizing waste and non-edible materials. Advanced biofuels also have a potentially lower carbon footprint, contributing to deeper decarbonization. The policy promotes research, development, and commercial deployment of such technologies. Supporting advanced biofuels aligns with sustainable growth and innovation in the bioenergy sector.

Ethanol production expansion

To boost ethanol availability, the policy encourages the establishment of new ethanol plants using diverse feedstocks, including surplus food grains like maize, sugarcane juice, and biomass. This expansion helps reduce wastage of agricultural produce and provides farmers with additional income streams. It also supports rural economies by creating jobs in feedstock collection and processing. The strategy aims to create a resilient supply chain for ethanol production. Encouraging multiple feedstock use minimizes reliance on any one crop and enhances overall sector stability.

Relaxation of procurement norms

The policy calls for easing procurement regulations to improve the market mechanism for ethanol. This includes allowing state nodal agencies to procure ethanol more flexibly from different sources. Such relaxation helps reduce bottlenecks and uncertainties faced by producers. Facilitation of direct contracts between ethanol producers and oil marketing companies is promoted. Streamlined procurement contributes to competitive pricing, incentivizing investment and scale-up in ethanol production.

National bioenergy mission

The policy proposes launching a dedicated National Bio-Energy Mission to provide strategic leadership and coordinate efforts across various stakeholders. The mission would oversee research, development, demonstration, and deployment of biofuels and bioenergy technologies. It aims to integrate policy support, infrastructure development, and skill-building initiatives. Acting as a nodal agency, the mission can promote public-private partnerships and international collaborations. This coordinated approach is essential for overcoming the technological and commercial challenges in the biofuel sector.

Category diversification

Apart from ethanol, the policy promotes other biofuels such as biodiesel, bio-CNG, bio-methanol, and bio-hydrogen to diversify the fuel mix. Biodiesel production from non-edible oils and used cooking oil reduces waste and dependency on fossil diesel. Bio-CNG serves as a clean alternative to natural gas, especially in transportation and cooking. Bio-methanol and bio-hydrogen are included as long-term options with high energy potential and lower emissions. Diversification helps India build a resilient, flexible biofuel economy catering to different sectors.

Incentives and support

The policy offers various financial incentives to attract investments, including viability gap funding, subsidies, and priority sector lending for biofuel projects. These measures are designed to reduce the initial capital burden and enhance project feasibility, especially for advanced biofuel technologies. The policy encourages state governments to provide additional support, such as tax exemptions and land allotments. Combined, these incentives aim to create a conducive environment for rapid sector growth. By mitigating financial risks, the policy aims to mobilize private capital and technology expertise.

Feedstock flexibility

The policy supports the use of a wide range of feedstocks for biofuel production to ensure a consistent and uninterrupted supply. Utilizing agricultural residues, food grains, oilseeds, and waste materials increases availability and reduces dependence on any single source. Flexibility in feedstocks also provides options to farmers and producers, improving economic resilience. It promotes the development of supply chains and logistics for diverse biomass sources. This approach bolsters rural livelihoods and supports circular economy principles by converting waste into valuable energy.

7.5.3. Biofuel ecosystem in India

India's biofuel ecosystem involves several critical players as shown in the figure below.

Critical Players Involved in the Biofuels Supply Chain					
Feedstock Producers	**Feedstock Suppliers**	**Technology, EPC**	**Biofuel Producers & Off takers**	**Logistics**	**By-product Off takers**
Farmers	Agriculture markets	Technology providers	Grain and Sugar Industry	Transport Industry	Animal feed
Agro-processing Industries	Traders	EPC Companies	Aviation Companies		Ash off taker
Ethanol Producers	Ethanol Producers		Oil Marketing Companies		Brick & cement companies
					Fertilizer components

Figure 29: Biofuels value chain

Feedstock producers

Feedstock producers, including farmers and agro-processing industries, provide the raw materials necessary for producing first-generation (1G) ethanol, second-generation (2G) ethanol, Compressed Biogas (CBG), and Sustainable Aviation Fuels (SAF). Feedstocks for 1G ethanol primarily consist of sugary materials like sugarcane, molasses, sweet sorghum, and sugar beet, as well as starchy sources such as broken rice, corn, and cassava. In contrast, 2G ethanol is produced using lignocellulosic biomass, including cane bagasse, leaves, agricultural residues like cotton and soya stalks, cereal straws (from rice, wheat, and corn), corn cobs and stover, grasses such as napier and bamboo, palm residues, and both soft and hardwoods. For CBG production, materials such as pressmud (a sugarcane industry byproduct), cereal straws, cane bagasse and trash, napier grass, cotton and soya stalks, and empty fruit bunches are utilized. SAF production employs low-carbon feedstocks, which include 1G ethanol among other sources.

Feedstock suppliers

Feedstock suppliers, including agricultural markets, traders, and ethanol producers (specifically SAF producers), bridge the gap between raw material sources and biofuel producers by procuring, aggregating, and transporting feedstocks.

Technology providers and EPC companies

Technology providers and Engineering, Procurement, and Construction (EPC) firms are responsible for setting up and operating efficient ethanol production plants. EPC companies oversee the entire plant development process, from initial design through to commissioning, while technology providers supply advanced solutions aimed at boosting production efficiency, lowering costs, and enhancing sustainability.

Biofuel producers and off takers

Biofuel producers, including both public and private organizations like grain and sugar industries, along with oil marketing companies (OMCs), play a pivotal role in the biofuel ecosystem. OMCs, aviation firms, and various other sectors that incorporate biofuels into their operations serve as key off-takers. Notably, OMCs are the main consumers of bioethanol and biodiesel, blending these biofuels with traditional fuels to achieve mandated blending targets.

Logistics

Logistics companies facilitating the transportation of raw materials, intermediate products, and finished biofuels.

Byproduct off takers

Byproduct off-takers use the byproducts generated during biofuel production, contributing to economic viability, waste mitigation, and circular economy principles.

7.5.4. Challenges associated with Biofuels sector in India

Despite its potential and the incentives provided by the Government of India, the biofuel industry faces several hurdles that need to be addressed for a substantial increase in its uptake. Highlighted below are the key challenges.

Feedstock quality and supply

A major challenge in the biofuel supply chain is the lack of standardized biomass collection processes, resulting in inconsistent quality regarding moisture, size, and contaminants. This variability forces refineries to invest extra time and resources in pre-treatment and quality control. Consequently, production costs increase, and delays become common, impacting overall efficiency. Improving and standardizing collection methods is crucial to ensure consistent feedstock quality. This will help lower costs, streamline operations, and support sustainable biofuel production growth.

Feedstock logistics

Collecting and transporting agricultural residues and other biofuel feedstocks to processing plants presents significant logistical challenges. This process often relies on unorganized aggregators who operate without standardized protocols, leading to inefficiencies and variability in feedstock quality. The lack of formal systems can cause delays, increased costs, and difficulties in maintaining a steady supply chain. Additionally, poor handling practices during collection and transport can result in contamination or degradation of the biomass. Establishing organized, standardized aggregation and transportation networks is essential to ensure consistent feedstock quality and reliable supply for biofuel production.

Land and water use

The relatively low yields of certain first-generation biofuel crops, such as sugarcane, mean that larger areas of agricultural land are required to produce sufficient feedstock for biofuel production. This expanded land use often comes at the expense of other important crops or natural ecosystems, putting additional pressure on land resources. Moreover, cultivating these crops on a large scale demands significant quantities of water and chemical fertilizers to maintain productivity. In regions where water availability is already limited, this increased consumption can worsen existing water scarcity problems, threatening local communities and ecosystems. Excessive use of fertilizers can also lead to soil degradation, pollution of water bodies, and disruption of biodiversity, raising concerns about the overall sustainability of relying heavily on 1G biofuels. Therefore, balancing biofuel production with environmental conservation and resource management is critical to avoid negative ecological impacts.

Food security

Diverting edible crops such as sugarcane and maize for biofuel production poses significant risks to India's food security by reducing the availability of these staple foods in the market. This competition for agricultural resources can lead to increased food prices, making essential staples less affordable for vulnerable populations. Additionally, prioritizing biofuel feedstocks risks undermining nutritional security, as these crops are important sources of calories and nutrients for many communities. Such diversion may also encourage monoculture farming, decreasing agricultural biodiversity and resilience. Hence, balancing biofuel production without compromising food supply and affordability remains a critical challenge for sustainable development.

7.5.5. Recommendations

Enhance feedstock collection system

Expanding innovative collection, aggregation, and supply chain models for diverse organic wastes and residues is essential to boost biofuel feedstock availability. This includes developing efficient systems to gather agricultural waste, municipal solid waste, and used cooking oil from scattered sources. Leveraging technology and data-driven logistics can streamline collection processes, reduce losses, and improve quality control. Collaborating with local communities, waste generators, and aggregators would help create organized supply chains that are reliable and scalable.

Incentivize farmers

Providing direct financial incentives and subsidies to farmers for collecting and supplying biomass is vital to encourage their active participation in the biofuel supply chain. These incentives help offset the additional labour, transportation, and storage costs associated with biomass collection, making it economically viable for farmers. By improving farmer engagement, the overall availability and consistency of feedstock can be significantly enhanced. Financial support also motivates the adoption of sustainable harvesting practices that protect soil health and productivity. Ultimately, such targeted subsidies strengthen the biomass supply chain and contribute to the growth and stability of the biofuel industry.

Foster R&D for emerging feedstocks

Supporting R&D for emerging feedstocks such as algae and engineered microorganisms is crucial for unlocking new biofuel sources with higher yields and lower environmental impacts. These novel feedstocks offer advantages like faster growth rates and the ability to thrive on non-arable land or wastewater, reducing competition with food crops. Alongside feedstock innovation, advancing processing technologies is essential to efficiently convert these materials into high-quality biofuels at commercial scale. Enhanced R&D efforts can lead to breakthroughs in cost reduction, scalability, and sustainability of biofuel production. By investing in these areas, India can significantly expand its biofuel potential and contribute to a more diverse and resilient energy portfolio.

Foster carbon markets

Facilitating access to carbon credit markets for stakeholders across the biofuel supply chain can provide significant financial incentives for sustainable practices and lower carbon emissions. By enabling farmers, producers, and suppliers to earn carbon credits, it encourages the adoption of environmentally friendly methods and investment in cleaner technologies. Expanding the Green Credit Programme to include agricultural feedstock would further promote the cultivation and collection of biomass with reduced environmental impact. This inclusion can create additional revenue streams for farmers and biomass aggregators, enhancing biofuel feedstock availability.

Strengthen community-based programs

Community-based programs aimed at developing biofuel production, distribution, and utilization will play a vital role in promoting sustainable energy solutions at the grassroots level. By involving local communities directly, these programs empower individuals to participate actively in the entire biofuel value chain—from cultivating or collecting feedstocks to producing and using biofuels for cooking, heating, or transportation. Such initiatives often provide training, technical support, and access to affordable technologies, enabling communities to produce biofuels efficiently and safely. Community-driven efforts facilitate the establishment of local supply networks, ensuring that biofuels are readily available and affordable in remote or underserved areas. Additionally, these programs help raise awareness about the environmental and economic benefits of biofuels, encourage behavioural change toward cleaner energy use, and create new livelihood opportunities, thus fostering socio-economic development alongside environmental sustainability.

8. Conclusion

Countries worldwide are facing three interconnected challenges: managing the energy transition, ensuring energy security, and creating sustainable employment. Clean energy presents a promising solution, but its success depends on strategies tailored to each nation's unique population and industrial needs. Extremes such as excessive regulation or lack of action can cause delays, higher costs, and lost job opportunities. As one of the fastest-growing economies, India has adopted a balanced approach to indigenizing manufacturing, positioning itself to achieve its energy and economic goals amid increasing global competition driven by shifting geopolitical dynamics.

Indigenizing clean energy technology manufacturing offers India significant benefits, including import substitution, greater resilience, and enhanced energy security through self-reliance. This approach can boost economic growth by generating jobs and fostering technological innovation, helping India remain competitive in a rapidly evolving global market. Building this technological advantage is essential for developing a sustainable, future-ready green economy. Additionally, India can capitalize on a fragmented global market by attracting foreign investment and diversifying supply chains currently concentrated in China. India should enhance its PLI schemes and overarching technology-focused trade policies by pinpointing specific clean energy supply chain segments or components to scale up with customized support and market safeguards. Additionally, India needs to reassess and adjust its policies to tackle domestic policy uncertainties, adapt to fluctuations in global demand, and guarantee the availability of essential inputs such as raw materials, technological know-how, financing, and other critical enablers within the domestic manufacturing ecosystem. Key priorities that India can focus on increasing the clean energy manufacturing sector are building competitiveness, increasing domestic demand and strengthening the ecosystem.

In a welcome move, on 4th September 2025, India's Goods and Services Tax (GST) Council, has reduced the GST rate on RE components from 12% to 5%. Taking effect from 22 September 2025, the components include solar power equipment, solar cookers and lamps, wind turbine generators, waste-to-energy systems, biogas plants and tidal or wave energy installations. At the same time, the GST on coal and lignite will see a steep increase from 5% to 18%, reflecting the government's push to make RE more cost-effective and competitive, while discouraging fossil fuel use. The reduction is expected to bring down capital costs for solar and wind power projects by approximately 5% while also reducing the costs for ongoing projects. Accordingly, the reduction in GST rates is expected to help the Indian companies ramp up domestic manufacturing of RE components, decreasing dependence on imports – particularly from China.

Despite intense competition, India must continue pursuing its goal of becoming a global clean energy manufacturing hub. Success depends on timely, strategic, and forward-looking policies focused on long-term objectives. By leveraging its strengths and implementing targeted actions, India can not only solve domestic energy challenges but also accelerate the global transition to sustainable energy, enhancing energy security, driving economic growth, and solidifying its role as a key player in the global clean energy landscape.

PwC India was originally incorporated in 1983 and is a member of the global network. The legacy firms of PwC have been present in India for over 150 years and have a deep understanding of the country's business environment. At present, our consultants operate out of 16 major cities such as Delhi NCR, Bengaluru, Chennai, Kolkata (registered office), Mumbai, etc. in the country and have a strong team of over 30,000 professionals involved in providing industry-focused Assurance, Tax and Advisory services across private sector, public sector and various levels of government in India and abroad, international donor agencies etc.

PwC India has a diverse set of professionals, which includes agriculture/agribusiness experts, economists, statisticians, sociologists, energy utilities experts, event management & marketing experts, fund management/Program management experts, rural management experts, fintech and financial services experts, financial risks and regulations specialists and digital services. PwC India has suitable resource pool and experience to provide technical and functional backstopping for the project. PwC India has successfully worked with a number of national, subnational and local/regional Government clients across Asia, South-East Asia and Africa.

The Climate and Energy team at PwC India, a dedicated team of over 500 professionals are working to find solutions to the many intricate problems facing the energy industry. This team includes experts in clean energy and climate change. Additionally, the team has worked on a variety of tasks for a variety of customers, including services like financial analysis, risk identification and mitigation strategies, market assessment, feasibility research, climate effect assessment study, transaction advising, and policy and regulatory review.

PwC India collaborates with governments and multilateral and bilateral financial institutions in the South-Asian region, Middle East, Africa, and Asia-Pacific region to advance the development of low-carbon technologies, supply and demand side energy management, energy efficiency policy, financing for renewable energy, investment evaluation and due diligence, marketing, and outreach for clean energy initiatives. Our greatest strength is combining the team's skills in technology, people, process, data, governance, and strategy to enable planning and decision-making that is based on a thorough grasp of markets, laws, regulations, and the effects of climate change.

Confederation of Indian Industry

The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering Industry, Government and civil society through advisory and consultative processes.

For 130 years, CII has been engaged in shaping India's development journey and works proactively on transforming Indian Industry's engagement in national development. With its extensive network across the country and the world, CII serves as a reference point for Indian industry and the international business community.

In the journey of India's economic resurgence, CII facilitates the multifaceted contributions of the Indian Industry, charting a path towards a prosperous and sustainable future. With this backdrop, CII has identified "Accelerating Competitiveness: Globalisation, Inclusivity, Sustainability, Trust" as its theme for 2025-26, prioritising five key pillars. During the year, CII will align its initiatives to drive strategic action aimed at enhancing India's competitiveness by promoting global engagement, inclusive growth, sustainable practices, and a foundation of trust.

Confederation of Indian Industry

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