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CENTRE FOR A **People-centric Energy Transition**

A Bill of Materials-Based Assessment of Critical Mineral Requirements and Cost Competitiveness in India's Clean Energy Transition

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The Ashoka Centre for a People-centric Energy Transition (ACPET) is a research-focused, transdisciplinary centre within Ashoka University, India, established to drive a sustainable, equitable, and "people-centric" shift towards net-zero emissions. It bridges the knowledge gap in energy transition by collaborating with industry and government to create scalable solutions, covering areas like renewable energy, policy, and technology. For further information about ACPET, please visit: acpet.ashoka.edu.in

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1. Introduction

India's clean energy transition is advancing at an unprecedented pace, underpinned by ambitious targets for renewable energy deployment, green hydrogen production, and energy storage to support long-term decarbonisation and energy security objectives. Solar Photovoltaics (PV), onshore and offshore wind, Green Hydrogen systems, and Battery Energy Storage Systems (BESS) are expected to form the backbone of India's low-carbon energy system. In line with its commitment to achieving 500 GW of non-fossil fuel–based capacity by 2030 and net-zero emissions by 2070 (Ministry of Power, 2026), these technologies are central to India's clean energy transition strategy, offering scalable, decentralised, and sustainable solutions to meet rising electricity demand while reducing dependence on imported fossil fuels.

However, the large-scale deployment of these technologies is intrinsically linked to the availability, affordability, and security of critical minerals and materials, many of which are currently imported and exposed to global supply-chain vulnerabilities. Key minerals such as silicon, silver, copper, indium, tellurium, glass, and other rare earth elements are indispensable inputs for clean energy infrastructure, including solar modules, inverters, wind turbines, and energy storage systems (IEA, 2021). The energy transition to renewables will involve large increases in the exploitation of so-called "critical minerals". The IEA estimates that annual production of these minerals will need to increase six-fold to deliver their Net Zero by 2050 scenario. These materials often classified as "critical minerals" play a decisive role in determining the cost, reliability, and scalability of clean energy technologies. The "critical" in critical minerals is the result of a range of economic, social, and technical factors that limit their supply relative to their growing demand. The methods to assess the criticality of minerals rely on their economic importance and the supply-side vulnerabilities that could lead to market tightness and greater volatility in prices (Tagotra, Niharika, Nidhi and Srivastava, Abhinav Sharma, and T.S. Gowthami, 2024). Ensuring a secure, resilient, and diversified supply chain for these minerals is therefore essential for strengthening India's energy security, maintaining economic competitiveness, and advancing environmental sustainability (R. Chadha and G. Sivamani, 2024).

Despite India's rapid progress in renewable energy deployment, there remains a critical gap in understanding the material/mineral intensity, cost implications, and supply chain risks associated with large-scale clean energy expansion. Existing policy and modelling frameworks have primarily focused on capacity addition, generation costs, and emissions reduction, with limited integration of supply side mineral and material level analysis across technologies such as Solar PV, wind, Green Hydrogen, and Battery Energy Storage Systems (BESS).

India's heavy reliance on imports for several critical minerals such as silicon, silver, copper, lithium, cobalt, and rare earth elements creates significant supply-side vulnerabilities, exposing the energy transition to global price volatility, geopolitical risks, and trade disruptions.

This lack of integrated analysis limits the ability of policymakers and stakeholders to design cost-effective, resilient, and resource-efficient energy transition strategies. Therefore, a comprehensive framework is required to evaluate how different deployment pathways influence material demand, supply chain risks, and overall system costs, and to identify optimal strategies for reducing import dependence while ensuring scalability and energy security.

This study adopts a bottom-up, technology-specific Bill of Materials (BoM) approach integrated with energy system modelling to assess material demand, cost implications, and supply chain dependencies across key clean energy technologies. The detailed BoM profiles are developed for each technology- Solar PV (including different configurations), Onshore and Offshore wind, Electrolysers and Battery energy storage system (BESS) by identifying key components and associated material requirements. These BoMs are derived from a combination of government reports, industry reports, academic literature, and manufacturer specifications**,** ensuring representation of current and emerging technology configurations. The study estimates total material demand over time**,** disaggregated by technology, component, materials and mineral, and evaluates the extent of import dependence of processed materials versus minerals. This is complemented by an assessment of cost implications**,** including material cost, mineral cost contributions to overall technology costs.

2. Literature review

A substantial and growing body of literature underscores the exponential increase in demand for critical minerals under global decarbonisation pathways. According to the International Energy Agency (2021, 2023), total mineral demand from clean energy technologies could double by 2040 under stated policy scenarios and increase up to fourfold under sustainable development trajectories.

Battery-related technologies particularly electric vehicles (EVs) and stationary energy storage systems are identified as the principal drivers of this surge. Demand for minerals used in these applications is projected to increase between 10-fold and over 30-fold by 2040, with lithium demand alone potentially rising more than 40 times under ambitious climate scenarios. Similarly, demand for graphite, nickel, and cobalt is expected to grow by 20–25 times, reflecting their indispensable role in prevailing battery chemistries.

In the power sector, renewable energy technologies also contribute significantly to rising mineral demand. Wind energy, especially offshore wind, is highly material-intensive due to its dependence on rare earth elements for permanent magnets, alongside substantial requirements for copper and steel. Solar photovoltaic (PV) systems, although less material-intensive per unit of capacity, contribute considerably to aggregate demand owing to their large-scale deployment.

Hydrogen technologies further expand the scope of mineral demand. Electrolysers rely on materials such as nickel, zirconium, and platinum group metals, thereby linking the scale and cost of hydrogen deployment to mineral availability and supply chain dynamics.

While projections of demand are relatively well established, recent literature increasingly highlights supply-side constraints and associated geopolitical risks. The International Energy Agency (2021) emphasizes that current supply trajectories and investment levels are insufficient to meet the requirements of accelerated energy transitions, raising concerns about potential market tightness and price volatility. A critical structural challenge lies in the high geographic concentration of both mineral extraction and processing. For several key minerals including lithium, cobalt, and rare earth elements production and refining are dominated by a limited number of countries, heightening exposure to trade restrictions, geopolitical tensions, and supply disruptions. Evidence suggests that the top three producing countries account for a substantial share of global supply, reinforcing systemic vulnerabilities across the value chain.

Moreover, environmental and social considerations associated with mineral extraction impose additional constraints on supply expansion. Collectively, these factors highlight that critical minerals can function either as enablers or as bottlenecks for the clean energy transition, depending on the adequacy of policy responses and investment strategies.

To quantify material requirements across clean energy technologies, Bill of Materials (BoM) and Material Flow Analysis (MFA) approaches have gained prominence. Studies such as McGovern et al. (2024), Tapoglou et al. (2024), Georgakaki et al. (2024), and Carrara et al. (2020) provide detailed estimates of material intensity for solar PV, wind turbines, and battery systems, enabling robust technology-level comparisons and demand projections. However, these approaches exhibit several important limitations. First, they predominantly focus on physical material quantities, with limited integration of economic cost structures. Second, they often rely on global average assumptions, which may not adequately capture country-specific conditions such as trade dependencies, industrial capacity, and supply chain configurations. Third, there is insufficient consideration of processed materials and midstream value chains an omission that is particularly consequential for emerging economies where manufacturing systems are heavily dependent on imported intermediates.

In the India context, the report by Ghosh and Pandey (A. Ghosh, S. Pandey, 2025) provides a comprehensive assessment of India's growing dependence on critical minerals in the context of its clean energy transition. The report underscores that India remains highly vulnerable due to its limited domestic reserves and strong dependence on imports of critical minerals required for the energy transition. However, several research gaps persist. While the study provides robust estimates of mineral demand and explores resource efficiency pathways, it offers limited quantitative assessment of the cost implications associated with alternative supply strategies. Furthermore, it does not integrate the cost of materials within clean energy technologies, focusing instead primarily on demand projections and cost modelling at the individual mineral level rather than at the technology or system level.

The report State of the Sector: Critical Energy Transition Minerals for India (Volumes I and II) (Chadha, R., Goel, S., Goldar, A., Jain, R., et al., 2025. State of the Sector: Critical Energy Transition Minerals for India, Vol. I, 2025; Chadha, R., S. Goel, A. Goldar, and R. Jain, 2025) provides one of the most comprehensive assessments of mineral security, covering demand dynamics, supply chain vulnerabilities, and policy responses. A key insight from Volume I is India's structural dependence on imports not only for raw minerals but, more critically, for processed materials and intermediate products. Despite the presence of some domestic mineral reserves, the country lacks adequate midstream processing and refining capacity, resulting in a heavy reliance on global value chains for higher value-added components.

Volume II complements this analysis through detailed mineral-level assessments (including lithium, nickel, copper, manganese, and neodymium), highlighting the high geographic concentration of global supply chains and the associated risks. Recent disruptions ranging from export restrictions and geopolitical conflicts to pandemic-induced shocks have further exposed the fragility of these supply chains, raising concerns regarding long-term resilience.

However, while these reports provide valuable insights into India's import dependence and supply chain vulnerabilities, they do not quantitatively evaluate the cost implications of alternative supply chain configurations. In particular, there is limited analysis of the relative cost competitiveness of importing raw minerals versus finished components an area that is critical for informing domestic manufacturing strategies and industrial policy design.

Despite the breadth of existing research, several key gaps remain. There is a lack of integrated analytical frameworks that combine BoM-based material requirements with cost and trade dimensions. Existing studies also provide insufficient focus on processed materials and midstream supply chains, especially in the context of emerging economies such as India. Furthermore, there is a limited empirical comparison of alternative import strategies, particularly with respect to cost trade-offs between raw materials and finished products. Finally, current literature inadequately integrates scenario-based technology deployment with material-level cost dynamics and learning effects. Addressing these gaps is essential for developing a more comprehensive understanding of the economic and strategic dimensions of critical mineral supply in the clean energy transition.

3. Rationale for the study

In this above context, developing a detailed Bill of Materials (BoM) for key clean energy technologies is a critical analytical exercise. A BoM systematically maps the types, quantities, and specifications of materials and components required across different technologies and sub-technologies (EcoGreen energy, 2025) . For India, such a granular understanding is essential to anticipate future demand for critical minerals such as lithium, cobalt, nickel, copper, silicon, silver, rare earth elements, and platinum group metals, which are vital for clean energy infrastructure but characterised by high import dependence and geopolitical concentration.

From a critical mineral security perspective, BoM analysis enables the identification of material-intensive components and supply bottlenecks across Solar PV, wind (both onshore and offshore), Green Hydrogen value chains (electrolysers), and BESS (IEA, 2023; WTW, 2023). It provides insights into whether India's reliance is higher on raw mineral imports or on processed and finished components, informing strategic decisions related to domestic mining, refining, manufacturing, and trade diversification. Such insights are particularly relevant in light of India's efforts to strengthen domestic manufacturing under initiatives like *Make in India* and to build resilient supply chains for strategic minerals. Additionally, this also aligns closely with the Government of India's long-term vision of Viksit Bharat 2047, which seeks to transform India into a developed, self-reliant, and globally competitive economy. Building resilient and secure supply chains for critical minerals is central to this vision, as it underpins industrial growth, energy security, and technological leadership in emerging clean energy sectors, while ensuring sustainable and inclusive economic development.

Furthermore, BoM analysis provides a foundation for evaluating economic and financial risks associated with clean energy deployment. Volatility in global critical mineral prices, supply disruptions, trade restrictions, and technological lock-ins can significantly affect project costs, investment viability, and long-term competitiveness (C. Konda and K. Rakheja, 2024). By linking material requirements with cost structures, BoM-based assessments help identify technologies and components that are most vulnerable to price shocks and supply constraints. This is particularly relevant for capital-intensive technologies such as offshore wind, large-scale BESS, and green hydrogen electrolysers, where material costs form a substantial share of overall project expenditure (SUNTSU, 2026).

to sum up the rationale of the study, developing a comprehensive Bill of Materials for Solar PV, onshore and offshore wind, Green Hydrogen, and BESS is a foundational exercise for India's clean energy planning. It bridges the gap between energy system expansion and material supply realities, enabling evidence-based policymaking across critical mineral security, circular economy planning, industrial strategy, and financial risk management. As India accelerates towards its Net Zero and energy transition goals, BoM analysis will play a crucial role in ensuring that the transition is not only clean, but also secure, resilient, and economically sustainable.

4. Objective of the study

The objective of this analysis is to quantify the material and critical mineral requirements associated with the large-scale deployment of clean energy technologies in India, and to assess the cost exposure under different deployment pathways like business as usual and Net zero scenarios (NITI Ayog, 2026).

5. Scope and Technologies Covered

In this study, 8 clean energy technologies (CETs) in Solar PV (Renewable Energy Magazine, 2024), 5 CETs in onshore Wind (L. McGovern, E. Tapoglou, and A. Georgakaki, 2024), 4 CETs in offshore Wind, 17 CETs in BESS (Y. Xiao, J. Xiao, H. Zhao, J. Li, G. Zhang, D. Zhang, 2024), and 3 electrolysers for Green Hydrogen production, were selected to be part of the exercise (A. Ghosh, S. Pandey, 2025). Altogether 37 clean energy technologies have been analysed in this study.

5.1. Solar PV

Crystalline silicon technologies particularly monocrystalline and poly-crystalline silicon continue to dominate the global PV market, accounting for over 90–95% of total installed capacity. Within this, monocrystalline modules have increasingly taken the lead due to their higher efficiency and declining costs. In contrast, thin-film technologies (such as CdTe and CIGS) occupy a relatively smaller market share, although they remain relevant for specific applications and continue to see incremental improvements.

Meanwhile, next-generation technologies, including perovskite and organic solar cells, are still largely in the research and development or early commercialization stages. These emerging technologies show significant potential for higher efficiencies and lower manufacturing costs, but challenges related to stability, scalability, and long-term performance need to be addressed before widespread deployment.

5.2. Wind energy

Wind energy has emerged as a key pillar of the global renewable energy transition, providing a clean and sustainable alternative to fossil fuel-based power generation. With wind resources being widely available and often abundant across many regions, its contribution to the electricity mix is steadily increasing and is expected to grow significantly in the coming years.

Based on application and location, wind energy systems are broadly categorized into two types. Onshore wind turbines are installed on land, in both rural and, in some cases, semi-urban areas. They represent the most widely deployed form of wind technology due to their cost-effectiveness, relatively faster installation timelines, and ease of operation and maintenance.

In contrast, offshore wind turbines are installed in bodies of water, typically in coastal regions or designated offshore wind farms. These turbines are generally larger and more powerful than their onshore counterparts, benefiting from stronger and more consistent wind speeds at sea, which enhances their efficiency. However, offshore projects require larger installation spaces and involve higher capital costs and greater technical complexity in construction and maintenance.

5.3. Battery Energy Storage System (BESS)

BESS is an advanced energy storage solution that utilizes rechargeable batteries to store excess electricity, often generated from renewable sources such as solar and wind in the form of chemical energy. This stored energy can later be converted back into electrical energy (AC) and dispatched when demand increases, renewable generation is low, or additional support is required to maintain grid stability. Some common types include lithium-ion batteries, lead-acid batteries, flow batteries and Sodium batteries.

5.4. Electrolysers:

A hydrogen electrolyser is a system that uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) through the process of electrolysis. When powered by renewable energy sources, this process produces green hydrogen, a clean, zero-emission fuel that plays a critical role in decarbonizing hard-to-abate sectors such as industry and transportation. The advancement of hydrogen technologies is being driven by multiple global factors, including the urgent need to address climate change, rising energy demand due to population growth, and the gradual depletion of fossil fuel resources. As a result, the electrolyser market is expanding rapidly, with Alkaline (ALK) and Proton Exchange Membrane (PEM) technologies currently dominating due to their relative maturity and ongoing improvements in efficiency and cost.

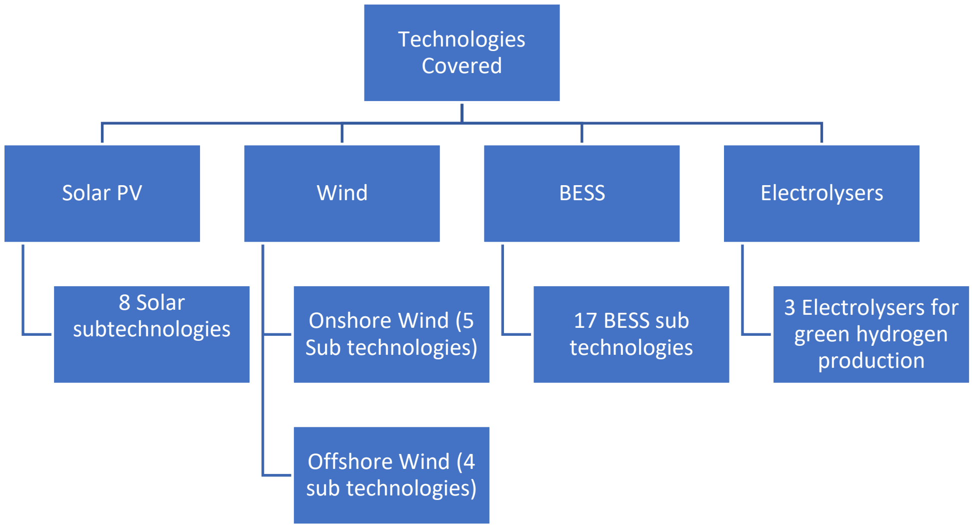

Figure 1. Technologies and sub-technologies covered in this study

Table 1. Technology, sub-technologies and Acronyms

Technology	Sub-Technology	Acronym	Very Short Description
Solar	Mono-Crystalline PV	mono-Si PV	High-efficiency silicon solar cells
	Polycrystalline PV	poly-Si PV	Lower-cost, lower-efficiency silicon cells
	Copper Indium Gallium Selenide Thin-Film PV	CIGS	Flexible, high-performance thin-film solar
	Amorphous Silicon Thin-Film PV	a-Si	Low-cost, low-efficiency thin-film solar
	Cadmium Telluride	CdTe	Cost-effective thin-film with fast production
	Perovskite/Silicon Tandem	—	Next-gen high-efficiency layered cells
	Perovskite APT	—	Emerging low-cost, high-efficiency material
	Heterojunction Silicon PV	HJT	High-efficiency hybrid silicon technology
Wind (Onshore)	Gearbox High-Speed Permanent Magnet Synchronous Generator	GB-HSPMSG	High-speed generator with gearbox and magnets
	Gearbox Doubly-Fed Induction Generator	GB-DFIG	Widely used, variable-speed wind generator
	Gearbox Squirrel Cage Induction Generator	GB-SCIG	Robust, simple fixed-speed generator

	Direct Drive Electrically Excited Synchronous Generator	DD-EESG	Gearless generator using electrical excitation
	Direct Drive Permanent Magnet Synchronous Generator	DDPMSG	Gearless, efficient permanent magnet generator
Wind (Offshore)	Gearbox Squirrel Cage Induction Generator	GB-SCIG	Durable generator for offshore use
	Direct Drive Permanent Magnet Synchronous Generator	DDPMSG	High-efficiency gearless offshore turbine
	Direct Drive High Temperature Superconductor	DD-HTS	Advanced lightweight high-efficiency generator
	Gearbox Medium Speed Permanent Magnet Generator	GB-MS PMG	Medium-speed efficient gearbox generator
Battery Energy Storage (BESS)	NASICON ($Na_3V_2(PO_4)_3$)	NVP	Sodium-ion battery with fast ion conduction
	Prussian Blue Analogues ($Na_2Fe[Fe(CN)_6]$)	(PBA)	Low cost, environmental friendly, ideal for storing large sodium ions in battery cathods
	Vanadium Redox Flow Battery	VRFB	Long-life flow battery for grid storage
	Lithium Nickel Manganese Cobalt	NMC 523	Balanced lithium battery chemistry
	Lithium Titanate	LTO	Ultra-fast charging, long cycle life battery
	Lithium Iron Phosphate	LFP	Safe, long-life lithium battery
	Sodium Iron Phosphate	NFP	Low-cost sodium-based battery alternative
	Lithium Nickel Manganese Cobalt	LNMC-811	High energy density lithium battery
	Polysulfide Bromide	PSB	Flow battery with liquid electrolytes
	Layered Sodium Manganese Oxide	NaMO2	Sodium-ion cathode material
	Sodium Nickel Manganese Cobalt	NaNMC	Sodium-based high-performance battery
	Lithium Nickel Manganese Cobalt	LNMC622	Balanced performance lithium battery

	Sodium-Nickel Chloride	NaNiCl2	High-temperature sodium battery
	Solid-State Batteries	ESS	Next-gen batteries with solid electrolyte
	Sodium-Sulfur	NaS	High-temperature grid-scale battery
	Lithium-Sulfur Batteries	Li–S	High energy density emerging battery
	Zinc-Bromine	ZnBr	Flow battery for long-duration storage
Electrolysers	Alkaline Electrolysers	AEL	Mature, low-cost hydrogen production
	Proton Exchange Membrane Electrolysers	PEMEL	Flexible, high-efficiency hydrogen production
	Solid Oxide Electrolysis	SOEL	High-efficiency, high-temperature electrolysis

6. Approach and Methodology: steps followed, key assumptions and consideration

6.1. Material-Based Modelling Approach

The assessment adopts a material-based modelling framework. Inputs are defined in the processed material forms actually used in CETs manufacturing, such as Silicon wafers, mountings and frames, Glass fibres, semiconductors, Carbon fibres, Membranes etc. Mineral ore inputs are not directly modelled, as CETs manufacturing does not consume ores, particularly in the Indian context, where midstream processing capacity is limited (Ministry of commerce and industry, Department of commerce, 2025).

6.2. Mineral-Based Modelling Approach

Critical mineral requirements are derived from material inputs using explicit material-to-mineral conversion factors. These factors represent the mineral content embedded within processed materials and are applied consistently across technologies and scenarios (Carrara, S., Alves Dias, P., Plazzotta, B., Pavel, C., 2020). This approach avoids conflating geological resource availability with manufacturing and processing constraints. It reflects mineral content within materials rather than ore grades. This approach acknowledges the current Indian manufacturing realities, where technology assembly parts rely on imported processed minerals rather than ore form due to the lack of domestic midstream processing capacity (Ministry of Mines, 2025).

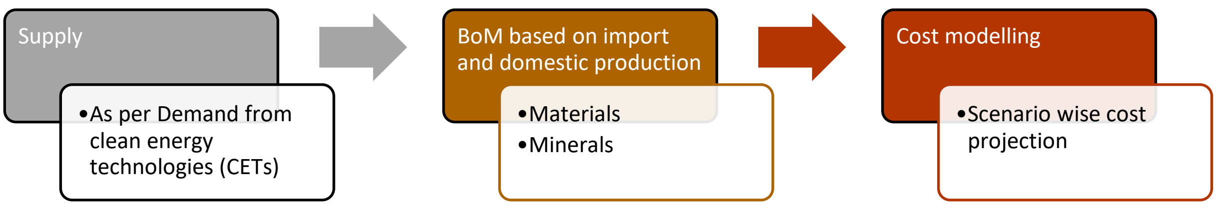

Figure 2. Methodology used for the study

6.3. Cost and Quantity Benchmarking

Two cost layers are reported separately: Material Cost, representing the cost of processed materials directly used in electrolyser components, and Mineral Cost, representing the embedded cost of critical minerals contained within those materials.

This separation avoids conflating geological availability with manufacturing and processing constraints which in simpler terms, means that just because a country has a mineral, it doesn't necessarily mean it can use it. The bottleneck is often processing and manufacturing, not the resource itself.

Base-year unit costs and quantities for materials and minerals are primarily derived from India's official trade statistics (TRADESTAT, Ministry of Commerce, Indian mineral yearbook)[1,2], using observed import values and quantities wherever available. Cost, Insurance, and Freight (CIF) data is used as the basis for estimating the cost of imported minerals and materials in this analysis. However, the cost modelling of clean energy technologies does not incorporate several important components, including electricity consumption during manufacturing, logistics and transportation expenses, and the costs of auxiliary materials and other miscellaneous processing inputs. As a result, the estimated values reflect only a partial measure of production costs and do not represent the full economic cost or final market price of the technologies.

For records with missing, suppressed, or incomplete quantity or mass information, a structured BoM imputation framework is applied.

Imputation follows a defined hierarchy:

(H1) mirroring partner-country reported quantities where available;

(H2) using unit price or unit weight inferred from non-suppressed nearby records or global medians;

(H3) estimating quantities as value divided by benchmark unit price;

[1] https://tradestat.commerce.gov.in/eidb/commodity_wise_import

[2] https://ibm.gov.in/writereaddata/files/1768904841696f5889c118d13.01.2026__FINAL_COPY_IMYB_BOOK_2023__E book.pdf

(H4) estimating quantities as mass divided by benchmark unit weight (preferred where mass data exists); and

(H5) applying engineering or process consumption norms where trade data is insufficient.

All imputed records are explicitly flagged by method (H1–H5) in the excel workbook, with benchmark values updated annually and supporting assumptions documented, ensuring transparency and traceability of the imputation process.

6.4. Scenario Design

Two deployment scenarios are modelled: Business-as-Usual (BAU) and Net Zero (NZ). BAU reflects moderate electrolyser deployment aligned with existing policy trajectories, while NZ reflects accelerated deployment consistent with long-term decarbonisation targets. Material composition and mineral intensity per unit remain identical across scenarios; differences arise solely from deployment scale (A. Ghosh, S. Pandey, 2025).

6.5. Temporal Framework

The BAU and NZ analysis is conducted over the period 2030–2070 at five-year intervals. This horizon captures both near-term scale-up and long-term system transformation dynamics.

6.6. Aggregation and Cost Estimation

Total material and mineral costs are calculated by multiplying unit-level requirements by scenario-specific deployment volumes for each time step. Results are aggregated by technology, cost category, and scenario to produce time-series cost trajectories.

6.7. Learning Curve Application to capture cost evolution from 2030 to 2070

Cost trajectories over time incorporate learning effects linked to cumulative installed capacity. Cost evolution for technologies is modelled using a standard one-factor learning curve linked to cumulative installed capacity. Unit material and system costs in year *t* are projected relative to a 2030 baseline according to

$$\mathrm{Cost}_t = \mathrm{Cost}_{2030} \times (1 - LR)^{\log_2\left(\frac{\mathrm{CumulativeCap}_t}{\mathrm{CumulativeCap}_{2030}}\right)},$$

where *LR* denotes the learning rate, defined as the fractional reduction in unit cost associated with each doubling of cumulative installed capacity.

Technology	Sub-category	Learning Rate (% per doubling)	Notes
Solar PV	Crystalline silicon (mono/poly)	**20–34% (Capex) / ~30–40% (LCOE)**	Among the highest learning rates; strong scale and manufacturing effects(IRENA, 2021). (IRENA, 2021)
	Thin-film (CdTe, CIGS)	**15–25%**	Slightly lower than crystalline but still significant learning
Wind Energy	Onshore wind	**12–17% (Capex) / ~30% (LCOE)**	Mature technology with steady improvements (IRENA, 2021)
	Offshore wind	**9–15% (Capex/LCOE)**	Lower learning due to high installation complexity (IRENA, 2021).
Hydrogen Electrolysers	Alkaline (ALK)	**~4–10%**	Early-stage scaling; cost reductions expected with deployment (Rozon, F.; McGregor, C.; et al., 2023)
	PEM	**~4–10%**	Similar to ALK; innovation-driven improvements
	SOEL	**~4–10%**	
Battery Energy Storage (BESS)	Lithium-ion (dominant)	**18–25%**	Strong learning driven by EV scale-up (industry consensus) (IRENA, 2017).
	Flow batteries	**10–20%**	Emerging; higher uncertainty (Steffie Banatvala, 2026)
	Sodium-ion / other emerging	**~15–25% (expected)**	Early-stage; projections vary

7. Results and Discussions

Cost modelling based on Bill of Materials (BoM) extraction from HS code-level trade data evaluates relative cost competitiveness between importing finished components versus raw minerals.

7.1. Solar

For solar PV, the results indicate that importing finished components remains consistently more cost-effective than importing raw minerals for domestic manufacturing under both Business-as-Usual (BAU) and Net Zero (NZ) scenarios through 2070.

Monocrystalline and Polycrystalline PV

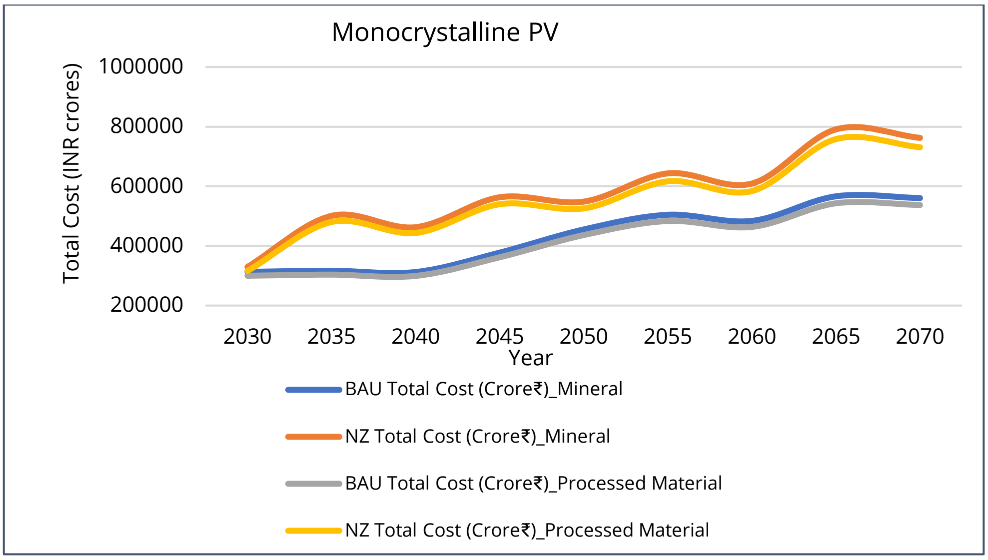

Figure 3. Cost projection in BAU and NZ scenario for Monocrystalline PV

Figures 3 and 4 indicate that importing processed materials remains more cost-effective than importing raw minerals for both monocrystalline and polycrystalline PV. Figure 4 further shows that total costs decline in the Net Zero (NZ) scenario after 2040, primarily due to a reduced share of polycrystalline technologies and increased dominance of monocrystalline installations. The relatively small gap between the cost curves in both figures reflects the added costs of material processing and manufacturing, including energy-intensive stages such as polysilicon production and cell fabrication. For instance, as illustrated in Figure 3, the cost difference between processed materials and raw minerals in 2040 is around INR 12,000 crore under the BAU scenario and INR 19,000 crore under the NZ scenario. However, this gap is insufficient to justify the establishment of a complete domestic PV manufacturing facility. Additionally, setting up such manufacturing would lead to higher electricity demand, given the energy- and resource-intensive nature of these processes. Overall, the relatively small cost differential indicates that developing domestic manufacturing based on raw mineral processing could increase total system costs, thereby reinforcing the economic advantage of importing finished components.

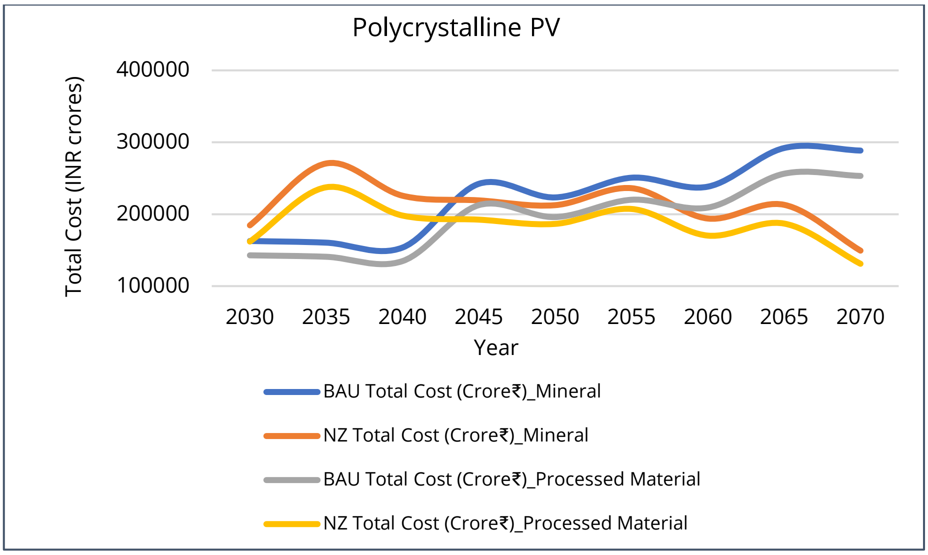

Figure 4. Cost projection in BAU and NZ scenario for Polycrystalline PV

Thin Film technology (CdTe & CIGS)

This cost advantage of importing processed materials over minerals holds across emerging thin-film options such as CdTe and CIGS through 2070. Figure 5 and 6 show that the gap between the costing of processed material and mineral is larger than crystalline technology which suggest that over the long term, scaling up domestic manufacturing for thin film technologies, supported by technological learning and innovation, can help moderate costs and improve competitiveness.

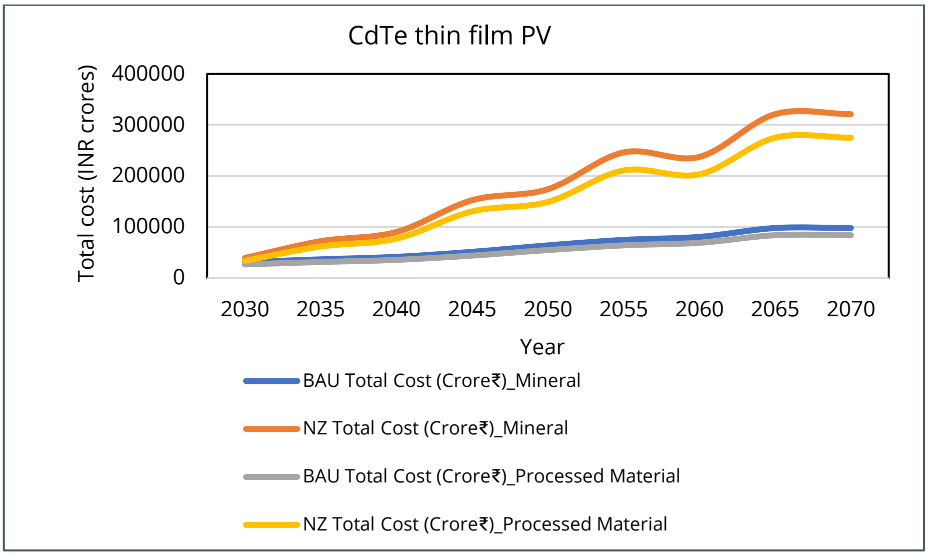

Figure 5. Cost projection in BAU and NZ scenario for CdTe thin film PV

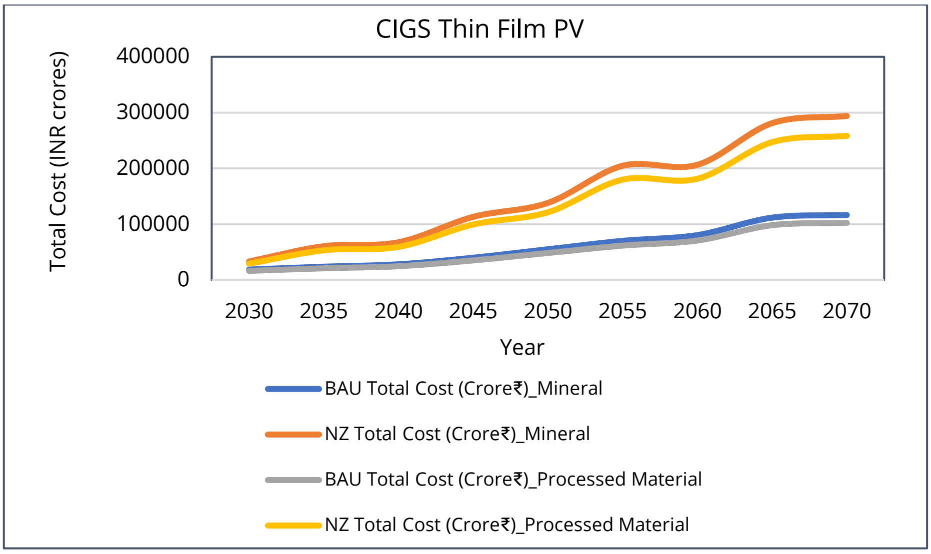

Figure 6. Cost projection in BAU and NZ scenario for CIGS thin film PV

The study also examined perovskite solar cells, which currently have higher costs mainly due to the use of gold electrodes. However, their economic viability could improve significantly with material substitution, such as replacing gold with copper or aluminium. Due to limited literature and lack of detailed compositional data, precise cost estimates for perovskite solar cells remain unavailable.

These findings indicate that domestic manufacturing alone may not be sufficient to offset cost pressures, especially given the continued dependence on critical minerals. Fully integrated, end-to-end manufacturing within India could, in the near term, be more expensive without significant scale and technological maturity. At the same time, the results underscore the importance of a complementary critical minerals strategy, including supply diversification, strategic sourcing, and international partnerships. Ensuring access to low-cost renewable energy for manufacturing processes will also be crucial in reducing material processing costs and enhancing overall cost stability.

7.2. Onshore Wind

In contrast to solar PV, onshore wind exhibits an opposite cost dynamic, wherein importing raw minerals is generally more cost-effective than importing processed or finished components.

DD-PMSG

The trend remains largely consistent across the time horizon up to 2070 for DD-PMSG onshore wind technology as importing raw mineral is more cost effective than importing processed materials shown in figure 7. A noticeable spike in costs is observed around 2050 under the Net Zero (NZ) scenario, primarily driven by higher deployment requirements and accelerated capacity additions. There is a wide gap between processed material and mineral cost over the years and this gap is much more in NZ scenario and gap is even widening towards 2070. As illustrated in Figure 7, under the Net Zero scenario, the cost differential between processed materials and raw minerals reaches approximately INR 95,000 crore by 2060. This substantial gap indicates that a significant share of costs in wind technology manufacturing arises beyond the procurement of critical minerals, reflecting the high expenses associated with processing, fabrication, and component manufacturing.

Over the long term, however, scaling up domestic manufacturing supported by technological learning, economies of scale, and innovation has the potential to reduce processed material costs and enhance overall competitiveness. The widening of this gap to nearly INR 129,000 crore by 2070 further reinforces this trend. Taken together, these findings suggest that while immediate large-scale investments may not be economically optimal, a phased approach with manufacturing expansion in the medium term would be more strategic and cost-effective.

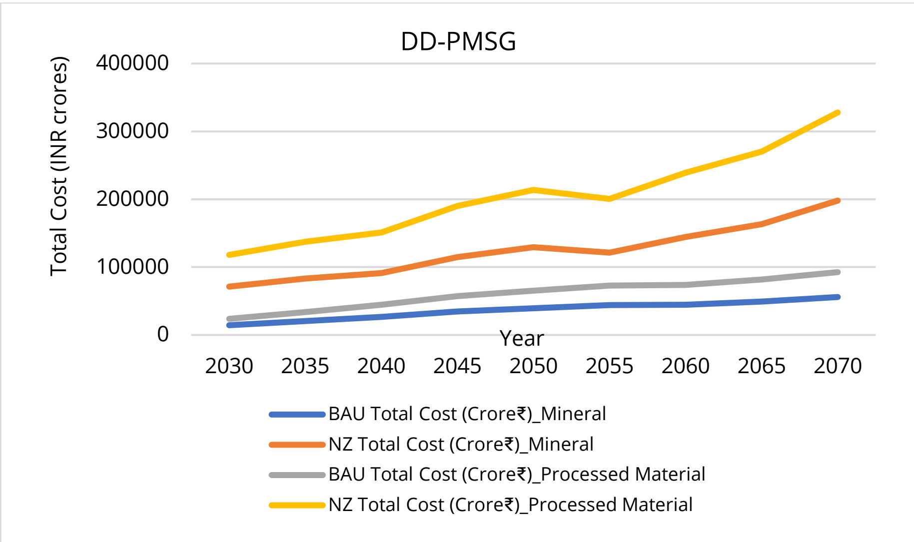

Figure 7. Cost projection in BAU and NZ scenario for DD-PMSG Wind technology

GB-MS-PMG

This technology also shows the same trend as DD-PMSG technology as shown below in figure 8. The relatively narrow gap between mineral and processed material costs in the GB-MS PMG curve indicates that domestic manufacturing based solely on raw material availability offers limited economic advantage unless supported by improvements in manufacturing efficiency and economies of scale.

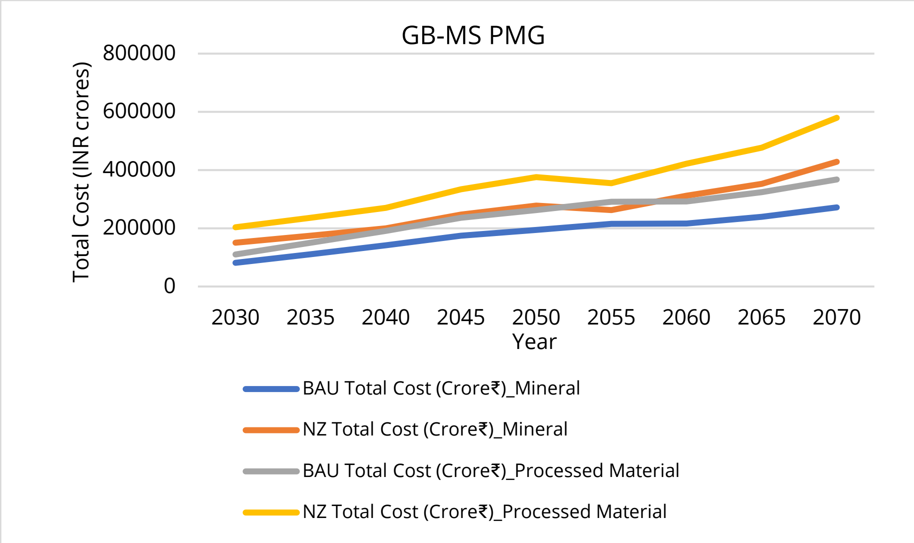

Figure 8. Cost projection in BAU and NZ scenario for GB-MS PMG Wind technology

DD-EESG

In the case of DD-EESG, shown below in figure 9, the gap is almost negligible, implying that importing minerals and importing finished components have nearly the same cost implications. This further suggests that undertaking energy-intensive domestic manufacturing without adequate efficiency gains could place additional pressure on energy systems, potentially offsetting benefits from localization.

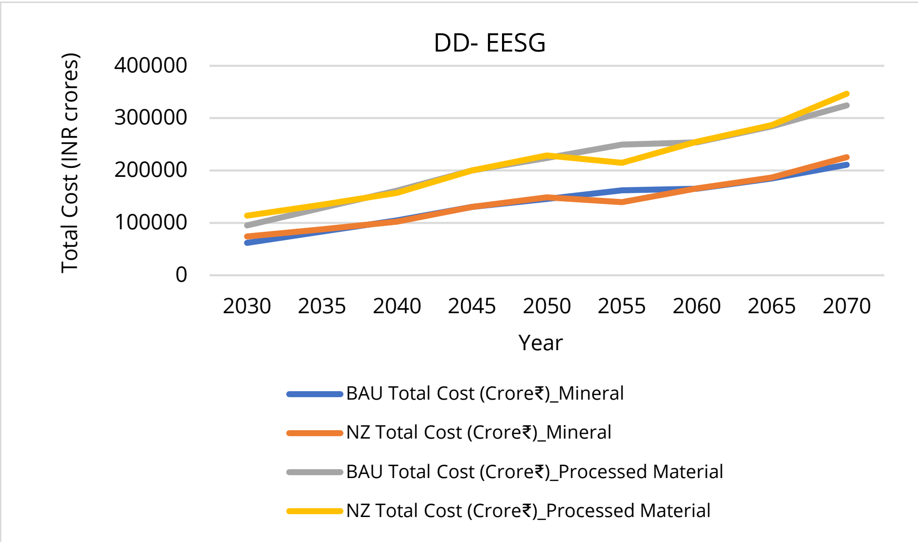

Figure 9. Cost projection in BAU and NZ scenario for DD-PMSG Wind technology

GB-DFIG & GB-SCIG

For GB-DFIG and GB-SCIG technologies (Figures 10 and 11), deployment becomes negligible beyond 2050 in NZ scenario. In the initial years (2030–2035), there is a significant cost gap between processed materials and raw minerals in NZ; however, this gap gradually narrows and becomes negligible in later years. Under the BAU scenario, both technologies reach peak deployment between 2045 and 2055. Post-peak, GB-DFIG shows a plateau in deployment, whereas GB-SCIG experiences a sharp decline.

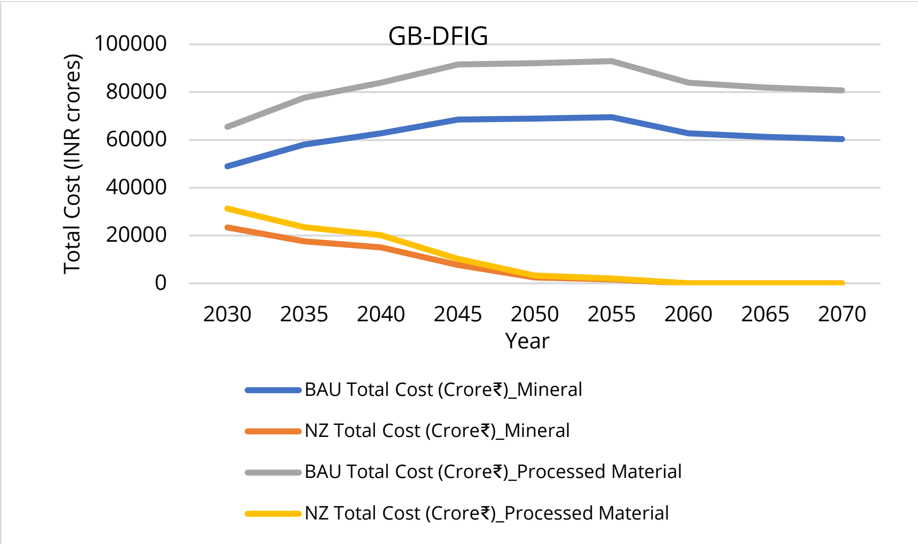

Figure 10. Cost projection in BAU and NZ scenario for GB-DFIG Wind technology

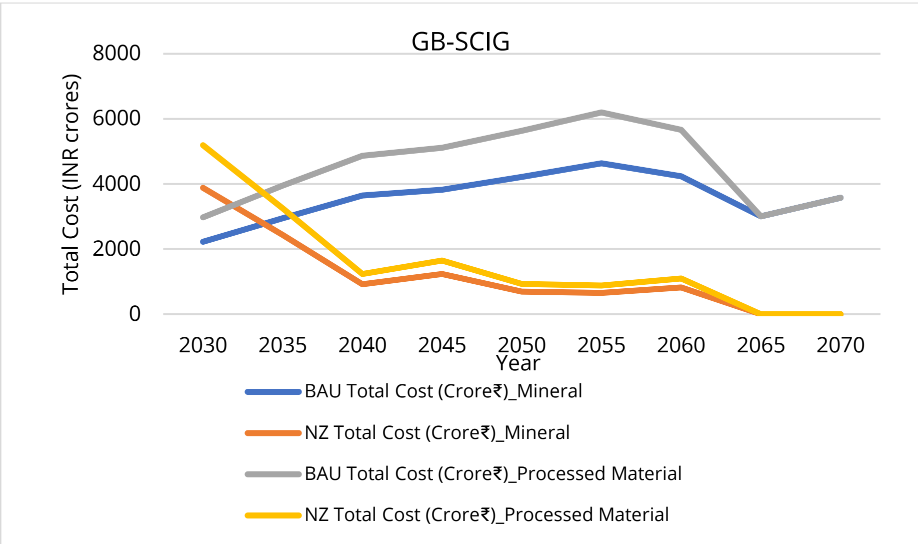

Figure 11. Cost projection in BAU and NZ scenario for GB-SCIG Wind technology

From a policy perspective, these findings highlight that while domestic manufacturing is crucial for enhancing energy security and fostering industrial development, it may not immediately lead to cost reductions without significant advancements in industrial capability, infrastructure, and technological maturity. Additionally, despite their relatively smaller share in total costs, critical minerals particularly rare earth elements remain strategically important due to import dependence and associated supply risks. This underscores the need for a complementary critical mineral's strategy focused on supply diversification, recycling, and international partnerships. Over the long term, scaling up domestic manufacturing, supported by technological learning and innovation, can help reduce processed material costs and improve competitiveness. Ensuring access to low-cost renewable energy, along with the development of robust manufacturing ecosystems and supporting infrastructure especially for offshore wind will be essential for stabilizing costs and enabling India's transition to a large-scale, wind-based energy system.

7.3. Offshore Wind

Offshore wind shows a cost pattern similar to onshore wind, where importing raw minerals for domestic manufacturing is generally more economical than importing processed or finished components.

GB-SCIG

In case of GB-SCIG, the trend shown in figure 12 shows that under the Net Zero (NZ) scenario, total costs are lower than in the BAU case, mainly because offshore wind sees relatively lower capacity additions, with a larger share of deployment shifting toward onshore wind. Also the gap between processed material cost and mineral cost is very low in BAU scenario and negligible in NZ scenario which suggest that importing the processed materials is cost effective than importing minerals and scaling up the domestic manufacturing which need a huge capital and manufacturing processes are also energy intensive.

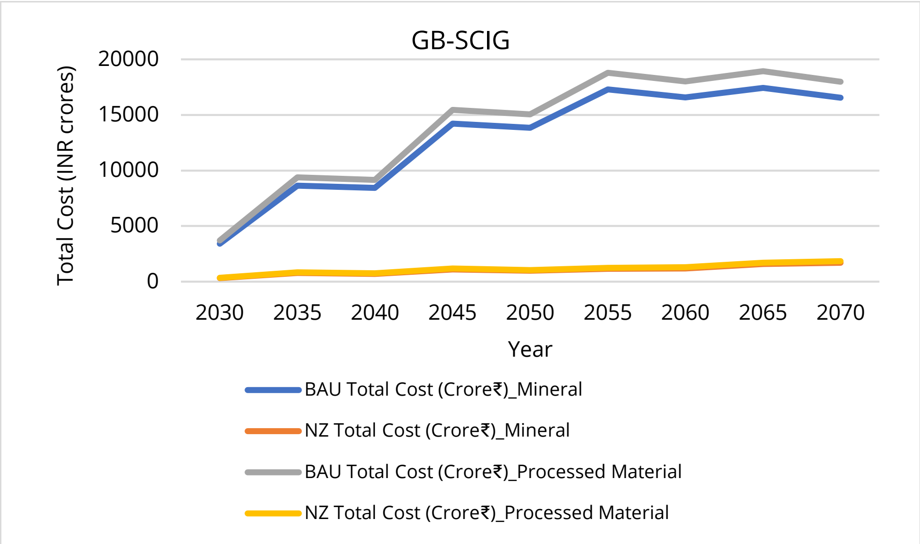

Figure 12.Cost projection in BAU and NZ scenario for GB-SCIG Offshore Wind technology

DD-PMSG

The costing trend in this technology, shown in figure 13 shows that this technology will be deployed widely in NZ scenario but in BAU its installation will be very limited. Also this technology shows the same trend as GB-SCIG where the gap in cost between processed materials and minerals very narrow, suggesting its better to import processed mineral to save our own resources.

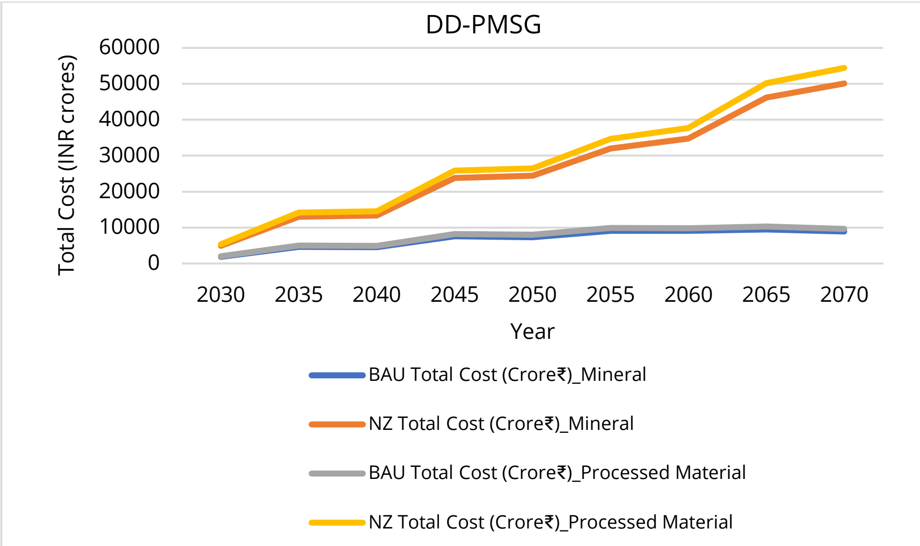

Figure 13. Cost projection in BAU and NZ scenario for DD-PMSG Offshore Wind technology

GB-MS-PMG

This technology shows the same costing trend for both BAU and NZ scenario but same as GB-SCIG, there is lower capacity addition of GB-MS-PMG in NZ scenario than in BAU scenario shown in figure 14. As it can be observed from all three offshore wind technology trends that the deployment of offshore technologies is much lower than onshore technologies.

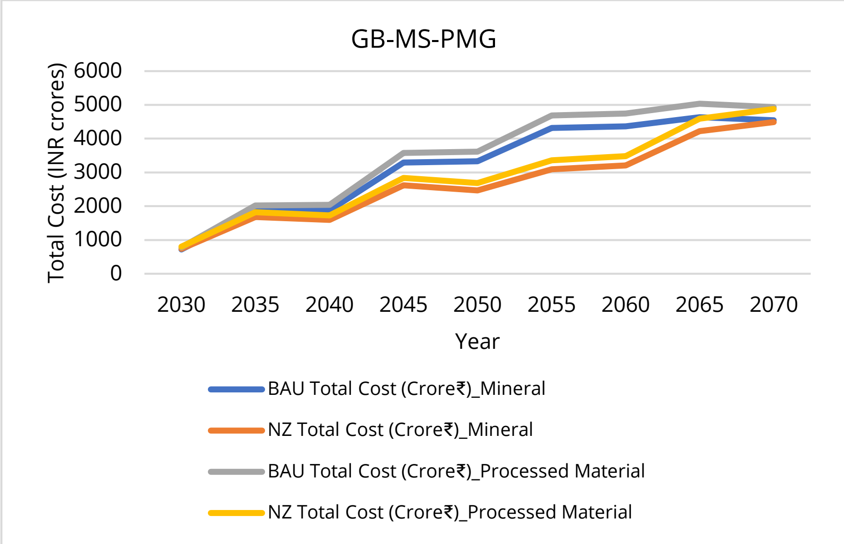

Figure 14. Cost projection in BAU and NZ scenario for GB-MS-PMG Offshore Wind technology

7.4. Battery Energy Storage Systems (BESS)

The comparative analysis of mineral and processed material costs across different Battery Energy Storage System (BESS) technologies reveals important insights into the cost-effectiveness of import strategies and the feasibility of domestic manufacturing in India.

Across all technologies, the differences observed between the Business-as-Usual (BAU) and Net Zero (NZ) scenarios are primarily driven by deployment scale. As storage capacity requirements increase under the NZ scenario, total costs rise proportionally, reflecting higher installation volumes rather than changes in cost structure or efficiency.

Lithium Iron Phosphate (LFP)

For Lithium Iron Phosphate (LFP) batteries, the cost projections indicate a steady and substantial increase in total deployment costs from 2030 to 2070 under both scenarios shown in figure 15. Processed material cost and Mineral costs increase consistently until around 2065, followed by a slight decline towards 2070 in BAU scenario. In NZ scenario, there is deployment of this technology is happening as there is cost increase for both Minerals and processed materials but that is lower than BAU scenario. Given this negligible difference between the material cost and mineral cost in both NZ and BAU scenario, the analysis suggests that importing processed materials may be more practical than importing raw minerals, as the marginal cost advantage does not justify the significant capital investment required for establishing domestic processing facilities, along with the associated energy and operational costs.

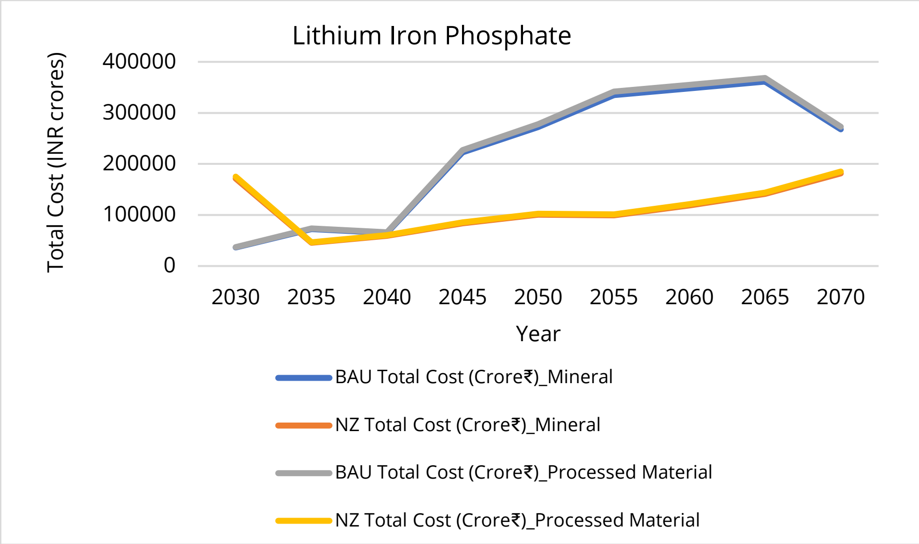

Figure 15. Cost projection in BAU and NZ scenario for LFP technology

LFP-LTO

In case of LFP-LTO technology, there is deployment in both BAU and NZ scenario as shown in figure 16. This technology picked up after 2045 and the trend suggest that importing mineral is cost effective than importing processed materials as the gap between the costs is widening over time. In this case, a key observation in NZ scenario is the widening gap between processed material and mineral costs, particularly after 2050, where the difference reaches approximately ₹40,000 crore. This indicates that the technology is highly processing-intensive and relies on advanced manufacturing techniques and specialized materials. Such technologies present strong opportunities for cost reduction through localized manufacturing from a domestic manufacturing perspective; this presents a strong opportunity for India to capture value through local production. However, the high technological complexity and substantial capital requirements associated with LTO processing may pose challenges, especially in the short to medium term.

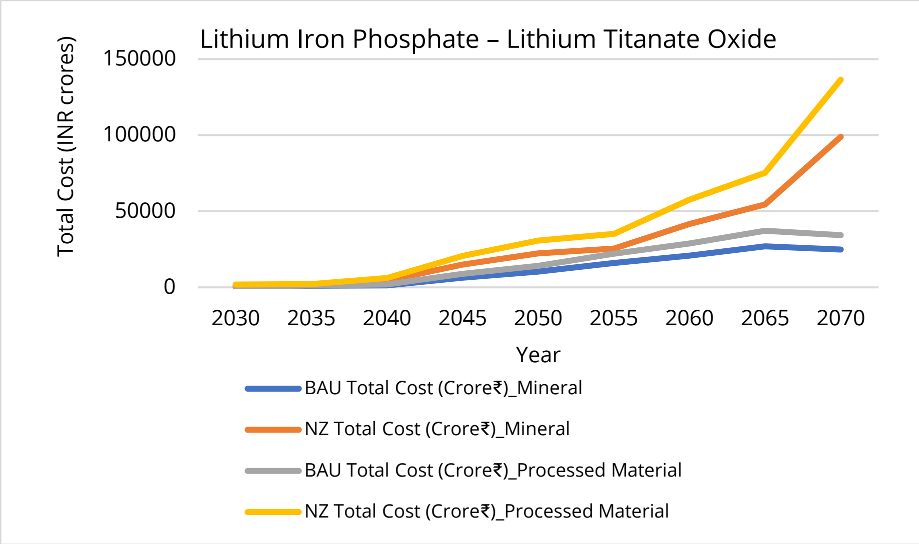

Figure 16. Cost projection in BAU and NZ scenario for LFP-LTO technology

Solid state batteries

Solid-State Batteries exhibit the opposite trend, where importing processed materials is more economical than importing raw minerals as shown in figure 17. As shown in figure 17, the difference between the mineral and processed material cost in year 2065 is 30000 Cr. Which suggests that it's better to import processed materials for short term and long term as well to avoid the capital required for manufacturing plant installation, critical mineral procurement and energy intensive processes unless the domestic manufacturing is supported by technological learning and innovation and reduction of critical minerals costing.

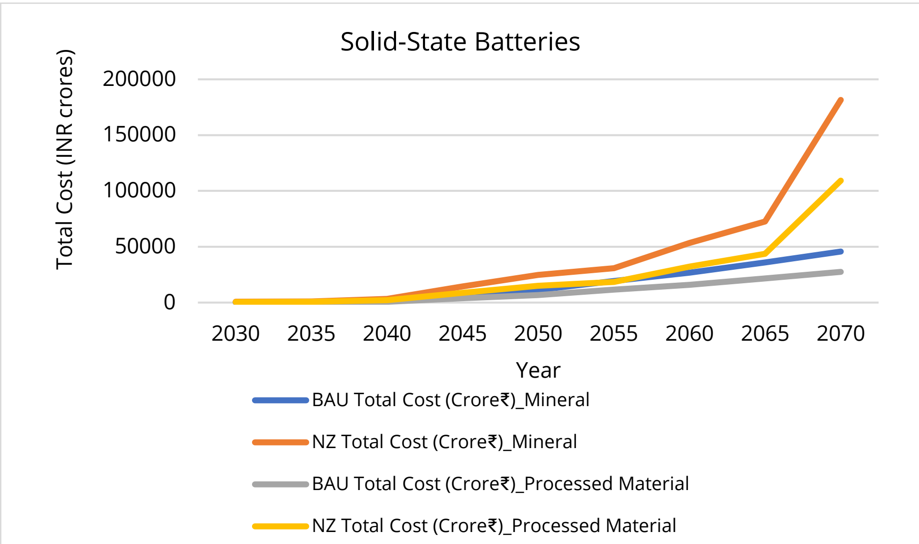

Figure 17. Cost projection in BAU and NZ scenario for ESS technology

Vanadium Redox Flow Battery

In the case of Vanadium Redox Flow Batteries (VRFB), the cost difference between importing raw minerals and processed components is negligible as shown in figure 18, indicating no clear economic advantage for either approach but in such cases, importing processed materials may be more practical, as it avoids the additional costs associated with establishing and operating manufacturing infrastructure. The same trend is happening for both NZ and BAU scenario.

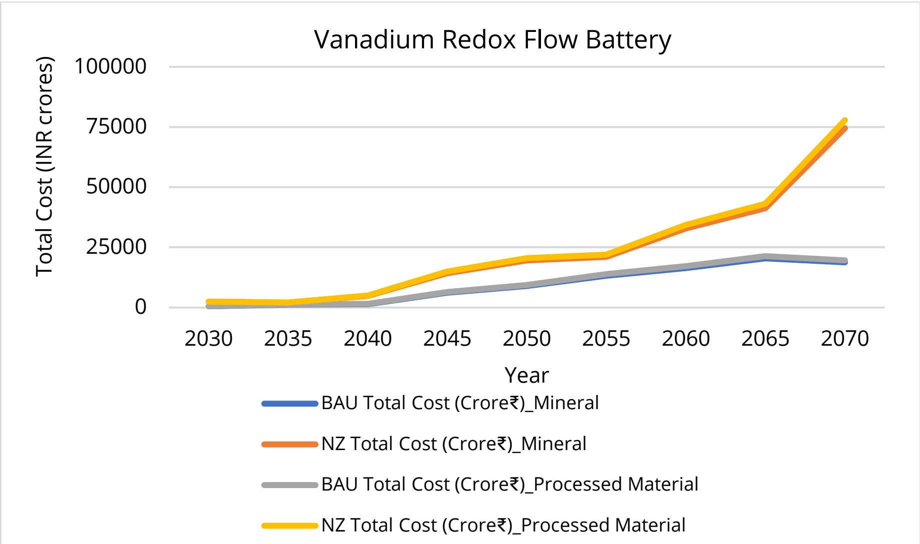

Figure 18. Cost projection in BAU and NZ scenario for VRFB technology

Lithium-Sulphur Batteries

Lithium-Sulphur batteries, exhibit the same trend as Solid state batteries, where importing processed materials is more economical than importing raw minerals as shown in figure 19. This substantial gap indicates that the overall cost structure is heavily dependent on raw material availability rather than processing or manufacturing.

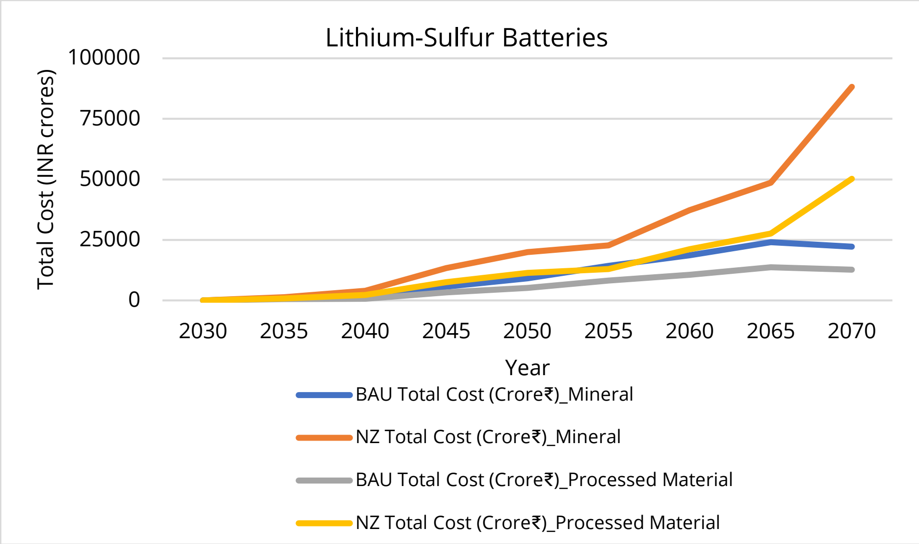

Figure 19. Cost projection in BAU and NZ scenario for Li-S technology

Zinc- Bromine

Zinc-Bromine batteries show the same trend as VRFB where the cost difference between importing raw minerals and processed components is negligible as shown in figure 20. This trend suggests no clear economic advantage for either approach.

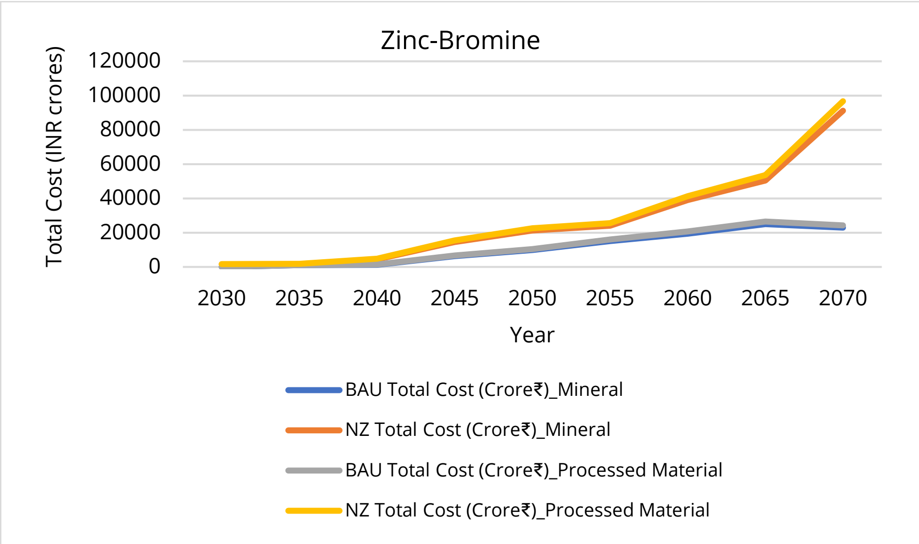

Figure 20. Cost projection in BAU and NZ scenario for ZnBr technology

Sodium-Sulphur

In the case of Sodium-Sulphur batteries, the costing trend is same as ZN-Br and VRFB as shown in figure 21 and hence no clear economic advantage in either approach.

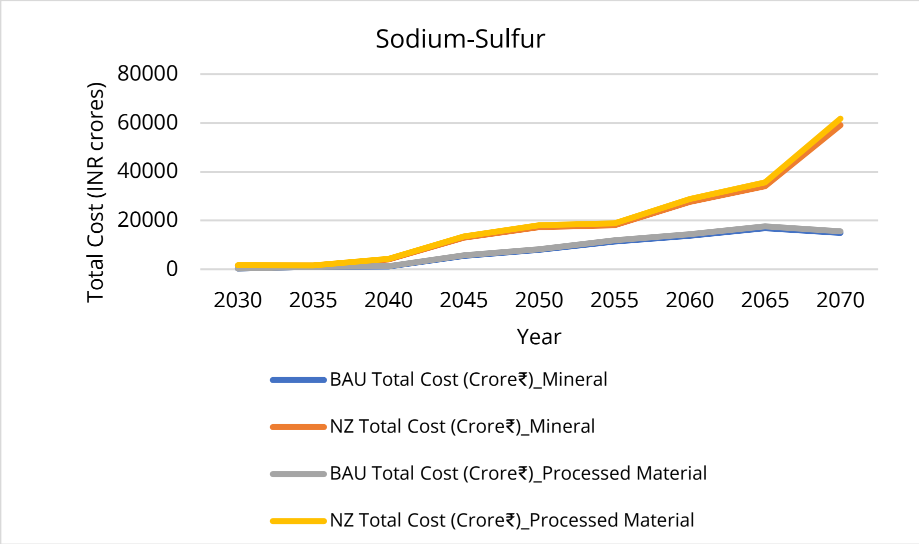

Figure 21. Cost projection in BAU and NZ scenario for Na-S BESS technology

Sodium Nickel Chloride

A similar trend as Lithium-Sulphur and Solid-state batteries is observed for Sodium-Nickel batteries, where material dependency outweighs processing-related cost benefits as shown in figure 22.

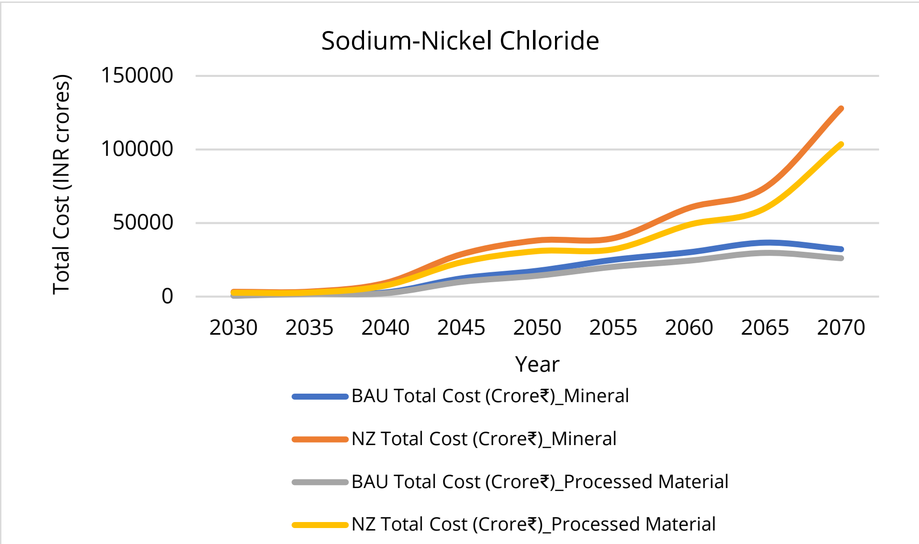

Figure 22. Cost projection in BAU and NZ scenario for NaNiCl2 technology

Overall, the relationship between mineral and processed material costs serves as a critical determinant of domestic manufacturing viability across BESS technologies in India. In technologies like LFP, VRFB, Zinc-Bromine, and Sodium-Sulphur, where both cost components are nearly equal, offer limited scope for economic gains through domestic processing. In such cases, importing processed materials may be more practical, as it avoids the additional costs associated with establishing and operating manufacturing infrastructure. Domestic manufacturing offers limited cost advantages unless it is supported by secure and affordable access to critical raw materials such as lithium. Meanwhile, emerging technologies such as Solid-State, Sodium-Nickel, and Lithium-Sulfur batteries are predominantly material-driven, underscoring the importance of securing raw material supply chains rather than focusing solely on manufacturing localization.

It is important to note that the Bill of Materials (BoM) analysis has also been conducted for a range of other BESS technologies, including Lithium Manganese Oxide (LMO), Lithium Nickel Cobalt Aluminium Oxide (NCA), Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Manganese Cobalt (LNMC), Lithium Cobalt Oxide (LCO), Lead-Acid, and Lithium Nickel Manganese Cobalt (LNMC 811). However, these chemistries are projected to gradually lose market share beyond 2030.

This transition is largely driven by the anticipated phase-out of cobalt-intensive technologies, owing to concerns related to cobalt's toxicity, high cost, and supply chain vulnerabilities. As a result, battery chemistries that rely heavily on cobalt are expected to become less favourable in future deployment pathways (A. Ghosh, S. Pandey, 2025).

In this evolving landscape, the demand for materials such as copper is expected to be primarily driven by technologies like Vanadium Redox Flow Batteries (VRFB), which currently hold a smaller but steadily growing market share, and Lithium Iron Phosphate (LFP) batteries, which, despite having a dominant presence today, are projected to experience a gradual decline over time. Overall, these trends highlight a broader shift in BESS technology preferences toward safer, more sustainable, and supply-secure alternatives.

7.5. Electrolysers

Electrolyser technologies including alkaline (AEC), PEML, and SOEL exhibit cost patterns similar to Wind where importing minerals is more cost effective than importing processed materials. Additionally, Net Zero scenarios show substantially higher costs than BAU, with a noticeable peak around 2045–2055, reflecting the scaling up the capacity and technology transition phase.

Alkaline electrolyser

The cost trend of Alkaline electrolyser shows a consistent trend where processed materials cost is significantly higher than mineral cost for both BAU and NZ scenario as shown in figure 23. In the Net Zero scenario, the cost differential between processed materials and raw minerals for the year 2055 is estimated at approximately INR 151,000 crore. This highlights that a significant proportion of total costs is driven by manufacturing, system integration, and advanced component production, rather than by raw material extraction alone.

This trend also underscores a strategic opportunity for domestic industry: with improvements in manufacturing efficiency and cost competitiveness, there is strong potential for the country to position itself as a global hub for battery production.

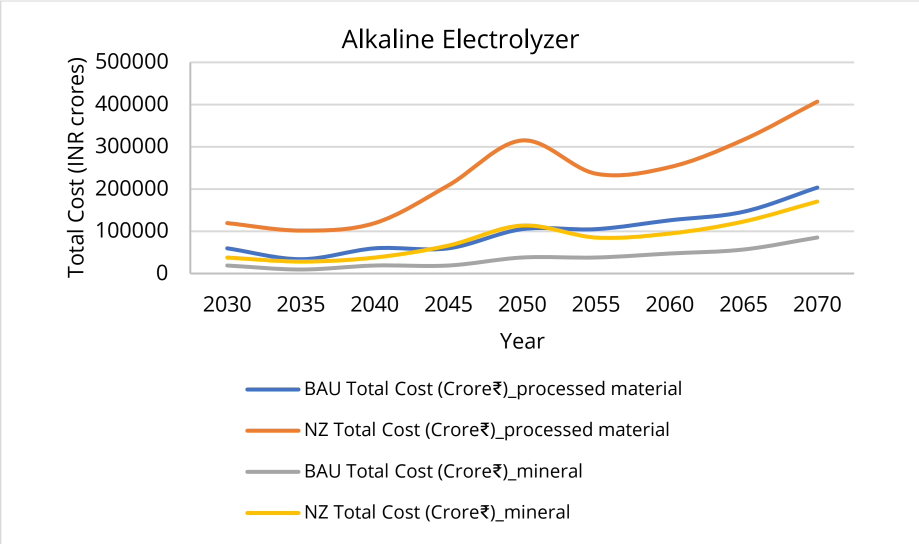

Figure 23. Cost projection in BAU and NZ scenario for AEC technology

PEMEL

The trend cost of implementation of PEMEL technology shows the same trend as Alkaline electrolyser as shown in figure 24. The gap of cost between processed material and mineral is particularly large in PEM electrolysers, suggesting that the scope for value addition through domestic manufacturing is highest in PEMEL,

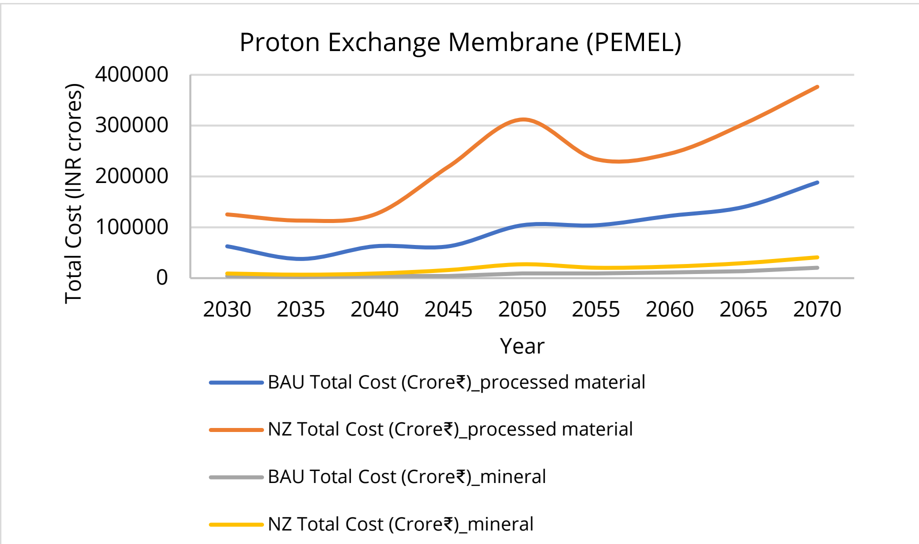

Figure 24. Cost projection in BAU and NZ scenario for PEMEL technology

SOEL

The installation of this electrolyser capacity is very limited across 2070 so the total cost is also very limited as shown in figure 25. The SOEL also shows the same trend as above two electrolyser technology as shown in figure 25. The only difference is that the gap between Processed material cost and mineral cost is relatively lower in this case.

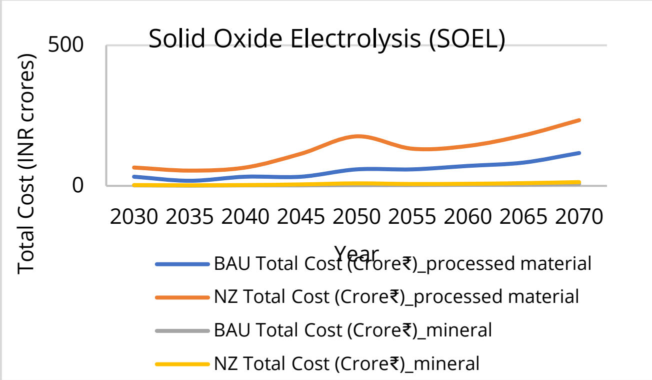

Figure 25. Cost projection in BAU and NZ scenario for SOEL technology

Since the gap between mineral cost and processed material gap is wide, investing solely in raw material sourcing would not yield significant cost advantages. Instead, building a robust manufacturing ecosystem can capture the dominant share of value and improve cost competitiveness. Among technologies, alkaline electrolysers are best suited for near-term large-scale deployment due to their lower costs and maturity, while PEM electrolysers offer the greatest long-term manufacturing opportunity due to their high processed material cost share and growing relevance in renewable-integrated systems. SOEL, although promising for future efficiency gains, remains more R&D-driven with comparatively lower immediate manufacturing leverage.

In terms of policy, India should adopt a multi-technology and manufacturing-led strategy, including targeted incentives such as PLI schemes for electrolyser components, support for scaling up the manufacturing, and investment in advanced material. Ensuring access to critical minerals should remain a supporting strategy, complemented by recycling and material efficiency improvements. Overall, the findings clearly indicate that India's competitive advantage in the hydrogen economy will come from becoming a global hub for electrolyser manufacturing and supply chains, rather than relying on mineral resource ownership, thereby aligning industrial growth with long-term decarbonization goals.

8. Result Summary

Technology	Sub-technology	Results
Solar	mono-Si PV	Importing processed materials remains more cost-effective than importing raw minerals across 2070. The cost of Mono PV technology is highest as the deployment is highest among solar techs
	poly-Si PV	Importing processed materials remains more cost-effective than importing raw minerals. Total costs decline in the Net Zero (NZ) scenario after 2040, primarily due to a reduced share of polycrystalline technology
	CIGS	This cost advantage of importing processed materials over minerals holds across emerging thin-film options such as CdTe through 2070. The increase in cost gap shows the scaling up domestic manufacturing for thin film technologies, supported by technological learning and innovation
	CdTe	Importing processed material is more cost effective than importing minerals. Same trend as CIGS
Wind (Onshore)	GB-MS-PMG	Importing raw mineral is more cost effective than importing processed materials. Gap between the cost is narrow
	GB-DFIG	Importing raw mineral is cost effective than importing processed materials. Initial years there is significant gap in total cost but later becomes negligible. Deployment become negligible beyong 2050 in NZ scenario
	GB-SCIG	Same trend as GB-DFIG. Under BAU this reached the peak deployment but there is sharp decline in installation post-peak
	DD-EESG	Importing minerals and importing finished components have nearly the same cost implications. Result suggest that better to import processed materials to avoid the manufacturing cost
	DDPMSG	Importing raw mineral is more cost effective than importing processed materials. Widening in cost suggest that there is lot of cost involved in manufacturing the components of wind materials apart from the cost of critical minerals.

Wind (Offshore)	GB-SCIG	the gap between processed material cost and mineral cost is very low in BAU scenario and negligible in NZ scenario which suggest that importing the processed materials is cost effective than importing minerals and scaling up the domestic manufacturing which need a huge capital and manufacturing processes are also energy intensive.
	DDPMSG	This technology will be deployed widely in NZ scenario but in BAU its installation will be very limited. Also the gap in cost between processed materials and minerals very narrow, suggesting its better to import processed mineral to save our own resources.
	GB-MS PMG	Importing minerals is more cost effective than importing processed materials but again the gap in cost id very narrow. There is lower capacity addition of GB-MS-PMG in NZ scenario than in BAU scenario
Battery Energy Storage (BESS)	VRFB	The cost difference between importing raw minerals and processed components is negligible, indicating no clear economic advantage for either approach but in such cases, importing processed materials may be more practical, as it avoids the additional costs associated with establishing and operating manufacturing infrastructure
	LTO	This technology picked up after 2045 and the trend suggest that importing mineral is cost effective than importing processed materials as the gap between the costs is widening over time.
	LFP	Given the negligible difference between the material cost and mineral cost in both NZ and BAU scenario, the analysis suggests that importing processed materials may be more practical than importing raw minerals
	NaNiCl2	Importing minerals is more cost effective than importing processed materials but again the gap in cost is narrow.
	ESS	This technology exhibit the trend, where importing processed materials is more economical than importing raw minerals
	NaS	The cost difference between importing raw minerals and processed components is negligible
	Li–S	Importing processed materials is more economical than importing raw minerals. This substantial gap indicates that the overall cost structure is heavily dependent on raw material availability rather than processing or manufacturing.

	ZnBr	The cost difference between importing raw minerals and processed components is negligible
Electrolysers	AEL	Importing minerals is more cost effective than importing processed materials.
	PEMEL	Importing minerals is more cost effective than importing processed materials. The gap of cost between processed material and mineral is particularly large.
	SOEL	The SOEL also shows the same trend as above two electrolyser technology. The only difference is that the gap between Processed material cost and mineral cost is relatively lower in this case.

9. Conclusion

This study develops a comprehensive Bill of Materials (BoM)-based analytical framework to evaluate the material, mineral, and cost implications of scaling clean energy technologies in India. By integrating material composition, mineral conversion, and HS code-level trade data, the analysis provides a granular understanding of how clean energy deployment translates into supply chain dependencies and economic exposure under Business-as-Usual (BAU) and Net Zero (NZ) scenarios over the period 2030–2070.

The findings highlight distinct, technology-specific cost asymmetries in import strategies across the clean energy value chain. In the case of Solar PV, importing finished components consistently proves to be more cost-effective than importing raw minerals, and this trend persists across both thin-film and emerging PV technologies. In contrast, wind energy technologies both onshore and offshore exhibit a structural advantage for mineral imports, indicating that domestic value addition through manufacturing and processing could be more economically viable in this segment.

For Battery Energy Storage Systems (BESS), the relationship between processed material costs and mineral costs emerges as a critical determinant of the optimal import strategy. The analysis shows a mixed pattern across different battery chemistries: in some cases, importing raw minerals is more cost-effective; in others, importing processed materials offers greater economic benefits; and for certain technologies, the cost difference between the two is negligible. This variation underscores the need for a differentiated approach within the BESS sector itself.

In the case of electrolysers, importing processed materials is consistently more cost-effective than importing raw minerals, with the cost gap widening significantly in the later years. This suggests increasing advantages in relying on global supply chains for higher-value components rather than investing heavily in upstream processing.

Overall, these results clearly indicate that a uniform industrial or trade policy would be suboptimal. Instead, a technology-specific and value-chain-sensitive policy approach is essential to ensure cost efficiency, competitiveness, and strategic resource utilization.

A key insight from the analysis is that deployment scale is the primary driver of long-term cost trajectories, rather than short-term trade price fluctuations. The pronounced cost divergence under the NZ scenario particularly around mid-century reflects accelerated capacity expansion, followed by stabilization as deployment plateaus and technology shares evolve. This underscores the importance of aligning material supply strategies with long-term energy transition pathways.

The study also highlights India's structural dependence on imported processed materials and intermediate goods, driven by limited domestic midstream processing capacity. This reinforces the distinction between resource availability and manufacturing capability, emphasizing that mineral security is not solely a function of geological endowment but also of processing, refining, and industrial ecosystem development.

From a policy perspective, the results underscore three critical priorities. First, strategic trade diversification must be guided by data-driven assessments of supplier reliability, governance quality, and long-term supply stability. Second, industrial strategy must be technology-specific, focusing domestic manufacturing efforts where cost competitiveness and value addition are achievable, particularly in wind technologies, BESS and electrolysers. Third, there is a need to strengthen midstream processing capabilities and circular economy systems, including recycling and material substitution, to reduce long-term import dependence.

Methodologically, the study contributes to the literature by bridging the gap between material flow analysis, cost modelling, and scenario-based energy planning. The BoM-centric approach enables a more realistic representation of supply chain constraints by focusing on processed material inputs rather than raw mineral availability, which is particularly relevant in the Indian context.

However, the analysis is subject to certain limitations. The cost framework is based on import (CIF) values and excludes factors such as energy costs, manufacturing overheads, and logistics, and therefore represents partial production costs rather than full system costs. Additionally, future technological changes, material substitutions, and policy interventions may alter material intensity and cost trajectories.

Overall, the study demonstrates that achieving India's clean energy and net-zero goals requires a coordinated strategy integrating material security, trade policy, and industrial development. A BoM-based analytical lens provides a robust foundation for aligning critical mineral supply chains with energy transition pathways, ensuring that the transition is not only low-carbon but also economically efficient, resilient, and strategically secure.

10. Policy recommendations

Adopt a Phased and Strategic Approach to Domestic Manufacturing

- Given the evolving cost differentials, large-scale domestic manufacturing should be pursued in a phased manner, aligning with periods when cost gaps widen and global competitiveness improves.
- Focus initially on high-value components and downstream processing, where value addition is highest, rather than immediate full-scale vertical integration from raw minerals.
- Encourage technology transfer, joint ventures, and innovation ecosystems to accelerate cost reductions over time.
- India's competitive advantage in the clean energy technology (CET) economy is likely to stem from its ability to emerge as a global hub for manufacturing and integrated supply chains, rather than from ownership of mineral resources. This approach aligns industrial development with long-term decarbonization objectives while enhancing economic competitiveness.

Strengthen Industrial Ecosystem and Upstream Linkages

- Expansion of CET manufacturing will significantly increase demand for iron & steel, aluminium, and specialty chemicals.
- Develop targeted policies to decarbonize and modernize these hard-to-abate sectors, ensuring that increased industrial activity does not lead to higher emissions.
- Domestic manufacturing provides limited cost advantages unless it is complemented by reliable and cost-effective access to critical raw materials such as lithium. At the same time, emerging battery technologies such as Thin film PV, solid-state, sodium-nickel, and lithium-sulfur are highly material-intensive, highlighting the need to prioritize secure and resilient raw material supply chains alongside efforts to localize manufacturing
- Promote circular economy approaches, including recycling of metals and battery materials, to reduce import dependence and resource pressure.

Plan for Substantial Increase in Electricity Demand

- Manufacturing of solar PV, wind components, and batteries is highly energy-intensive, implying a considerable rise in electricity demand.
- Ensure that this additional demand is met through clean and reliable power sources, to avoid undermining climate objectives.

- Promote dedicated renewable energy supply, green open access, and storage integration for manufacturing clusters to ensure cost competitiveness and sustainability.

Develop Integrated Manufacturing Clusters with Efficient Land Use

- Large-scale manufacturing facilities will require significant land allocation, potentially creating pressure on land resources.
- Establish integrated industrial clusters or parks for CET manufacturing to optimize land use, enable shared infrastructure, and reduce logistical costs.
- Incorporate sustainable land-use planning, minimizing environmental and social impacts, and prioritizing brownfield development where feasible.

Address Fiscal Implications and Optimize Public Spending

- Incentivizing domestic manufacturing through subsidies, PLI schemes, and infrastructure support can have implications for the fiscal deficit.
- Shift from broad-based subsidies to targeted, performance-linked incentives that reward efficiency, scale, and innovation.
- Leverage private investment and blended finance mechanisms to reduce the burden on public finances while ensuring sectoral growth.

Enhance Supply Chain Resilience and Material Security

- Diversify sourcing strategies for critical minerals while simultaneously building domestic processing capabilities where economically viable.
- Invest in R&D for alternative materials and next-generation technologies to reduce dependence on scarce or high-risk inputs such as cobalt.
- Domestic manufacturing provides limited cost advantages in some CETs unless it is complemented by reliable and cost-effective access to critical raw. At the same time, emerging battery technologies such as solid-state, sodium-nickel, and lithium-sulfur are highly material-intensive, highlighting the need to prioritize secure and resilient raw material supply chains alongside efforts to localize manufacturing

Align Industrial Growth with Long-Term Competitiveness

- The BoM trends suggest that manufacturing costs can decline over time with learning-by-doing, economies of scale, and innovation.
- Policies should therefore aim to build long-term competitiveness, enabling the country to emerge as a global manufacturing hub, particularly in sectors like batteries and renewable energy components

11. References

1. A. Ghosh, S. Pandey, 2025. Strategies to Address India's Critical Minerals' Vulnerability through Resource Efficiency. ACPET.
2. C. Konda and K. Rakheja, 2024. India's hunt for critical minerals. Institute for Energy Economics and Financial Analysis.
3. Carrara, S., Alves Dias, P., Plazzotta, B., Pavel, C., 2020. Raw Materials Demand for Wind and Solar PV Technologies in the Transition Towards a Decarbonised Energy System. Publ. Off. Eur. Union.
4. Chadha, R., Goel, S., Goldar, A., Jain, R., et al., 2025. State of the Sector: Critical Energy Transition Minerals for India, Vol. I, 2025. State of the Sector: Critical Energy Transition Minerals for India, Vol. I. CEEW, CSEP, ICRIER, IISD, Shakti.
5. Chadha, R., S. Goel, A. Goldar, and R. Jain, 2025. State of the Sector: Critical Energy Transition Minerals for India. Vol. II. Delhi.
6. EcoGreen energy, 2025. Understanding BOM Reports in the Solar Industry: A Key to Quality Assurance. URL https://eco-greenenergy.com/understanding-pv-bom-reports-in-the-solar-industry-a-key-to-quality-assurance/#:~:text=What%20Is%20a%20BOM%20Report,taken%20in%20selecting%20each%20component.
7. IEA, P., 2023. Energy Technology Perspectives 2023.
8. IEA, P., 2021. The Role of Critical Minerals in Clean Energy Transitions.
9. IRENA, 2021. RENEWABLE POWER GENERATION COSTS IN 2020.
10. IRENA, 2017. ELECTRICITY STORAGE AND RENEWABLES: COSTS AND MARKETS TO 2030. International Renewable Energy Agency.
11. L. McGovern, E. Tapoglou, and A. Georgakaki, 2024. Material requirements for wind turbines.
12. Ministry of commerce and industry, Department of commerce, 2025. Ministry of commerce and industry, Department of commerce.
13. Ministry of Mines, 2025. INDIAN MINERALS YEARBOOK 2023.
14. Ministry of Power, 2026. Non-Fossil Fuel Share In Total Installed Power Capacity.
15. NITI Ayog, 2026. A Study Report On - Scenarios Towards Viksit Bharat and Net Zero: An Overview (Vol. 1).

16. R. Chadha and G. Sivamani, 2024. Projecting critical minerals need for India’s energy transition: How much of which minerals are needed for the transition (Working paper).
17. Renewable Energy Magazine, 2024. Rethink Energy publishes solar perovskite forecast to 2040.
18. Rozon, F.; McGregor, C.;, Owen, M, Owen, M, 2023. Long-Term Forecasting Framework for Renewable Energy Technologies’ Installed Capacity and Costs for 2050.
19. Steffie Banatvala, 2026. Energy storage trends to watch in 2026: analysts. Recharge.
20. SUNTSU, 2026. BOM Analysis & Cost Reduction.
21. Tagotra, Niharika, Nidhi, Srivastava, Abhinav Sharma, and T.S. Gowthami, 2024. Critical minerals for India’s clean energy transition. New Delhi, India.
22. WTW, 2023. Renewable Energy Supply Chain Risk Report 2023.
23. Y. Xiao, J. Xiao, H. Zhao, J. Li, G. Zhang, D. Zhang, 2024. Prussian Blue Analogues for Sodium-Ion Battery Cathodes: A Review of Mechanistic Insights, Current Challenges, and Future Pathways.

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