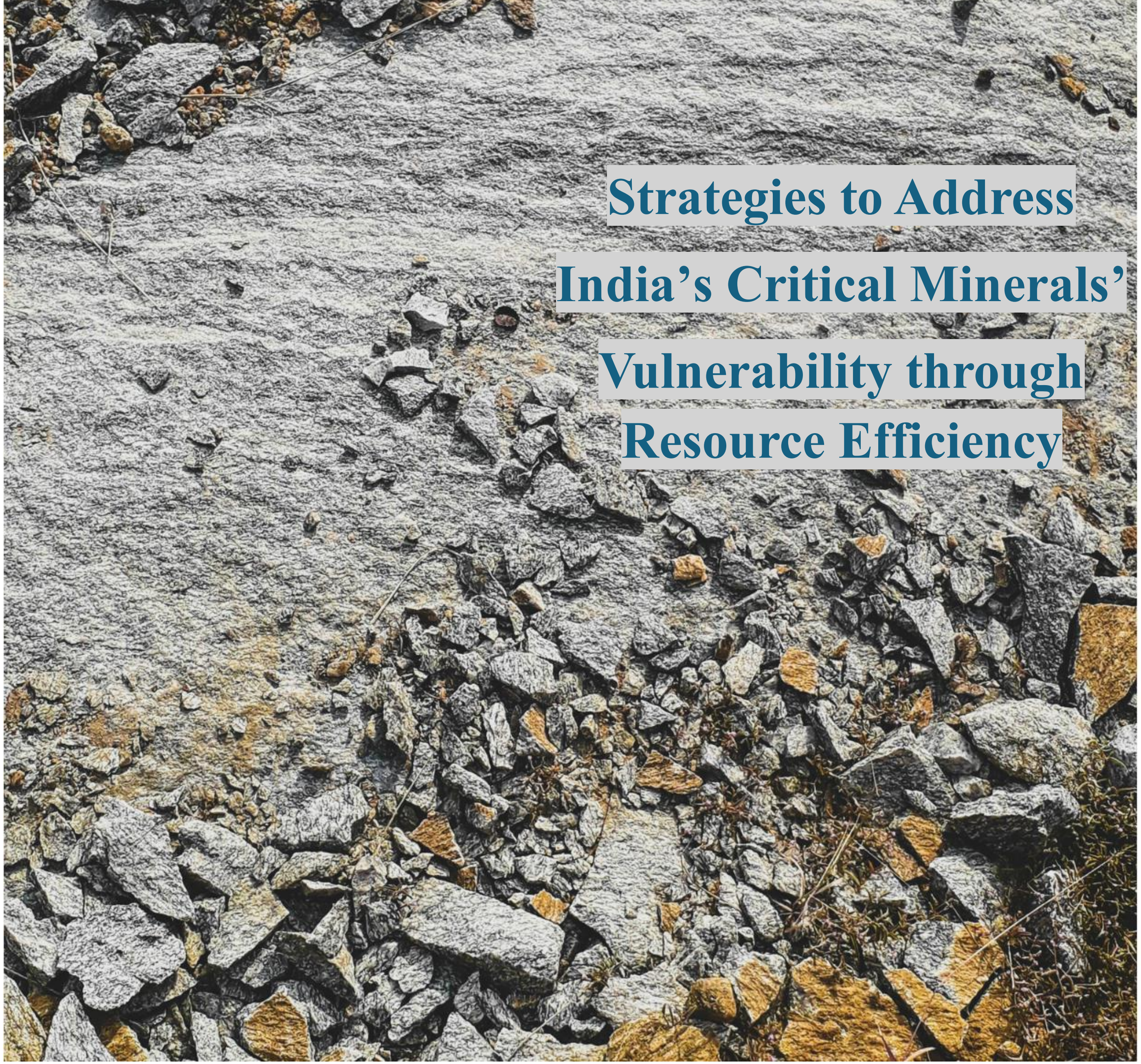

Strategies to Address India’s Critical Minerals’ Vulnerability through Resource Efficiency

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Report Title

Strategies to Address India's Critical Minerals' Vulnerability through Resource Efficiency

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Abstract

India's clean energy transition is essential for achieving its ambitious climate targets, including 500 GW of non-fossil fuel capacity by 2030 and net-zero emissions by 2070. This transition necessitates a significant supply of critical minerals (CMs) essential for manufacturing renewable energy (RE) technologies such as solar, wind, battery storage systems, and green hydrogen electrolysers. This study, commissioned by NITI Aayog and conducted by the Ashoka Centre for a People-Centric Energy Transition (ACPET), projects the demand for 30 CMs across five RE segments - Solar Photovoltaics (PV), Concentrating Solar Power (CSP), Wind (onshore & offshore), stationary Battery Energy Storage Systems (BESS) for Solar PV, and Green Hydrogen Electrolysers - until 2070.

Using the deterministic scenario from India Energy Security Scenarios (IESS) 4.0, the study employs a technological assessment framework, material intensity analysis, and market share projections to estimate mineral requirements. Findings indicate that Copper, Nickel, Silicon, Graphite, Vanadium, Cobalt, Rare Earth Elements (REEs), and Lithium will see substantial growth in demand, with some minerals projected to increase over 100 times their 2023 levels.

The study highlights the aggressive growth of cumulative demand/requirement of each CM until 2070 across the above-listed RE segments to portray the need for a comprehensive strategy, including resource efficiency, domestic mineral exploration, recycling initiatives, and international collaborations, to mitigate supply vulnerabilities and support India's sustainable energy future.

1. Introduction: Background, Problem Statement, Literature Review

India's clean energy transition is critical for achieving its climate goals of 500 GW[1] of non-fossil fuel capacity by 2030 and net-zero emissions by 2070[2]. This transition demands substantial quantities of CMs[3] which are essential for manufacturing RE systems like solar, wind, energy storage systems, and green hydrogen electrolysers. The Ministry of Mines, Government of India, has identified 30 CMs[4] essential for national security and economic growth. Given their scarcity, addressing the growing demand for these minerals has become crucial in India's transition to a low-emission economy and in achieving its 'Net Zero' targets to successfully meet its renewable energy ambitions and foster a sustainable development future.

NITI Aayog has tasked ACPET to project the demand for the CMs required in various Solar PV, CSP, Onshore & Offshore Wind, BESS for Solar PV, and Green Hydrogen Electrolyser technologies, from 2023 to 2070, based on the installed capacity of RE plants given in the Deterministic Scenario (T3) of India Energy Security Scenarios (IESS). In the computation exercise conducted by ACPET, 22 CMs from the 30 listed by the Ministry of Mines have been analyzed across all RE segments. Among these 30 CMs, two categories, REEs and Platinum Group Elements (PGEs), encompass multiple individual minerals. Specifically, the Ministry of Mines lists 17 minerals under REEs and 6 under PGEs, bringing the total number of critical minerals to 51. This study covers 30 of these 51 CMs, including Cobalt, Copper, Gallium, Germanium, Graphite, Indium, Lithium, Molybdenum, Niobium, Nickel, Silicon, Strontium, Tellurium, Tin, Titanium, Tungsten, Vanadium, Zirconium, Selenium, and Cadmium. Among the REEs, Dysprosium, Neodymium, Praseodymium, Terbium, Yttrium, Cerium, Lanthanum, and Gadolinium have been included, while among the PGEs, Platinum and Iridium have been covered. This comprehensive coverage ensures that the study captures the most relevant minerals essential for clean energy technologies and infrastructure.

2. Data and Methodology

2.1. Technological Assessment Framework

In this study, 8 clean energy technologies (CETs) in Solar PV, 2 CETs in Solar CSP, 5 CETs in onshore Wind, 4 CETs in offshore Wind, 20 CET based on 6 chemistries, i.e., lithium, vanadium,

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[1] Press Information Bureau. (2023, April 5). *Government declares plan to add 50 GW of renewable energy capacity annually for next 5 years to achieve the target of 500 GW by 2030*. Press Information Bureau. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1913789

[2] Press Information Bureau. (2023, August 3). *Net zero emissions target*. Press Information Bureau. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1945472

[3] International Energy Agency. (2024). *Mineral requirements for clean energy transitions*. IEA Publications.

[4] Ministry of Mines. (2023, June). *Annual report 2022-23*. Ministry of Mines, Government of India. https://mines.gov.in/admin/download/649d4212cceb01688027666.pdf

sodium, lead, nickel, and bromine, in BESS, and 3 electrolysers for Green Hydrogen production, were selected to be part of the exercise. These CETs were selected based on the Technology Readiness Level (TRL), Efficiency of technology, and End of Life (EOL) of technology, determined from the systemic literature review. TRL indicates the maturity of the CETs. CETs with TRL level 4 to 9 have been selected for the exercise[5].

TRL = f (Validation Stage, Testing Environment, Integration Level, Documentation, Demonstration)

As for EOL of CETs, the CET that retire at least 20 years from the date of their commercialization has been considered.

2.2. Assessment of the requirement of critical minerals in RE technologies for all the RE segments

This exercise considered RE segment-specific cumulative capacities provided in India Energy Security Scenarios 2070, i.e., IESS Version 4.0. IESS uses sector-specific levers with four defined levels - Level 1 (Pessimistic) assumes minimal interventions; Level 2 (Business-As-Usual) reflects achievable efforts based on historic and current trends; Level 3 (Optimistic/Deterministic) aligns with climate commitments; and Level 4 (Heroic) targets highly ambitious goals within technical limits. In the exercise, firstly, the total requirement of a CM required in a CET, under a RE segment has been projected for trajectory 3, i.e., Deterministic, until 2070 using the cumulative capacity values mentioned along T3 in IESS, market share of the CET, and mineral intensity of the CM in the CET. This has been done for all 30 CMs, for all the CETs each CM requires under all RE segments. Secondly, the total requirement of a CM required in all the CETs in a RE segment has been calculated until 2070 by summing the total requirement of a CM required in a CET in a RE segment across all the CETs the CM is required in in a RE segment. Again, this has been done for all the 30 CMs under a RE segment. Finally, the total requirement of each CM across all RE segments has been calculated until 2070 by summing up the total requirement of a CM required in all the CETs the CM is required in a RE segment across all the RE segments. This has been done for all 30 CMs. Refer to equations 4, 5, 6 in section 2.5 for the above calculations.

We have used data from various studies on mineral intensity. Mineral intensity is measured in tonnes per gigawatt (t/GW) for renewable energy segments like Solar PV, CSP, and Wind. For BESS, it is measured in tonnes per gigawatt-hour (t/GWh). For data on Electrolysers, data on Green Hydrogen production projection in million tonnes (Mt) until 2070 has been provided by NITI Aayog, which has been considered along with the data on efficiency of the three electrolysers secured from literature to generate capacity values of the electrolysers in t/GW.

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[5] Australian Renewable Energy Agency. (2014). *Technology readiness levels for Renewable Energy Sectors*. https://arena.gov.au/assets/2014/02/Technology-Readiness-Levels.pdf

Furthermore, data on the market share of CETs has been considered from the literature. However, many of these technologies are not fully commercialized yet. Due to this, the market share of these technologies is uncertain. Moreover, projection of the market share until 2070 was also not available in the literature. To address this data gap, we used a heuristic approach, where market share has been projected as a function of TRL, efficiency, and EOL of the CETs. TRL being a key factor, we have considered the assumption while projecting the market share that for CETs under any RE segment with TRL 8-9, the market share is to decrease over the years for all the trajectories gradually. On the other hand, for CETs with TRL level 4-7, the market share is to increase over the years, for all the trajectories gradually. This assumption comes from the idea that gradually, with time, the technologies will mature, causing their market share to increase. Due to this, the market share of CETs, which are mature at the current time, will fall gradually with time. This is because market share is given on a scale of 0 to 1, so with the increase in CETs under a RE segment in the market, the market share of each CET falls. It is to be noted that the market share of CETs also varies across trajectories. Table 7 in the appendix gives the market share of all the CETs under all the RE segments considered in this exercise for the Deterministic trajectory.

2.3. Material Intensity

Table 1 in the appendix presents mineral requirements for various Solar PV CETs. Crystalline Silicon PV types include Monocrystalline Silicon (mono-Si), Polycrystalline Silicon (poly-Si), and Heterojunction Silicon (HJT); Thin-Film PV technologies include Copper Indium Gallium Selenide (CIGS), and Cadmium Telluride (CdTe); and Perovskite technologies include perovskite/silicon tandem and Perovskite APT. CMs include Nickel, Tin, Copper, Silicon, Indium, Gallium, Selenium, Cadmium, Tellurium, Molybdenum, Tungsten, Graphite, Titanium, Lithium, and Germanium, highlighting the diverse material needs of the technologies.

Table 2 in the appendix provides data on the mineral requirements for two types of CSP CETs - Parabolic Troughs (a linear concentrating system) and Solar Power Towers (a point-focus system). The CMs include Copper, Molybdenum, Nickel, Titanium, Vanadium, and Niobium, offering a comprehensive look at the raw material demands of these CSP technologies.

Table 3 in the appendix outlines mineral requirements for different Wind Technology types, categorized by onshore and offshore wind turbine systems, specifically focusing on direct-drive and gearbox technologies. CMs include Copper, Molybdenum, Neodymium, Nickel, Dysprosium, Praseodymium, Terbium, and Yttrium.

Table 4 in the appendix provides a comparative overview of various BESS CETs, highlighting the CM requirements for each. Each technology is listed with its category abbreviation alongside the quantities of specific minerals needed in tonnes per gigawatt hour (t/GWh). The CMs tracked include Graphite, Lithium, Cobalt, Nickel, Copper, Vanadium, Cadmium, Cerium, and Lanthanum, offering a comprehensive look at the raw material demands of these storage technologies. The technologies include Lithium cobalt oxide, Lead-

Acid, Lithium-Ion, Vanadium Redox Flow Battery, Nickel-Cadmium, Lithium Titanate, Lithium Iron Phosphate, Nickel-Metal Hydride, Lithium Nickel Manganese Cobalt variants, Sodium-Nickel Chloride, Polysulfide Bromide, Lithium Manganese Oxide, Solid-State Batteries, Lithium Nickel cobalt, Aluminium Oxide, Sodium-Sulphur, Lithium-Sulphur Batteries, and Zinc-Bromine. It is to be noted that Lead-Acid, Polysulfide Bromide, and Zinc-Bromine technologies have no CMs, and hence are outside of the scope of this study.

Table 5 in the appendix outlines that the CMs required for green hydrogen production vary across different electrolyser technologies. Alkaline Electrolysers (AEL) primarily rely on copper, zirconium, nickel, graphite, and cobalt. Proton Exchange Membrane Electrolysers (PEMEL) utilize copper, graphite, iridium, platinum-group metals, and silicon. Solid Oxide Electrolysis (SOEL) requires a diverse range of CMs, including Copper, Zirconium, Nickel, Silicon, Titanium, Lanthanum, Strontium, Gadolinium, Cerium, and Yttrium.

Overall, 42 CETs have been considered for this demand/requirement projection exercise for CMs.

2.4. Cumulative Capacity

Table 6 in the appendix gives the cumulative capacity (given in GW for Solar, Wind, and Electrolysers, and GWh for BESS) of Solar PV, CSP, Onshore Wind, Offshore Wind, BESS, and Electrolysers for deterministic trajectory.

It is to be noted here that for BESS, IESS 4.0 only provided Trajectory 2 cumulative capacity values. Due to this, trajectory 3 was constructed using cumulative capacity values of Solar PV because BESS is considered for Solar PV in this exercise. Equations 1 and 2, respectively, give the calculations:

$$\Delta r_{T,t_k} = \frac{C_{T,t_k} - C_{T-1,t_k}}{C_{T-1,t_k}} \text{ ……... (1)}$$

Where,

- $\Delta r_{T,t_k}$ is the Rate of Change of trajectory values of Solar PV cumulative capacity, for time period “k”, where $t = \{t_{2023} \dots \dots, t_{2070}\}$, where, $k = 2023, \dots \dots, 2070$, given for trajectory 3.
- C_{T,t_k} is the Cumulative capacity of Trajectory 3 of Solar PV, for time period “k”.
- C_{T-1,t_k} Cumulative capacity of Trajectory 2 of Solar PV, for time period “k”.

And,

$$\rho_{T,t_k} = Y_{T-1,t_k} + (\Delta r_{T,t_k} * Y_{T-1,t_k}) \text{ ……... (2)}$$

Where,

- ρ_{T,t_k} is the projected cumulative capacity of BESS for trajectory 3, for time period “k”.
- Y_{T-1,t_k} is Cumulative capacity of Trajectory 2 of BESS, for time period “k”.

Here, “T” is trajectory 3. So “$T - 1$” is trajectory 2. “t” is a set of years.

Furthermore, the equation 3 below gives the formula for generating capacity values[6] for electrolysers based on efficiency and green hydrogen production projection per annum.

$$X_{T,t_k} = \frac{P_{t_k} * e_y * 10^9}{8670 * 10^6} \text{ ……... (3)}$$

Where,

- X_{T,t_k} Capacity of Electrolyser in time period “k”, where, $k = 2023, 2030, 2047, 2070$.
- P_{T,t_k} is estimated Green Hydrogen Production in time period “k”.
- e_y is the efficiency of electrolyser “y”. Here, y = 1,2,3.

Green Hydrogen Production is given in million tonnes for year “k”. To convert this value to Kg, a factor of 10^9 is multiplied. Efficiency of Electrolyser “y” is given in $\frac{\text{KWh}}{\text{Kg}}$. To convert KWh to GWh, the equation is divided by a factor of 10^6. To convert from GWh to GW, we divide by 8760 hours, that is, the total hours in a year.

Efficiency of AEL is 50 KWh/kg[7] of green hydrogen produced. Whereas efficiency of PEMEL is 60 KWh/Kg[7], and efficiency of SOEL is 37 KWh/Kg[8] of green hydrogen produced. Here, electrolyzer efficiencies represent the amount of electricity required to produce one unit of hydrogen, typically measured in kilowatt-hours (kWh) per kilogram (kg) of H_2 output. This metric indicates how efficiently an electrolyzer converts electrical energy into hydrogen, with lower values signifying higher efficiency. The green hydrogen production projection provided by NITI Aayog is 5 Mt, 16.5 Mt, and 37 Mt for years – 2030, 2047, and 2070 respectively.

2.5. Calculation of the Total Requirement of critical minerals

We have assumed that mineral intensity remains constant over the years and across all trajectories. This assumption is based on the fact that reductions in mineral intensity for selected technologies typically result from innovations driven by high mineral prices. However, since future prices are uncertain and influenced by various global supply and demand factors, it is challenging to estimate changes in mineral intensity at this stage.

Let “m” be the set of CMs, that is 30. Let “i” be the set of CETs across all the RE segment, that is, 42. Let “R” be the set of RE segments, that is 5. Finally, let “t” be the set of years, that is, 4. Thus, equation 4 given below describes the calculation for the requirement of a critical mineral “j” in a CET “l” classified a RE segment “p” in year “k”:

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[6] Khan, M. H. A., Sitaraman, T., Haque, N., Leslie, G., Saydam, S., Daiyan, R., ... & Kara, S. (2024). Strategies for life cycle impact reduction of green hydrogen production–Influence of electrolyser value chain design. *International Journal of Hydrogen Energy*, *62*, 769-782.

[7] Khan, M. H. A., Sitaraman, T., Haque, N., Leslie, G., Saydam, S., Daiyan, R., ... & Kara, S. (2024). Strategies for life cycle impact reduction of green hydrogen production–Influence of electrolyser value chain design. *International Journal of Hydrogen Energy*, *62*, 769-782.

[8] Schropp, E., Naumann, G., & Gaderer, M. (2024). Hydrogen production via solid oxide electrolysis: Balancing environmental issues and material criticality. *Advances in Applied Energy*, *16*, 100194.

$$L_{T,m_j,i_l,R_p,t_k} = \mu_{T,i_l,R_p,t_k} * N_{T,R_p,t_k} * M_{m_j,i_l,R_p} \text{ ……... (4)}$$

Where,

- $m = \{m_{1 \ldots\ldots\ldots}, m_n\}$; Where, $j = 1, \ldots \ldots, n$
  $\Rightarrow m = \{m_{1 \ldots\ldots\ldots}, m_{30}\}$; Where, $j = 1, \ldots \ldots, 30$
- $i = \{i_1 \ldots \ldots, i_a\}$; Where, $l = 1, \ldots \ldots, a$
  $\Rightarrow i = \{i_1 \ldots \ldots, i_{42}\}$; Where, $l = 1, \ldots \ldots, 42$
- $R = \{R_1 \ldots \ldots, R_b\}$; Where, $p = 1, \ldots \ldots, b$
  $\Rightarrow R = \{R_1 \ldots \ldots, R_5\}$; Where, $p = 1, \ldots \ldots, 5$
- $t = \{t_1 \ldots \ldots, t_c\}$; Where, $k = 1, \ldots \ldots, c$
  $\Rightarrow t = \{t_1 \ldots \ldots, t_4\}$; Where, $k = 1, \ldots \ldots, 4$.
- "j" represents one of the 30 CMs.
- "p" represents one of the 5 renewable energy (RE) segments - Solar PV, CSP, Wind, BESS, or Electrolysers.
- "l" represents one of the 42 CETs across all RE segments.
- "k" represents one of the 4 time periods - 2023, 2030, 2047, and 2070
- L_{T,m_j,i_l,R_p,t_k} is the the requirement of CM "j" in CET "l" of a RE segment "p", in year "k".
- μ_{T,i_l,R_p,t_k} is the Market Share of CET "l" of a RE segment "p", in year "k".
- N_{T,R_p,t_k} is the generalized cumulative capacity of a RE segment "p", in year "k". Previously, we have defined the cumulative capacity for trajectory 3 of Solar PV as "C_{T,t_k}", of BESS as "ρ_{T,t_k}", and of Electrolysers as "X_{T,t_k}". However, for the generalized equation, we need a generalized representation of cumulative capacity, common for all the 5 RE segments. Hence, we shall use "N_{T,R_p,t_k}" as the generalized cumulative capacity of a RE segment "p".
- M_{m_j,i_l,R_p} is the material intensity of mineral "p" required in CET "l" of RE segment "p"

The second step is to calculate the total requirement of each critical mineral "j" across all the CETs under each RE segment "p" in time period "k". Equation 5 below gives the calculation. Figures 1-9 under section 3.1, are plotted using this equation.

$$Z_{T,m_j,R_p,t_k} = \sum_{l=1}^{a} L_{T,m_j,i_l,R_p,t_k} \text{ ……... (5)}$$

Where,

- Z_{T,m_j,R_p,t_k} is the total requirement of critical mineral "j" of a RE segment "p", in year "k".

Here, given Solar PV is $R_1, i = 1, \ldots., 8$, since there are 8 CETs in Solar PV. Similarly, given CSP is $R_2, i = 9,10$, since there are only two CETs listed under CSP. Given Wind is $R_3,\ i = 11, \ldots., 19$, since 9 CETs are listed under Wind. Given BESS is $R_4, i = 20, \ldots\ldots, 39$, since 20 CETs are listed under BESS. And, finally, given Electrolysers is $R_5, i = 40, \ldots\ldots, 42$, since three CETs are listed.

Lastly, we calculate the total requirement of each critical mineral "j" across all the RE segments in time period "k". Equation 6 below gives the calculation. Figures 10-15 under section 3.2, are plotted using this equation.

$F_{T,m_j,t_k} = \sum_{p=1}^{b} Z_{T,m_j,R_p,t_k}$ …….. (6)

Where,

- F_{T,m_j,t_k} is the total requirement of critical mineral "j" across all RE segments in year "k".

3. Results and Analysis

3.1. Cumulative Requirement under each RE Segment

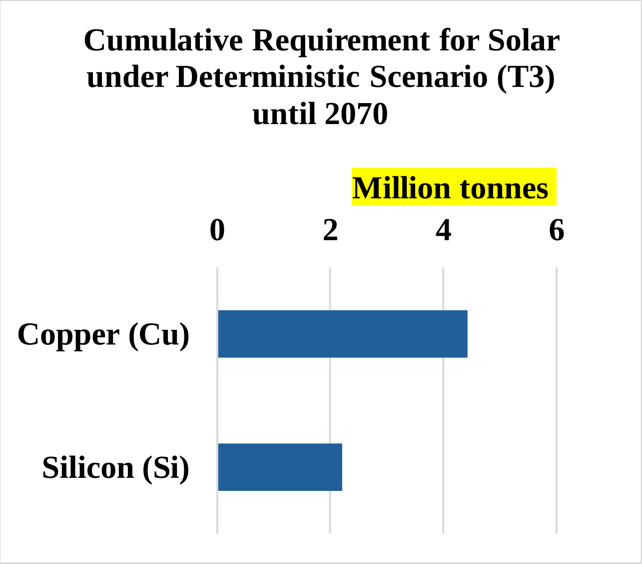

Figure 1

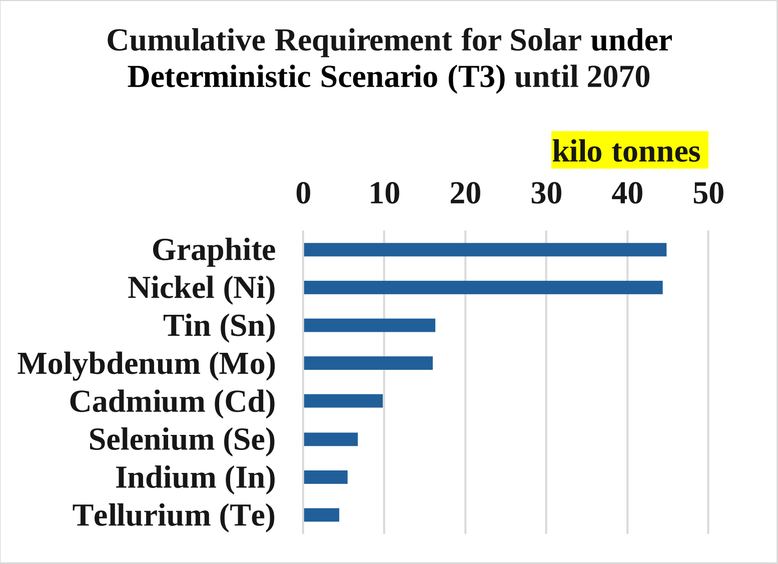

Figure 2

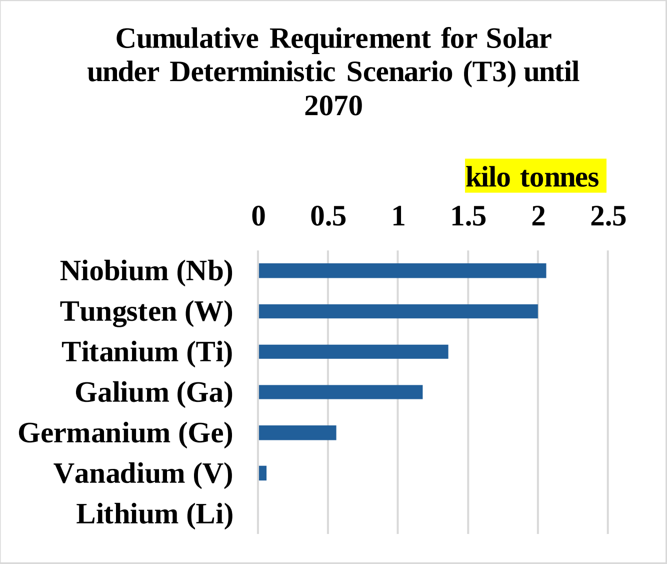

Figure 3

In Figures 1, 2, and 3, Copper (Cu) has the highest cumulative requirement among all CMs needed for the solar PV RE sector. This is primarily because Copper is used in nearly all CETs, except for Perovskite (silicon tandem). Silicon follows closely behind, as it is essential for most CETs. Although Nickel (Ni) and Graphite are only required in Perovskite technologies, their cumulative demand is notably high due to the assumption that Perovskite technologies will see significant market penetration. Other CMs are needed in moderate quantities, while Lithium (Li) has an almost negligible demand, as it is only required in Perovskite APT in very small amounts.

For CSP in Figures 1, 2, and 3, Copper again has the highest cumulative mineral requirement, followed by Nickel and Molybdenum. Vanadium (V) is required in small quantities in both CETs analyzed, leading to relatively low demand. While Niobium (Nb) is only needed for Solar Power Towers and Titanium (Ti) exclusively for Parabolic Troughs, both are required in moderately high quantities. However, due to the lower market penetration of CSP compared to PV, the overall demand for all CMs in CSP remains moderate.

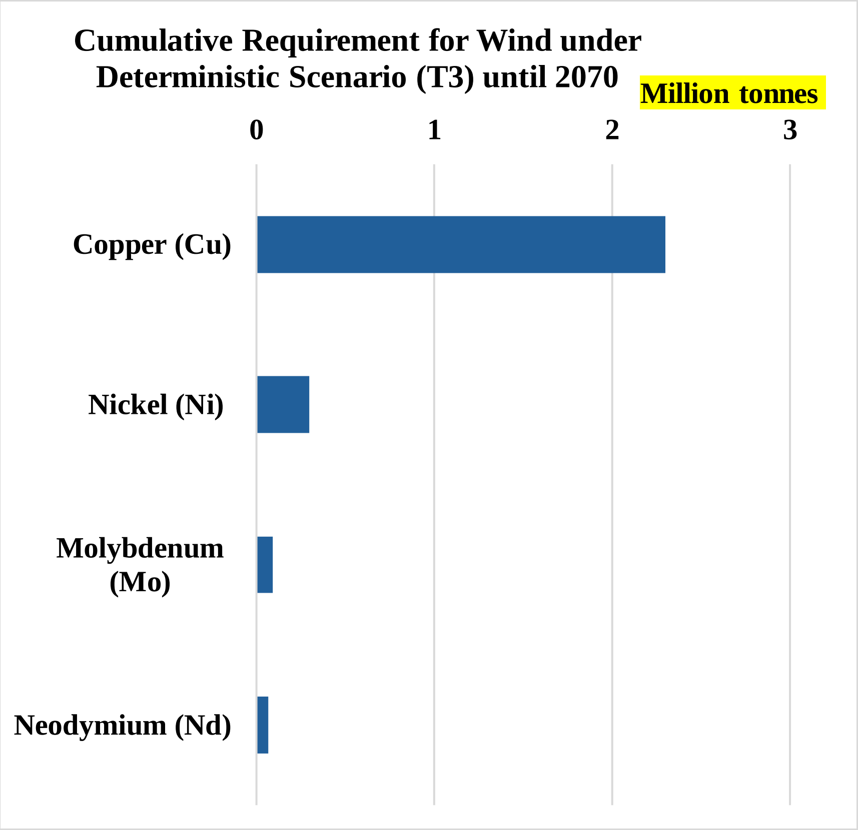

Figure 4

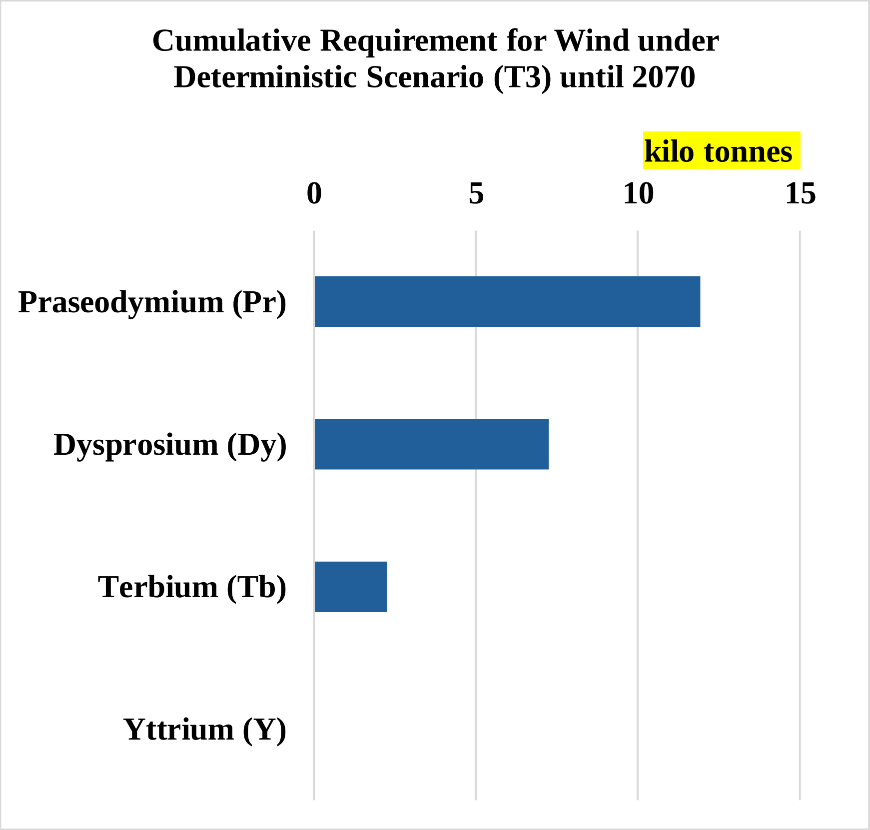

Figure 5

In Figures 4 and 5, Copper has the highest cumulative requirement among all CMs in both onshore and offshore wind technologies, followed by Nickel, due to their substantial use across all CETs. Individually, the demand for REEs is moderate; however, when considered collectively, their cumulative requirement by 2070 is significantly high, emphasizing their critical role in the expansion of wind energy infrastructure. Among the REEs, Yttrium has the lowest demand, as it is only needed in one offshore CET, DD-HTS.

It is important to note that the mineral intensity has been kept constant for the CETs used in both offshore and onshore wind technologies.

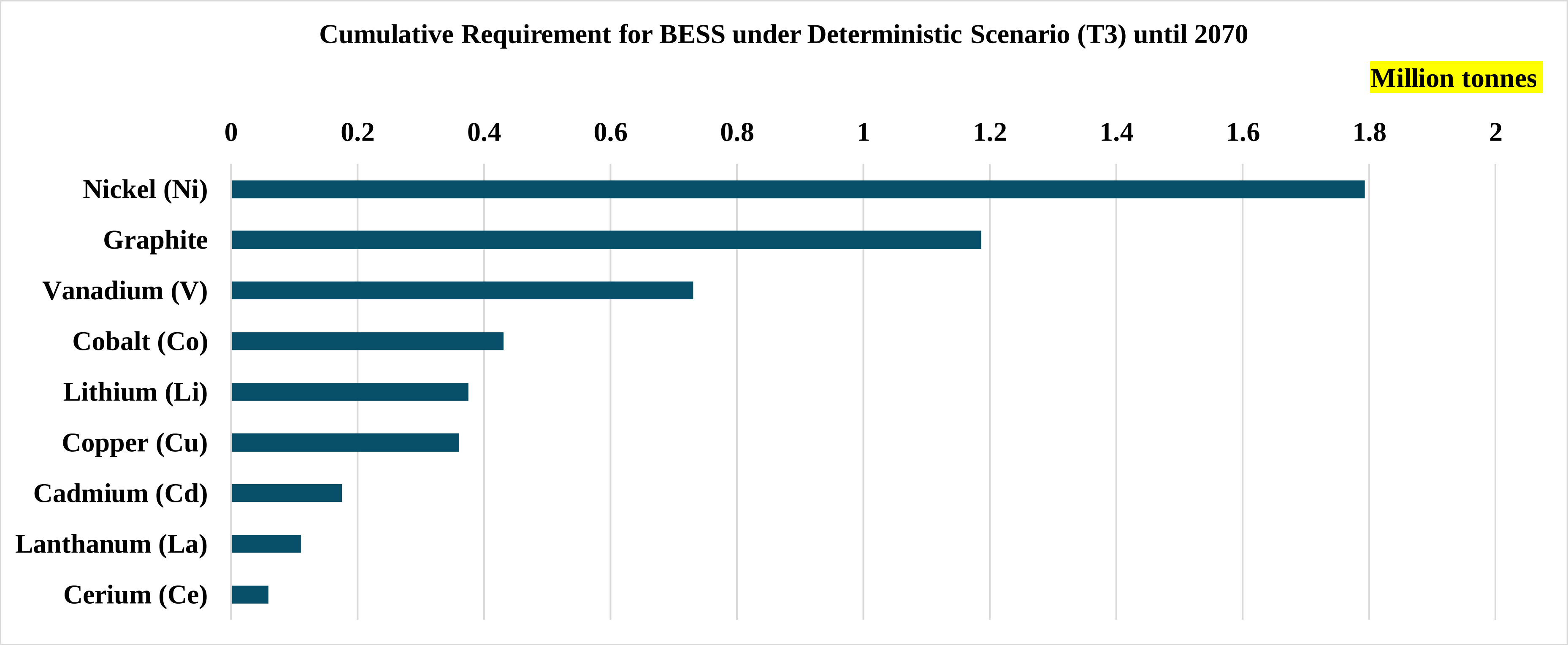

Figure 6

In Figure 6, Nickel registers the highest cumulative demand due to its presence in most CETs. Graphite follows closely, despite being required in fewer CETs. This can be attributed to the fact that many of the CETs requiring Graphite are at TRL 4–7, implying a growing market share as these technologies mature toward 2070. Vanadium, although used in only one CET, Vanadium Redox Flow (VRF) batteries, has a notably high demand due to the large quantity required per unit of technology. Similarly, Cobalt and Lithium are essential across almost all CETs, leading to substantial cumulative demand. REEs - Lanthanum and Cerium, despite being needed solely in Nickel-metal hydride batteries, show significant demand because this CET is at TRL 8–9, indicating a high level of commercial readiness.

It is important to note that while Lithium is a fundamental mineral for batteries used in EVs and portable electronics, its role in stationary BESS is more widespread but in smaller quantities per unit. This results in a considerable cumulative demand for Lithium, though not the highest among the critical minerals.

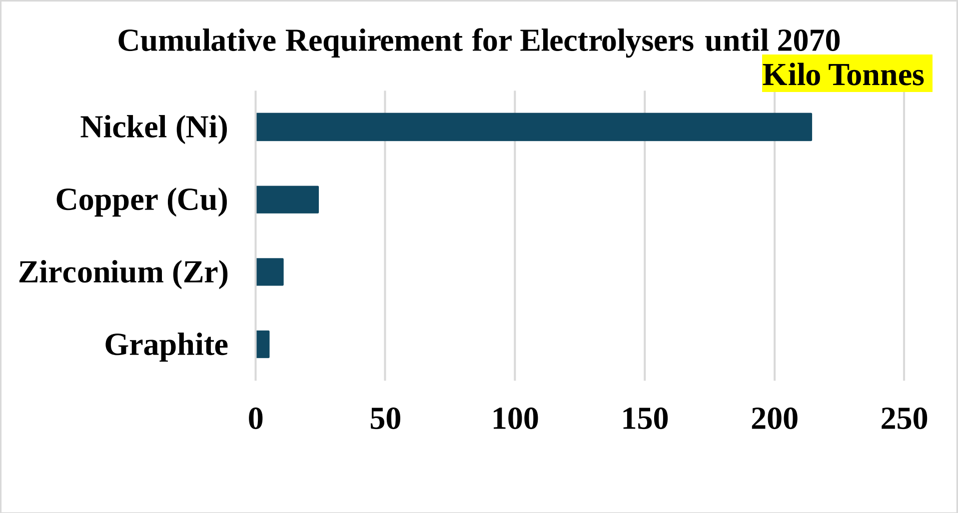

Figure 7

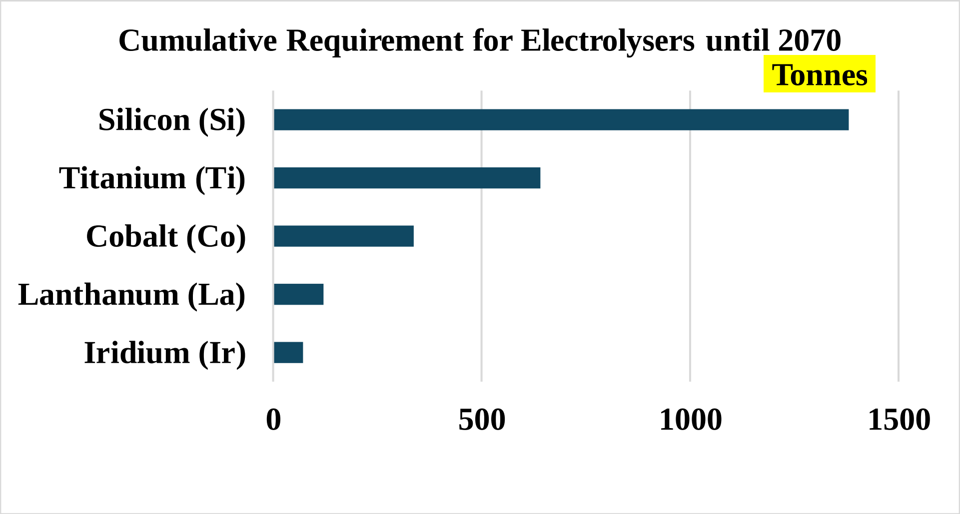

Figure 8

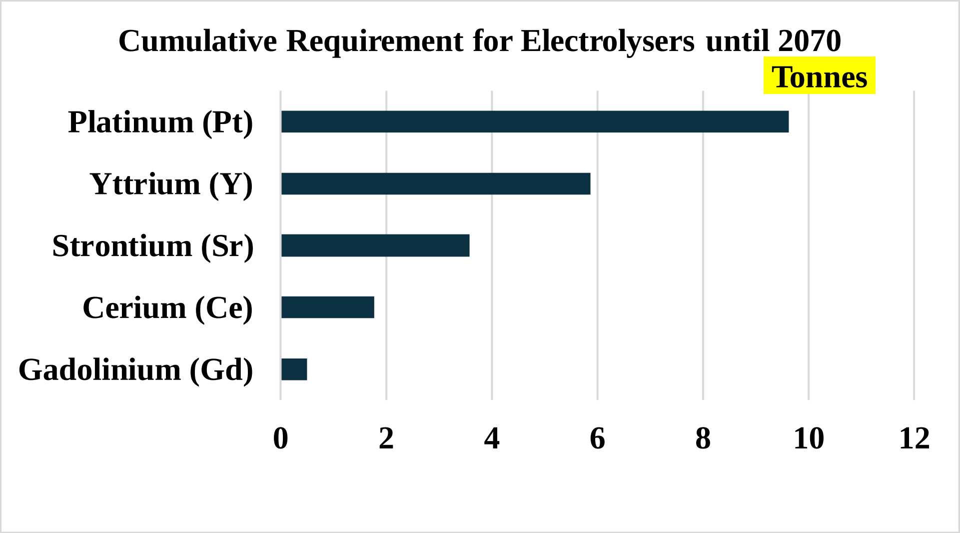

Figure 9

In figure 7, 8, and 9, Nickel projects the highest mineral cumulative requirement in electrolysers. Other highly required CMs are Zirconium, Graphite, and Copper. Moderate demand is seen in Silicon, Titanium, Lanthanum, Iridium, and Cobalt. Minimal growth is observed among Yttrium, Strontium, Platinum-Group Metals, and Cerium. Gadolinium records the least requirement.

3.2. Cumulative Requirement cumulative of all RE Segments

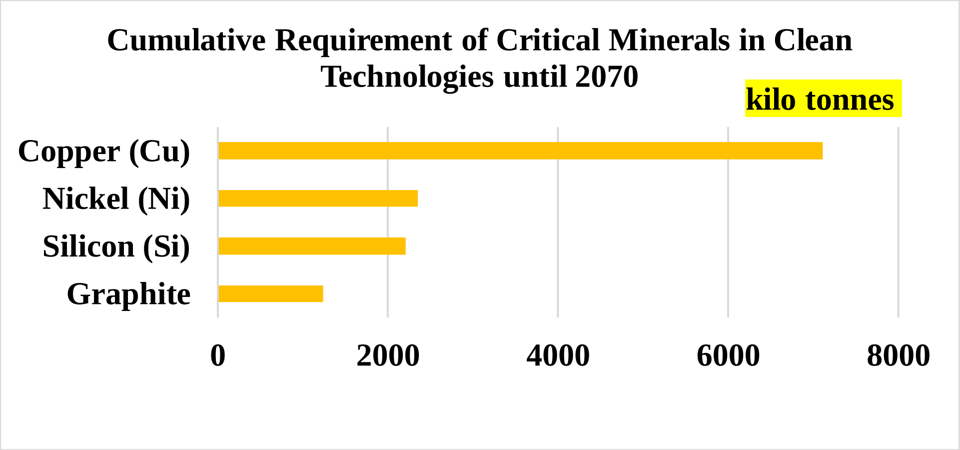

Figure 10

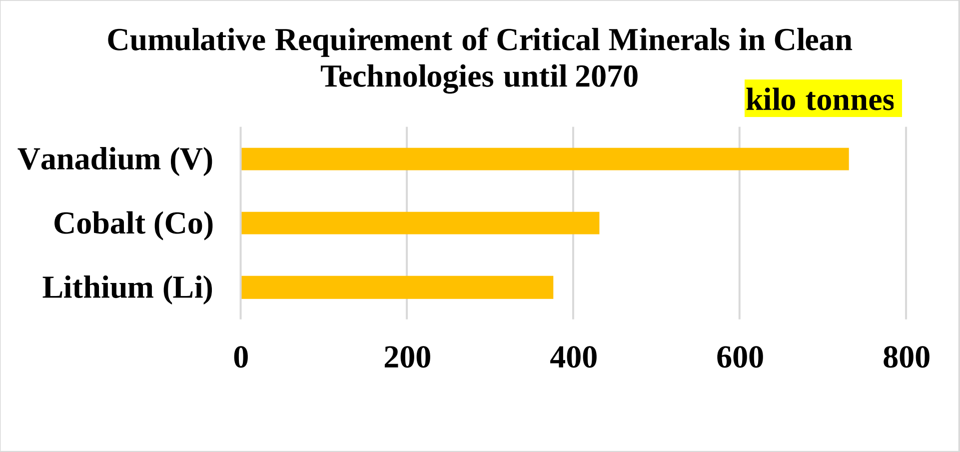

Figure 11

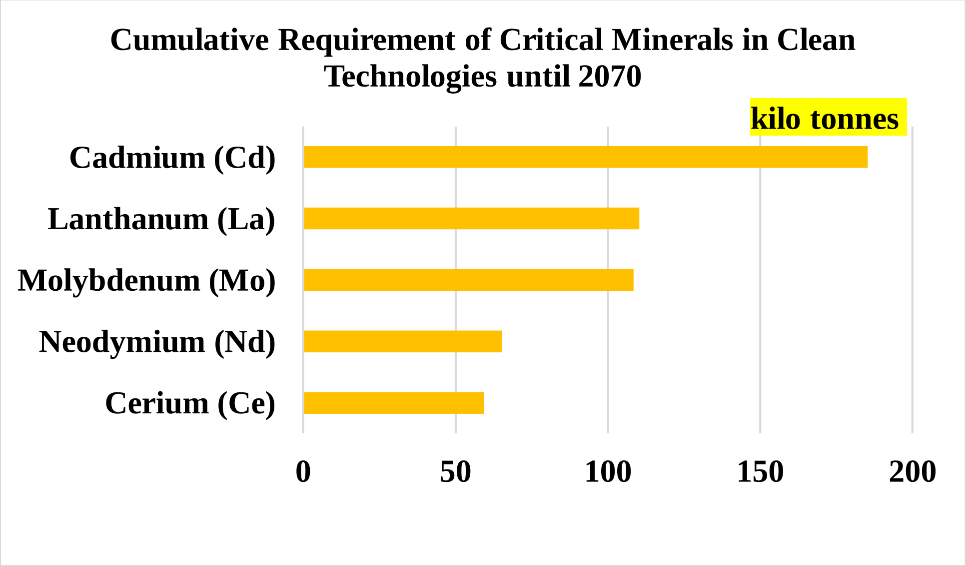

Figure 12

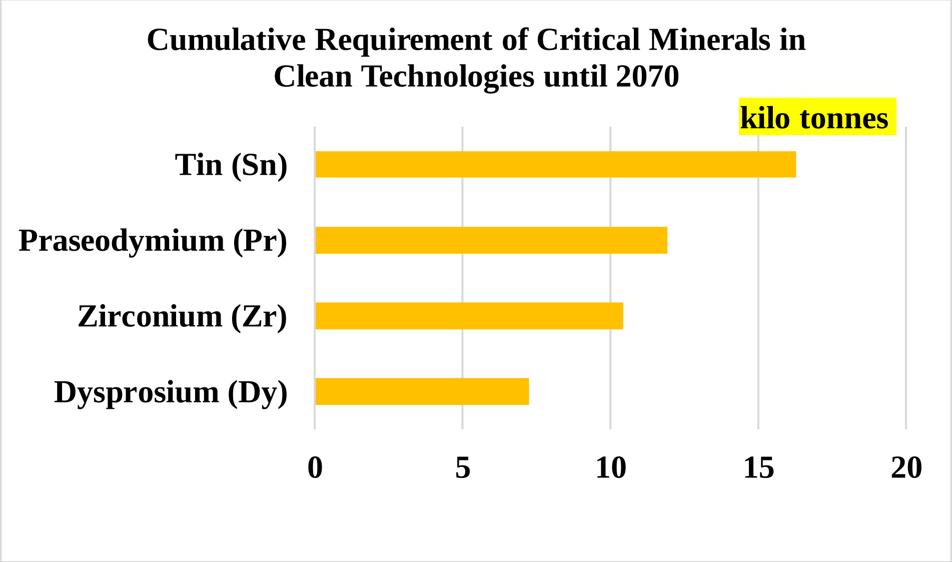

Figure 13

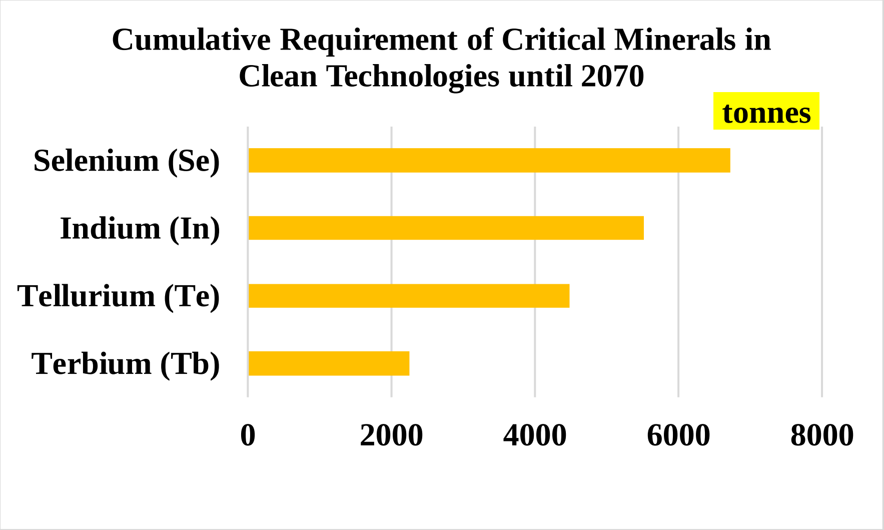

Figure 14

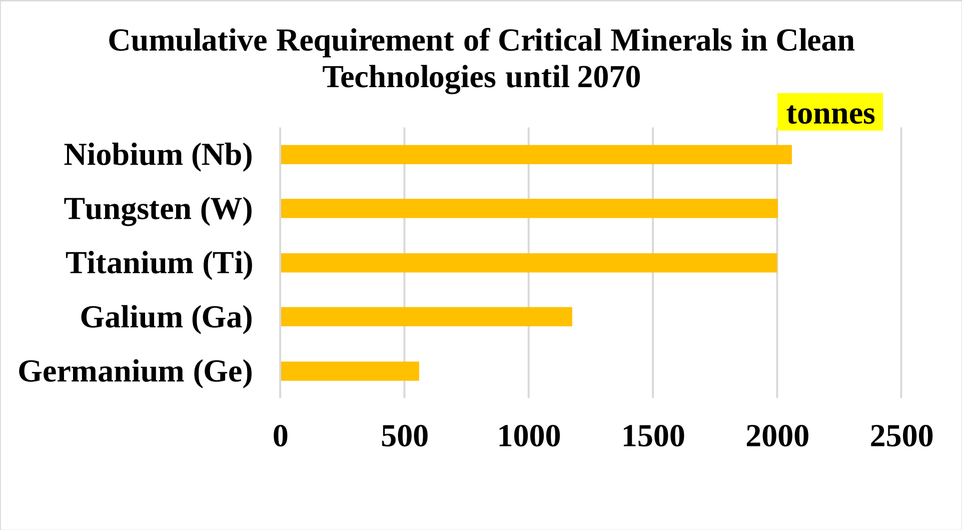

Figure 15

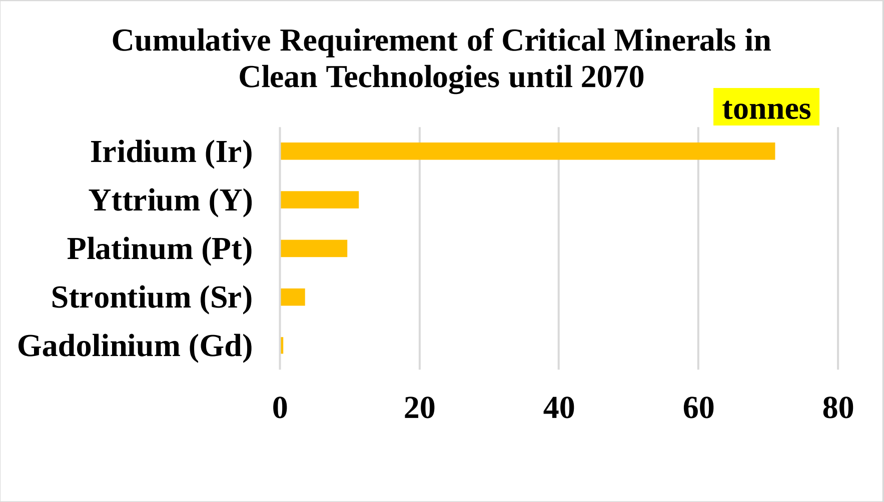

Figure 16

Figures 10-16 show the cumulative requirement of CMs across all the RE segment until 2070. Figure 10 shows that Copper, Silicon, Nickel, and Graphite have the highest cumulative requirement. This is followed by Vanadium, Cobalt, and Lithium in figure 11, Neodymium, Lanthanum, Cerium, Molybdenum, and Cadmium in figure 12, and finally by Zirconium, Praseodymium, Dysprosium, and Tin. Whereas, as shown in figure 14 and 15, CMs like Terbium, Tellurium, Selenium, Indium, Niobium, Tungsten, Titanium, Germanium, and Gallium show moderate requirements. Finally, as shown in figure 16, Iridium, Strontium, PGE, Gadolinium, and Yttrium shows the least requirement.

This requirement paired with domestic resources and imports, tells us the criticality of the CMs. Given the high requirement of several CMs whose domestic resources are negligible and even non-existent, it is very important to secure their supply for a smooth transition towards NZ by 2070.

4. Discussion

Our study's results and analysis indicate that Copper, Nickel, Silicon, Graphite, Vanadium, Cobalt, Rare Earth Elements (REEs), and Lithium will experience the highest cumulative demand. A 2024 policy brief by the Institute for Energy Economics and Financial Analysis (IEEFA) identifies Copper, Cobalt, Graphite, Lithium, and Nickel as India's five most CMs for the clean energy transition. Using 2023 as the base year, our projections estimate substantial growth in cumulative demand for these minerals by 2070 - Copper is expected to increase 18 times, Nickel 172 times, Graphite nearly 122 times, Cobalt 101 times, and Lithium 147 times.

These demand patterns are influenced by several factors. Copper and Nickel are required in large quantities across all renewable energy (RE) segments. REEs are required in large quantities in wind energy, while Graphite, Vanadium, Cobalt, and Lithium are particularly essential for battery energy storage systems (BESS)[9].

Crystalline silicon (c-Si) solar cells, including monocrystalline and polycrystalline types, dominate the global solar market, holding over 80% of the share. Monocrystalline silicon panels, with efficiencies reaching up to 26%, are favored for their high performance, while polycrystalline panels, with efficiencies around 21%, offer a more cost-effective alternative. Thin-film solar technologies, such as Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), and Amorphous Silicon (a-Si), collectively account for around 20% of the market. These technologies provide advantages in flexibility and lower manufacturing costs, with efficiencies ranging from 12% for a-Si to over 21% for CdTe and CIGS. Emerging third-generation solar technologies, like Perovskite cells remain in the research phase, with efficiencies typically below 20%. While they currently have a negligible market share, ongoing advancements in materials and efficiency improvements may enhance their competitiveness in the future, leading to an initially low demand for Nickel and Graphite, which is projected to increase over time[10]. This study has compared the material demands for construction and large-scale application of existing or near-term Concentrating Solar Power (CSP) technology. The market share of CSP within the RE sector remains relatively small compared to PV, partly due to cost competitiveness and efficiency differences. While CSP offers advantages in energy storage through thermal storage systems, its efficiency levels, are lower than high-efficiency PV technologies, impacting its scalability in some regions[11]. In India, onshore wind energy dominates due to lower costs and existing infrastructure,

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[9] Passerini, S., Barelli, L., Baumann, M., Peters, J., & Weil, M. (2024). *Emerging Battery Technologies to Boost the Clean Energy Transition: Cost, Sustainability, and Performance Analysis* (p. 337). Springer Nature.

[10] Ranabhat, K., Patrikeev, L., Revina, A. A. E., Andrianov, K., Lapshinsky, V., & Sofronova, E. (2016). An introduction to solar cell technology. Journal of Applied Engineering Science, 14(4).

[11] Pihl, E., Kushnir, D., Sandén, B., & Johnsson, F. (2012). Material constraints for concentrating solar thermal power. *Energy*, *44*(1), 944-954.

while offshore wind is in the early development stage. Onshore turbines primarily use gearbox doubly-fed induction generators (GB-DFIG) and gearbox permanent magnet synchronous generators (GB-PMSG), offering moderate efficiency and capacity. Offshore turbines, including direct drive permanent magnet synchronous generators (DD-PMSG) and direct drive electrically excited synchronous generators (DD-ESG), are more efficient and larger in scale. Critical minerals like copper and high-strength alloys are essential, with offshore turbines requiring more REEs for permanent magnets. With India's offshore wind expansion, demand for REEs is expected to rise, increasing import dependence, while copper's demands will also surge. Future advancements in superconducting generators and electrically excited synchronous generators (EESG) could reduce REE dependence[12]. In the stationary battery energy storage sector, lithium-ion batteries dominate the market due to their high energy density, efficiency, and declining costs, with key chemistries including lithium iron phosphate (LFP) and nickel manganese cobalt (NMC). LFP batteries, known for their safety, thermal stability, and long cycle life, require more copper but eliminate the need for nickel and cobalt, making them geopolitically and environmentally favorable. They currently lead in utility-scale storage due to lower costs and reliability. NMC batteries, which have higher energy density than LFP but contain significant amounts of nickel, cobalt, and manganese, are preferred for residential and behind-the-meter storage applications. As the market shifts away from cobalt-rich chemistries, variants such as NMC 532, 622, and 811 are gaining traction. Vanadium flow batteries (VFBs) are emerging as a long-duration storage alternative, requiring large amounts of vanadium but offering nearly unlimited cycle life and high efficiency in large-scale renewable integration. Sodium-ion batteries, still in early commercialization, offer a lower-cost alternative with reduced mineral constraints, though they currently have lower energy density than lithium-ion counterparts. Future advancements, including solid-state batterie, are expected to enhance efficiency and reduce mineral dependency, though commercial viability remains a challenge[9]. In electrolysers, although CETs have yet to reach full-scale market adoption, our projections indicate that post-2030, demand for Nickel in these technologies will surge, followed closely by Copper.

5. Conclusion

India's clean energy transition relies heavily on the availability of CMs essential for manufacturing renewable energy technologies. This study projects the demand for 30 CMs across five key renewable energy segments - Solar PV, CSP, Wind, BESS, and Green Hydrogen Electrolysers - until 2070. The findings indicate a substantial rise in cumulative mineral requirements, with

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[12] Chadha, R., & Sivamani, G. (2024, June 7). *Projecting critical minerals need for India's energy transition: How much of which minerals are needed for the transition?* Working Paper: Minerals & Mining. Centre for Social and Economic Progress (CSEP).

Copper, Nickel, Silicon, Graphite, Vanadium, Cobalt, REEs, and Lithium emerging as the most critical due to their widespread application across multiple technologies. Given India's limited domestic reserves of several of these minerals, ensuring a stable and resilient supply chain is crucial for achieving its renewable energy goals. This study emphasizes the vast scale of critical mineral requirements for India's clean energy transition, highlighting the urgent need for resource efficiency strategies, domestic exploration, recycling initiatives, and strengthened international collaborations.

Annexure

Material Intensity

Table 1: Mineral Intensities (in t/GW) of Solar PV Technologies[12,13,14]

Solar PV Technology	Nickel (Ni)	Tin (Sn)	Copper (Cu)	Silicon (Si)	Indium (In)	Gallium (Ga)	Selenium (Se)	Cadmium (Cd)	Tellurium (Te)	Molybdenum (Mo)	Tungsten (W)	Graphite	Titanium (Ti)	Lithium (Li)	Germanium (Ge)
Crystalline Silicon															
Monocrystalline Silicon (mono-Si) PV			4450	3000											
Polycrystalline Silicon (poly-Si) PV			4450	3000											
Heterojunction Silicon (HJT) PV			4450	3000											
Thin film solar cell															
Copper Indium Gallium Selenide (CIGS) Thin-Film PV		6	4470		29.9	10.5	60	0.4		23.8					
Amorphous Silicon (a-Si) Thin-Film PV			4450	112.5											35
Cadmium Telluride (CdTe)		103.3	4450					87.7	40	70					
Perovskite															
perovskite/silicon tandem	0.132	0.456	0		2.259					0	0	0	0.972	0	
Perovskite APT	3.223	12.509	2.987		4.707					3.427	6.417	143.733	1.944	0.0024	

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[13] Wagner, L., Suo, J., Yang, B., Bogachuk, D., Gervais, E., Pietzcker, R., ... & Goldschmidt, J. C. (2024). The resource demands of multi-terawatt-scale perovskite tandem photovoltaics. *Joule*, *8*(4), 1142-1160.

[14] Prabhu, V. S., Shrivastava, S., & Mukhopadhyay, K. (2022). Life cycle assessment of solar photovoltaic in India: a circular economy approach. *Circular Economy and Sustainability*, 1-28.

Table 2: Mineral Intensities (in t/GW) of Solar CSP Technologies[15]

Solar CSP Technology	Categories	Copper (Cu)	Molybdenum (Mo)	Nickel (Ni)	Titanium (Ti)	Vanadium (V)	Niobium (Nb)
Parabolic troughs	**Linear concentrating systems**	3200	200	940	25	1.9	0
Solar power towers	**Point Focus**	1400	56	1800	0	1.7	140

Table 3: Mineral Intensities (in t/GW) of Onshore & Onshore Wind Technologies**Error! Bookmark not defined.**[12,16]

Wind Technology	Category	Wind turbine types	Copper (Cu)	Dysprosium (Dy)	Molybdenum (Mo)	Neodymium (Nd)	Nickel (Ni)	Praseodymium (Pr)	Terbium (Tb)	Yttrium (Y)
					Onshore					
GB-HS-PMSG (GB HS PMG)	Gearbox	Gearbox High Speed Permanent Magnet Synchronous Generator	5000	6	109	28	340	9	1	
GB-DFIG	Gearbox	Gearbox Doubly-Fed Induction Generator	3000	17	109	180	240	35	7	
GB-SCIG	Gearbox	Gearbox-Squirrel Cage Induction Generator	3000	17	109	180	240	35	7	
DD-EESG	Direct Drive	Direct Drive Electrically Excited Synchronous Generator	950	6	119	51	440	4	1	
DD-PMSG	Direct Drive	Direct Drive Permanent Magnet Synchronous Generator	1400	2	99	12	430	0	0	
					Offshore					

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[15] Pihl, E., Kushnir, D., Sandén, B., & Johnsson, F. (2012). Material constraints for concentrating solar thermal power. *Energy*, *44*(1), 944-954.

[16] 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. *Publications Office of the European Union. Luxembourg*.

DD-EESG	Direct Drive	Direct Drive Electrically Excited Synchronous Generator	950	6	119	51	440	4	1	
DD-PMSG	Direct Drive	Direct Drive Permanent Magnet Synchronous Generator	1400	2	99	12	430	0	0	
DD-HTS	Direct Drive	Direct Drive High temperature semiconductor	950	6	119	51	440	4	1	0.3
GB-MS PMG	Gearbox	Gearbox Medium Speed Permanent Magnet Synchronous Generator	5000	6	109	28	340	9	1	

Table 4: Mineral Intensities (in t/GWh) of BESS Technologies[12,17]

BESS Technology	**Categories**	**Graphite**	**Lithium (Li)**	**Cobalt (Co)**	**Nickel (Ni)**	**Copper (Cu)**	**Vanadium (V)**	**Cadmium (Cd)**	**Cerium (Ce)**	**Lanthanum (La)**
Lithium cobalt oxide	**LCO**		112	959	0	0				
Lead-Acid	**Pb-A**									
Lithium-Ion	**Li-on**		160	130	350					
Vanadium Redox Flow Battery	**VRFB**					21	5000			
Nickel-Cadmium	**NiCd**				1500			1200		
Lithium Titanate	**LTO**									
Lithium Iron Phosphate	**LFP**	1100	87	0	0	433				
Nickel-Metal Hydride	**Ni-MH**				1800				420	780
Lithium Nickel Manganese Cobalt	**NMC-811**	750	90	76	608	333				
Lithium Nickel Manganese Cobalt	**NMC-111**		118	313	312					
Lithium Nickel Manganese Cobalt	**NMC-523**	883	117	183	467					
Lithium Nickel Manganese Cobalt	**NMC-622**	883	100	170	508	317				
Sodium-Nickel Chloride	**NaNiCl2**				1500					
Polysulfide Bromide	**PSB**									
Lithium Manganese Oxide	**LMO**		97	0	0	0				

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[17] International Energy Agency. (2023). *Energy technology perspectives 2023*. International Energy Agency. https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf

Solid-State Batteries	**ESS**		200			
Lithium Nickel cobalt aluminium Oxide	**NCA**	733	106	117	618	283
Sodium-Sulphur	**NaS**					
Lithium-Sulphur Batteries	**Li–S**		200			
Zinc-Bromine	**ZnBr**					

Table 5: Mineral Intensities (in t/GW) of Electrolysers for Green Hydrogen[18,19,20,7,8]

Technology	**Copper (Cu)**	**Zirconium (Zr)**	**Nickel (Ni)**	**Graphite**	**Cobalt (Co)**	**Iridium (Ir)**	**Platinum (Pt)**	**Silicon (Si)**	**Titanium (Ti)**	**Lanthanum (La)**	**Strontium (Sr)**	**Gadolinium (Gd)**	**Cerium (Ce)**	**Yttrium (Y)**
alkaline electrolysers (AEL)	533.33	245	5066.67	114.67	8									
proton exchange membrane electrolysers (PEMEL)	0.53			1.7		1.4	0.19	1.05	0.61					
solid oxide electrolysis (SOEL)	14.149	0.90761	1.791					14.149	6.5084	1.2882	0.038128	0.0053167	0.01895	0.062563

Cumulative Capacity

Table 6: Cumulative Capacity of Solar PV, CSP, Wind, BESS, & Electrolysers

Year	**2023**	**2030**	**2047**	**2070**
Solar PV (GW)	56.2	200	943.7	1600
sSolar CSP (GW)	0.556	1.859	7.21	32.69
Onshore Wind (GW)	46.12	90	484.79	700

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[18] Teixeira, B., Brito, M. C., & Mateus, A. (2024). Strategic raw material requirements for large-scale hydrogen production in Portugal and European Union. *Energy Reports*, *12*, 5133-5144.

[19] International Energy Agency. (2021, May 5). *Estimated levelised demand for selected minerals in electrolysers and fuel cells today (log scale)*. International Energy Agency. https://www.iea.org/data-and-statistics/charts/estimated-levelised-demand-for-selected-minerals-in-electrolysers-and-fuel-cells-today-log-scale

[20] Koj, J. C., Wulf, C., Schreiber, A., & Zapp, P. (2017). Site-dependent environmental impacts of industrial hydrogen production by alkaline water electrolysis. *Energies*, *10*(7), 860.

Offshore Wind (GW)	0	14.19	71.91	150
BESS (GWh)	0	39	2251	4874
Alkaline electrolysers (AEL) (GW)	0.0	28.5	94.2	211.2
Proton exchange membrane electrolysers (PEMEL) (GW)	0.0	34.2	113.0	253.4
Solid oxide electrolysis (SOEL) (GW)	0.0	21.1	69.7	156.3

Source: IESS (NITI Aayog)

Market Share

Table 7 gives the market share of each clean technology in Solar PV, Solar CSP, Onshore Wind, Offshore Wind, BESS, and Electrolysers respectively.

Year	**2023**	**2030**	**2047**	**2070**
Solar PV Technology				
Monocrystalline Silicon (mono-Si) PV	0.57	0.5	0.3	0.210
Polycrystalline Silicon (poly-Si) PV	0.33	0.3	0.18	0.130
Heterojunction Silicon (HJT) PV	0.05	0.1	0.12	0.120
Copper Indium Gallium Selenide (CIGS) Thin-Film PV	0.02	0.04	0.07	0.070
Amorphous Silicon (a-Si) Thin-Film PV	0.01	0.01	0.01	0.010
Cadmium Telluride (CdTe)	0.02	0.05	0.07	0.070
Perovskite/silicon tandem	0	0	0.13	0.195
Perovskite APT	0	0	0.13	0.195
Solar CSP				
Parabolic troughs	0.95	0.85	0.65	0.55
Solar power towers	0.05	0.15	0.35	0.45
Onshore Wind				
GB-HS-PMSG (GB HS PMG)	0.17	0.2	0.24	0.25
GB-DFIG	0.42	0.37	0.27	0.25

GB-SCIG	0.27	0.22	0.14	0.13
DD-EESG	0.06	0.08	0.12	0.12
DD-PMSG	0.08	0.13	0.23	0.25
Offshore Wind				
DD-EESG	0	0.6	0.56	0.51
DD-PMSG	0	0.13	0.12	0.12
DD-HTS	0	0.13	0.12	0.12
GB-MS PMG	0	0.14	0.2	0.25
BESS				
Lithium cobalt oxide	0.07	0.06	0.04	0.03
Lead-Acid	0.07	0.06	0.04	0.03
Lithium-Ion	0.07	0.06	0.04	0.03
Vanadium Redox Flow Battery	0.07	0.06	0.04	0.03
Nickel-Cadmium	0.07	0.06	0.04	0.03
Lithium Titanate	0.07	0.06	0.04	0.03
Lithium Iron Phosphate	0.07	0.06	0.04	0.03
Nickel-Metal Hydride	0.07	0.06	0.04	0.03
Lithium Nickel Manganese Cobalt	0.04	0.05	0.06	0.07
Lithium Nickel Manganese Cobalt	0.04	0.05	0.06	0.07
Lithium Nickel Manganese Cobalt	0.04	0.05	0.06	0.07
Lithium Nickel Manganese Cobalt	0.04	0.05	0.06	0.07
Sodium-Nickel Chloride	0.04	0.05	0.06	0.07
Polysulfide Bromide	0.04	0.05	0.06	0.07
Lithium Manganese Oxide	0.04	0.05	0.06	0.07
Solid-State Batteries	0.03	0.04	0.05	0.06
Lithium Nickel cobalt aluminum Oxide	0.03	0.04	0.05	0.06
Sodium-Sulfur	0.03	0.04	0.05	0.06
Lithium-Sulfur Batteries	0.03	0.04	0.05	0.06

Zinc-Bromine	0.02	0.03	0.04	0.05
Electrolysers				
alkaline electrolysers (AEL)	0	0.55	0.4	0.2
proton exchange membrane electrolysers (PEMEL)	0	0.4	0.4	0.2
solid oxide electrolysis (SOEL)	0	0.05	0.2	0.6

Source: Author’s computation