

From Ground to Grid: The Environmental Footprint of Minerals in Renewable Energy Supply Chains

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Abstract

Renewable energy technologies, while often labeled as clean or net-zero alternatives to fossil fuels, involve substantial use of critical minerals in products like electric vehicles, solar panels, wind turbines, and battery storage systems. This aspect is frequently underappreciated, yet studies indicate it could be a significant area of environmental impact. For instance, research has shown that a typical electric vehicle needs around six times the mineral resources of a conventional vehicle, while an onshore wind turbine requires nine times the mineral input compared to a gas power plant of similar capacity. This paper seeks to analyze the environmental effects linked to the critical minerals required by certain renewable energy technologies. The study begins with an estimation of the future megawatt capacities for each type of renewable technology. Next, it calculates the specific mineral quantities necessary for each model, followed by an assessment of the environmental repercussions tied to their extraction and processing. The results highlight the unique environmental challenges posed by the rising demand for minerals in solar and wind energy systems, taking into account various adoption scenarios.

Keywords

Clean Energy Transitions, Mineral Extraction, Environmental Impacts, Solar Photovoltaic (PV), Life Cycle Assessment (LCA), Carbon Emissions

1. Introduction

Renewable energy technologies have emerged as favored alternatives to traditional fossil fuel-based energy generation, often heralded as clean solutions. In order to

meet the Paris Agreement's goal of keeping a global average temperature increase below 1.5 degrees Celsius, current renewable capacity needs to triple. Implementing strategies such as storing trackers flat, reducing DC capacity, using high-resolution data collection, and expanding the irradiance range further help mitigate these challenges [1]. However, massive integration of renewables requires large capital investments and the use of massive quantities of critical elements: copper, lithium, nickel, cobalt, rare earth elements and others. These elements are essential in various renewable technologies, ranging from wind turbines and electricity networks to electric vehicles. However, their availability is often limited and geographically concentrated.

Renewable technologies rely on a variety of minerals, with copper and zinc being dominant among them. Additionally, there is a substantial demand for chromium, nickel, and silicon. Notably, the demand for minerals in renewable technologies can far exceed that of fossil fuel-based technologies. Comparatively, a typical electric car requires six times the mineral inputs of a conventional vehicle, while an onshore wind plant demands nine times more mineral resources than a gas-fired plant of the same capacity [2]. For instance, this translates to a demand for cobalt that is six to thirty times higher and a demand for rare earth elements that is three to seven times higher, depending on the policy support and stringency. To better understand the demand for these minerals, it is essential to consider the varying market shares of different renewable technology models and forecast their growth. In particular, electric vehicle (EV)-related minerals, such as lithium, are projected to experience the highest demand. California mandated that 100% of vehicles sold must be electric by 2035. As electric vehicles (EVs) reach a higher penetration of the car sector, cities will need to provide publicly accessible charging stations to meet the charging demand of people who do not have access to a private charging spot like a personal garage [3].

The extraction of these materials has led to severe environmental impacts. In addition to the ecological effects, mining activities have led to social conflict and generated carbon emissions that were not accounted for at the end stage of production. Previous studies have also pointed to the trade-off of climate change impacts vs other environmental impacts entailed in metal-intensive renewable energy production. While deploying these technologies is crucial to limit global warming below 1.5°C they are likely to exacerbate mining threats to biodiversity. Land use impacts depend on the mining sites. A recent study used satellite image analysis to assess land use change at three copper mines, showing results ranging from below 5 to about 20 hectares of built-up land needed per thousand tonnes of copper ore extracted. Previous studies showed that increasing air flow velocity over the PV panel led to a decrease in temperature across all layers of the panel. This reduction in temperature directly contributed to an improvement in the efficiency of solar panels due to an increase in the bandgap of the solar cells [4].

1.1. Importance

Numerous studies have examined the overall environmental impacts of solar

farms, wind farms, batteries, and storage systems. However, these studies often overlook the specific impacts associated with the minerals used in these installations. This paper aims to comprehensively understand the mineral requirements and potential environmental consequences associated with every new megawatt-hour (MWh) of solar or wind generation, as well as the battery and storage systems. By doing so, it offers a more precise depiction of the minerals needed to meet energy demand and store renewable energy efficiently.

Understanding these environmental impacts is crucial for solar farms, wind farms, battery manufacturers, storage system developers, and other stakeholders. It enables them to incorporate these externalities into their projects and guides environmental management agencies and investors in their decision-making processes. Moreover, this analysis facilitates a straightforward comparison of environmental impacts between different solar and wind models. Such comprehensive analysis is vital for making informed choices while considering both environmental factors and cost analysis [5].

1.2. Objective

The objective of this master's project is to assess the environmental impacts associated with the extraction and processing of critical minerals used under different scenarios for the deployment of renewable energy technologies.

The central question of this study is: What are the environmental impacts of the extraction of raw materials required for the massive deployment of PV panels and wind turbines? The subsequent research questions include comparing the environmental impacts of different demand scenarios and technologies [6].

2. Methods

This study focuses on solar PV and wind turbines because these demand more raw materials than other renewable technologies.

In order to obtain the environmental impacts of each mineral required for the projected renewable installations capacity, the method consists of the following three steps:

- Step one is to determine the demand forecast, predicting the required megawatt capacity for each type of renewable energy technology across three different future energy transition scenarios. This allows me to determine the scale of mineral usage in each scenario.
- Step two is to determine the minerals needed for each technology type and calculate the required quantities based on the demand forecast.
- Step three is to collect data on the environmental impacts of each mineral during its mining stage. For the scope of this paper, only the mining stage will be focused on at this time.

Additional data that addresses other processing stages is included in the dataset but is not considered in the final results.

The final results highlight the environmental impacts for specific minerals by

the total annual demand of each technology under different deployment scenarios. All the data collected will be summarized in the dataset [7].

2.1. Wind Models Overview

The two main types of wind turbines are direct drive and gearbox. The simplest way to differentiate the two is that the gearbox requires connection to the generator in order to speed up the rotation of blades. On the other hand, the direct drive doesn't require a gearbox to be connected to the generator, therefore, it has fewer moving parts. (Table 1)

Table 1. Types of generators and turbines and their applications.

Type of Generator	Type of Turbine	Application
Direct drive	High-Temperature Superconductors (HTS)	Offshore
Direct drive	Electrically Excited Synchronous Generator (EESG)	Onshore
Gearbox	Electrically Excited Synchronous Generator (EESG)	Onshore
Direct drive	Permanent Magnet Synchronous Generator (PMSG)	Onshore and offshore
Gearbox	Permanent Magnet Synchronous Generator (PMSG)	Onshore and offshore
Gearbox	Double-Fed Induction Generator (DFIG)	Onshore and offshore
Gearbox	Squirrel Cage Induction Generator (SCIG) - Without full converter	Onshore
Gearbox	Squirrel Cage Induction Generator (SCIG) - With full converter	Offshore
Gearbox	Wound Rotor Induction Generator (WRIG)	Onshore

For gearbox models, the medium-speed (>80 rpm) configuration requires higher permanent magnets content than the lower-speed drives. The high-speed (>900 rpm) configuration contains electromagnet generators (high-speed induction generators with multistage gearboxes) [8].

By eliminating gearboxes, direct-drive permanent magnets show improvements in weight reduction and have become favorable for offshore applications. The direct-drive turbines manufactured by Siemens and General Electric are based on permanent magnet generators.

Another direct-drive model that does not require permanent magnets is the one used by Enercon, which utilizes an electrically excited generator.

Other rising stars include hybrid drives, which combine gearboxes with permanent magnets and grant more reliability than multistage gearbox counterparts. High-temperature superconductors (HTS) are based on direct-drive configuration

and help decrease weight and save quantities of neodymium and dysprosium demanded. (Figure 1)

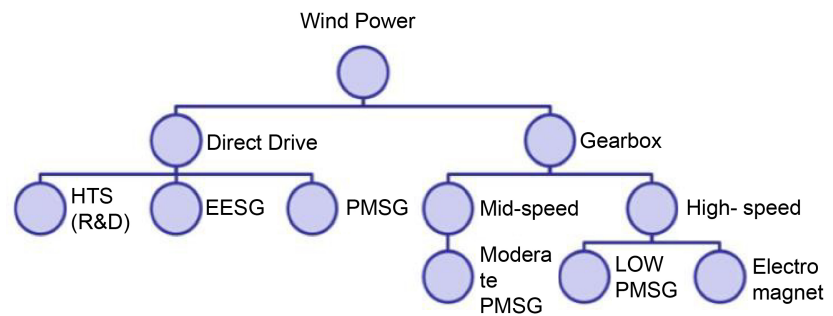


Figure 1. Wind models overview

2.2. Solar Models Overview

The most common solar PV panels are:

- Wafer-based crystalline silicon (c-Si), either single-crystalline or multi-crystalline silicon (these two are considered together as one type in this study)
- Cadmium telluride (CdTe)
- Copper indium gallium diselenide (CIGS)
- Amorphous silicon (a-Si)

The latter three are commonly referred to as “thin-film technologies”, which is much thinner than the 150 - 200 μm silicon-based wafers PV cells. Other technologies such as multi-junction cells or hybrid devices, are upcoming technologies on the horizon that are expected to be introduced for commercial use. However, it is important to note that extensive research is still required before these technologies can be fully implemented. While this study doesn’t delve into the specifics, it highlights the ongoing advancements in the field [9].

Currently, c-Si panels have the greatest share of the global market (95.4%). Thin-film panels are fairly new, and their popularity is attributed to lower cost and flexible installation. Thin film PV modules typically operate at an efficiency range of 6 to 8 percent, significantly lower than the 16 to 18 percent efficiency achieved by monocrystalline solar cells. Due to this reduced efficiency, the installation of a larger array is necessary with thin film solar technology to generate an equivalent amount of energy obtained from monocrystalline or polycrystalline alternatives. That’s why c-Si panels, both single-crystalline and multi-crystalline, are still maintaining an absolute advantage in the market.

2.3. General Scenario for Wind and Solar

When setting up the demand scenarios, there are four factors being taken into account:

- Power generation capacities: Future capacities not only depend on the current deployment rate but also depend on the policy agenda. Different carbon reduction goals will alter the requirements for generation capacity.

- Plant lifetime: Fluctuations in capacity, the rate of replacement, and maintenance all affect the quantities of materials needed.
- Sub-technology market shares: Each model has different levels of efficiency and its applicable areas. It is worth noting that all sub-technologies sum up to one, so an increase in one sub-technology must mean a decrease in the other. Costs, efficiency, and mineral intensities are the key differences among different subtypes.
- Material intensities: Generally, material intensities are likely to decrease as technology becomes more mature.

By considering all four factors, this study looks at three different renewable energy demand scenarios: LDS (Low Demand Scenario), MDS (Medium Demand Scenario), and HDS (High Demand Scenario). The description and rationale for each scenario are presented in **Table 2**, and subsequently, the implications for each technology, solar and wind, are summarized [10].

Table 2. General scenario overview for wind and solar energy.

General Scenario for Wind and Solar	Description	Goal	Source
Low Demand Scenario (LDS)	All scenarios in the ETP report are constructed using a combination of forecasting to reflect known trends in the near term and “backcasting” to develop plausible pathways to a desired long-term outcome. The scenarios should not be considered as predictions, but as analyses of the impacts and trade-offs of different technology choices and policy targets, thereby providing a quantitative approach to support decision making in the energy sector. The ETP scenarios are complementary to those explored in the International Energy Agency (IEA) World Energy Outlook (WEO). LDS is developed given the current technology available.	Pledged to limit temperature increase within 2.7°C.	The Energy Technology Perspectives (ETP) 2017 report published by the IEA.
Medium Demand Scenario (MDS)	Same as LDS.	50% chance of limiting average future temperature increases to 1.75°C. Energy sector emissions reach net zero around 2060.	The Energy Technology Perspectives (ETP) 2017 report published by the IEA.
High Demand Scenario (HDS)	The scenario was set up based on multiple simulations and outputs from various computer models. It is a technical pathway, not a political prognosis. It refers to technically possible measures and options without taking into account societal barriers. Efficiency and renewable potentials need to be deployed even more quickly than in the 2.0°C Scenario (which was not included in this paper), and avoiding inefficient technologies and behaviors is an essential strategy for developing regions in this scenario.	Pledged to limit temperature increase within 1.5°C. 100% renewable primary energy in 2050.	The Institute for Sustainable Futures of the University of Technology Sydney.

For solar and wind, the scenario forecasts are in line with the demand forecast calculated in the Carara's studies. At global level, the first two scenarios are selected from the Energy Technology Perspectives (ETP) 2017 report published by the IEA 2017. The third is the most aggressive, which is selected from an exercise developed by the Institute for Sustainable Futures of the University of Technology Sydney. The details of the three scenarios are as follows: LDS - IEA ETP Reference Technology Scenario. The demand for future renewables under this scenario aligns with commitments made by countries under the Paris Agreement to limit GHG emissions and enhance energy efficiency. The scenario aims for a maximum global temperature rise of 2.7°C in the future. MDS - IEA ETP Beyond 2 Degrees Scenario. This is in line with a 50% probability of constraining average temperature increases to 1.75°C by 2100. This scenario also anticipates net zero emissions from the energy sector around 2060.

HDS - Institute for Sustainable Futures 1.5°C 2019 Scenario. This scenario outlines a mitigation pathway targeting a long-term temperature increase within 1.5°C, with 100% renewable primary energy by 2050.

To summarize, the low-demand scenario pursues a climate target of 2.7°C, slightly better than business as usual, given by current technologies and policy support. Medium demand pursues a climate target of 1.75°C. High demand pursues a climate target of 1.5°C, with 100% renewable primary energy by 2050 [11].

2.4. Wind Demand Scenarios

There are two main trends that must be considered when determining the sub-technology market shares for wind. There is a continued use of permanent magnet technologies since permanent magnets (notably direct drive) are well suited to offshore environments due to their reduction in weight and better performance despite their costs and high mineral intensity. Thus, DD-PMSG and GB-PMSG are likely to see rises in their market shares. Due to recent Chinese export restrictions, the manufacturing industry is trying to rely less on rare earths.

Single-stage gearbox with a smaller permanent magnet and HTS generators will be favored (Netherlands, Organization for Applied Scientific Research).

LDS: The results are derived from time series data, with a prediction of increasing HTS generators in the offshore market.

MDS: The results are derived from time series data. During the data analysis process, the trends have been adjusted to reflect increased adoption of generators with permanent magnets, particularly direct drive. The adoption rate is adjusted to a higher level in offshore market compared to onshore market.

HDS: Regarding the onshore market, the results are derived from time series data.

During the data analysis process, the trends have been adjusted to reflect increased adoption of generators with permanent magnets, particularly direct drive. Regarding the offshore market, the forecasted demand for various sub-technologies is assumed to closely resemble current global average numbers. Generally, the

amount of minerals required increases with the size of the turbines. This trend is most obvious for steel, aluminum, and polymer materials requirements. For example, the total amount of steel required increases from 200 to 620 t by increasing the rotor size from 90 to 150 meters, which is summarized as an increase around 200%. Aluminum and polymer materials can also increase around 150% and 250%, respectively. Estimates for rare- earth elements, chromium, nickel, manganese, and molybdenum, are obtained based on published information, which has been summarized by Carrara's paper.

2.5. Solar-PV Demand Scenarios

Because of the current technology advantages that c-Si panels have, they will likely have the same market shares for all LDS, MDS, and HDS scenarios. Thin-film technologies have much higher mineral requirements, so they are expected to show higher demand only in HDS.

LDS: By 2050, c-Si will dominate the market, accounting for approximately 99%.

MDS: Assuming current aggregate levels and market share compositions for thin-film technologies, we project a linear increase in the share of thin-film technologies in the MDS scenario until it reaches 10% by 2025.

HDS: The HDS scenario experiences substantial growth in thin-film technologies, with CdTe and CIGS panels each reaching a 10% share, a-Si growing to 3%, and the remaining 77% allocated to c-Si.

Structural materials are used across all the PV models. These materials include concrete, steel, plastic, glass, aluminum, and copper. No major innovations are underway for these materials, therefore the material intensity in 2050 is set at 80%, 90%, and 100% of the current values in the LDS, MDS, and HDS.

The quantity demanded for silicon used in c-Si technology will be significantly reduced. It has now reached 4 t/MW, compared to 16 t/MW in 2004. The prediction for silicon usage is drawn based on this ongoing trend. All other materials that are specific to each model show decreasing quantities demanded in the HDS thanks to production process advancement [12].

2.6. Estimates of Annual Global Demand

The annual global demand for minerals used in solar and wind technologies is calculated by the annual global demand from the base year 2018, multiplied by the forecast factors. Each of the minerals has their own forecast factors, which is provided by the Joint Research Centre. The forecast factor is also adjusted differently across the three scenarios in the years 2030 and 2050.

The final environmental impact is calculated by multiplying the annual global demand by the impact per unit of minerals. The environmental impacts include CO_{2eq} emissions, freshwater eutrophication, freshwater ecotoxicity, water use, and acidification potential. For all five categories, the numbers are flat throughout all scenarios, including for both solar and wind.

3. Results

3.1. Solar

Based on the forecast factors provided in Carara *et al.*'s 2020 paper, it is clear that steel and concrete exhibit the highest demand within the structural materials category. In terms of technology-specific materials, silicon and silver demonstrate the greatest demand. (Figure 2, Figure 3)

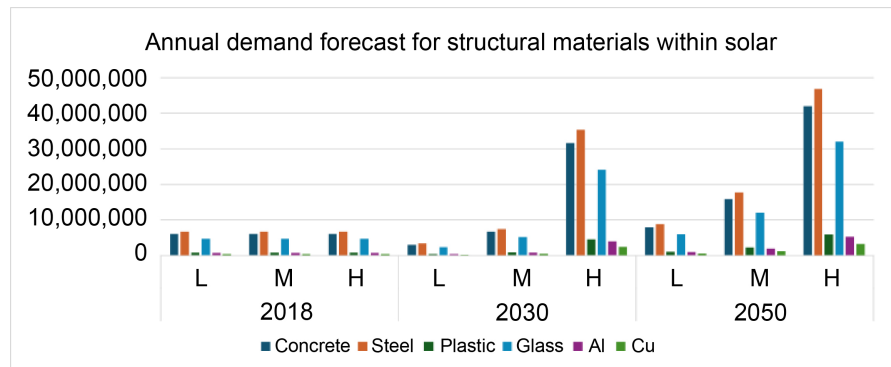


Figure 2. Annual demand forecast for structural materials within solar.

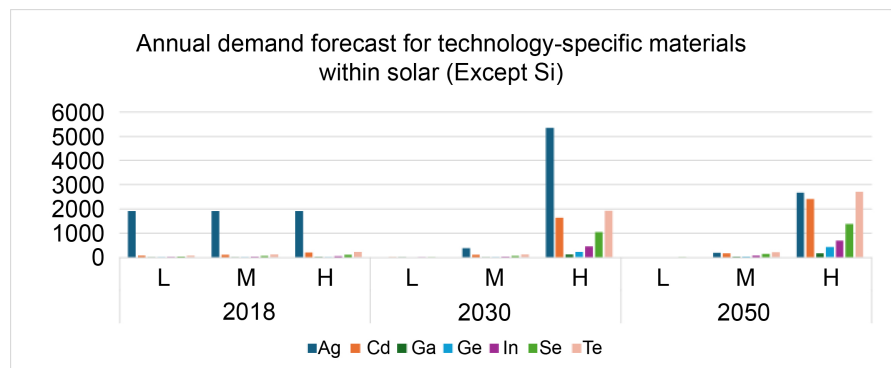


Figure 3. Annual demand forecast for technology-specific materials within solar (Except Si).

3.2. Wind

The graph provides a clear representation of the anticipated annual demand for wind structural materials on a global scale. It clearly indicates that concrete and steel are expected to have the highest demand in this category. Furthermore, when focusing on wind technology-specific materials, the graph unmistakably highlights neodymium and praseodymium as the materials with the highest projected demand [13]. (Figure 4, Figure 5)

3.3. Environmental Impacts

Table 3 presents the CO_{2eq} emissions from mining stage for minerals with consistent data available. Both Table 3 and Table 4 data are collected from various life-cycle assessment studies. For consistency, only mining-stage impacts are included.

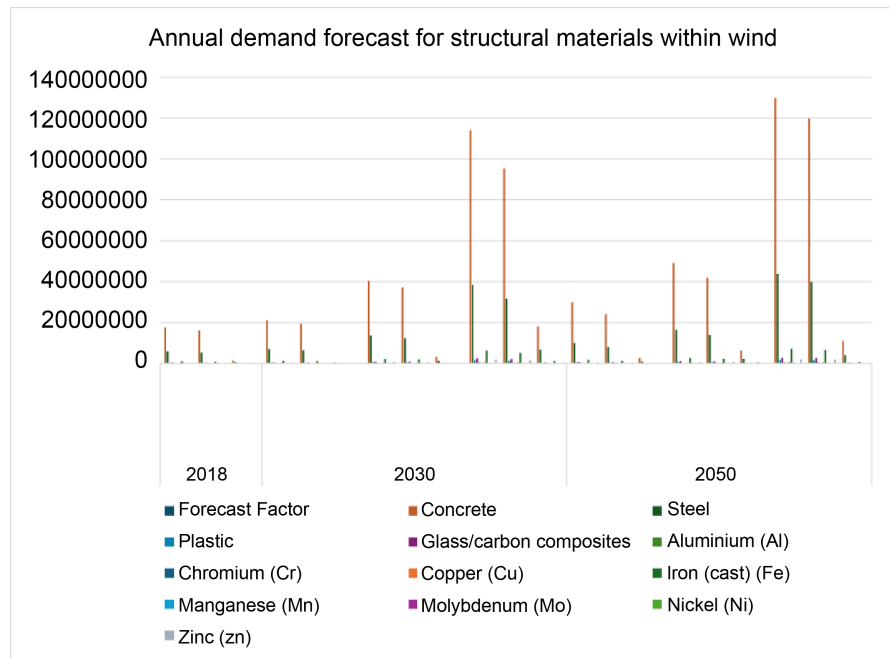


Figure 4. Annual demand forecast for structural materials within wind.

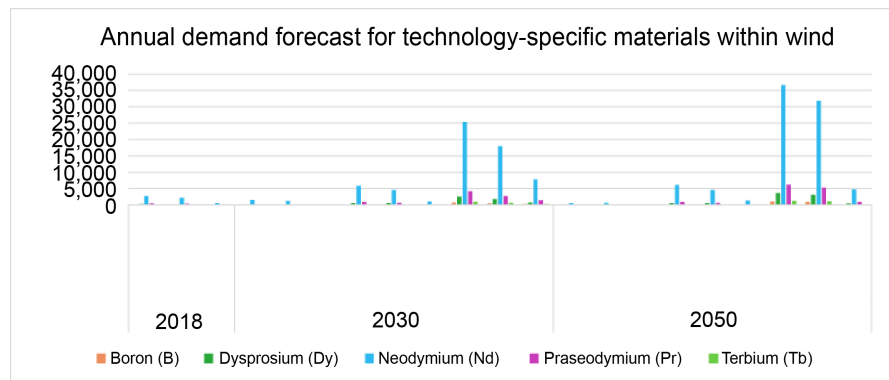


Figure 5. Annual demand forecast for technology-specific materials within wind.

Table 3. CO₂ emissions from mineral processing by country and source.

Minerals	Countries of Extraction Sites	Processing Stage	Data Source	CO ₂ eq Emission (tCO ₂ -eq per metric tons of minerals)
Iron and Steel	Average of major countries	Mining	IEA (2021)	0.03
Class 1 Nickel (sulfide)	Average of major countries	Mining	IEA (2021)	5.3
Lithium Carbonate	Average of major countries	Mining	IEA (2021)	1.46
Zinc	Average of major countries	Mining	IEA (2021)	1.18
Aluminium	Average of major countries	Mining	IEA (2021)	4.9
Cobalt	Average of major countries	Mining	IEA (2021)	2.09
Copper	Australia	Mining	Northey <i>et al.</i> 2013	3.21

Continued

Copper	Canada	Mining	Northey <i>et al.</i> 2014	1.63
Copper	Chile	Mining	Northey <i>et al.</i> 2015	2.4
Copper	Finland	Mining	Northey <i>et al.</i> 2016	0.45
Copper	Laos	Mining	Northey <i>et al.</i> 2017	2.84
Copper	South Africa	Mining	Northey <i>et al.</i> 2018	8.51
Copper	Turkey	Mining	Northey <i>et al.</i> 2019	1.07
Copper	PNG	Mining	Northey <i>et al.</i> 2020	1.26
Copper	USA	Mining	Northey <i>et al.</i> 2021	4.38
Copper	Average of major countries	Mining	IEA (2021)	3.2
Neodymium Oxide	Average of major countries	Mining	IEA (2021)	13.2

Table 4. Environmental impacts of mineral processing.

Other Impacts	Countries	Activity Stage	LCA Studies	Literature Source	Freshwater Eutrophication (kg phosphate-equiv / kg of metal)	Freshwater Ecotoxicity (CTUeco/kg)	Water Use (m ³ /kg)	Acidification Potential (kg SO ₂ -equiv / kg of metal)
Aluminium	Global	Production	Cradle to gate	Nunez and Jones, 2016	0.011		0.018	0.13
Aluminium	Global, except China	Production	Cradle to gate	Nunez and Jones, 2016	0.0053		0.01	0.09
Cobalt	Average of major countries			IEA (2021)	0.0000318	0.52	0.057	
Copper	Average of major countries			IEA (2021)	0.01	9.25	0.032	
Rare Earth Elements (REE)	Average of major countries			IEA (2021)	0.0213	538	0.635	
Iron	Average of major countries			IEA (2021)			0.0006	
Nickel	Average of major countries			IEA (2021)	0.014	17.52	0.053	
Lithium	Average of major countries			IEA (2021)	0.0013	5310	0.773	
Silver (from couple production)	Papua New Guinea and Sweden	Refining	Cradle to gate	Farjana <i>et al.</i> , 2019	1.58	330.61	5.45	6.79
Silver (from combined production)	Papua New Guinea and Sweden	Refining	Cradle to gate	Farjana <i>et al.</i> , 2020	0.05	54.03	0.36	3.98

Among the minerals for which CO₂ emission data is available, aluminum and copper are the only ones that have available data and are present in the solar technology demand forecast at the same time. From **Figure 6**, aluminum has higher

total annual CO₂ emission than copper. When comparing CO₂ emissions data for minerals extracted from different geographies, copper is chosen based on the available data. From **Figure 7**, I conclude that copper extracted from South Africa and USA has the highest total annual emissions. **Figures 8-11** present the associated environmental impacts (freshwater eutrophication, freshwater ecotoxicity, water use and acidification potential) for solar [14].

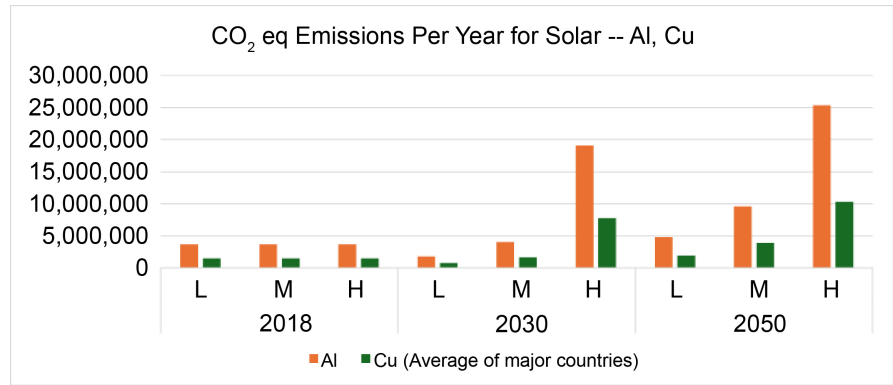


Figure 6. CO₂eq emissions per year for solar—Al, Cu.

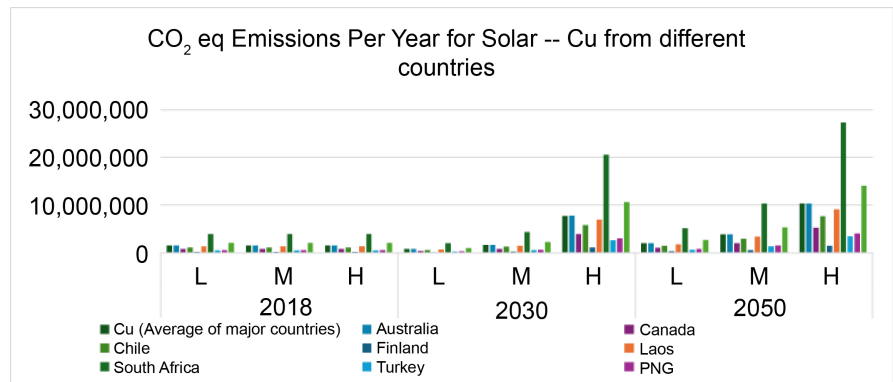


Figure 7. CO₂eq emissions per year for solar—Cu from different countries.

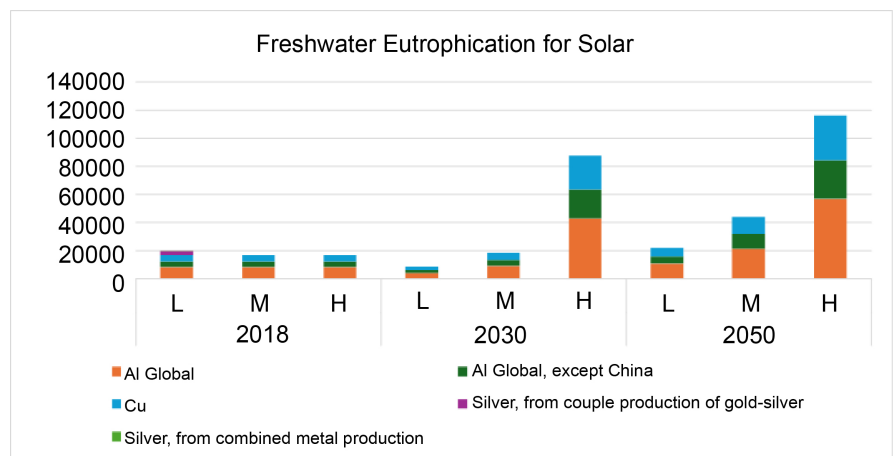


Figure 8. Freshwater eutrophication for solar.

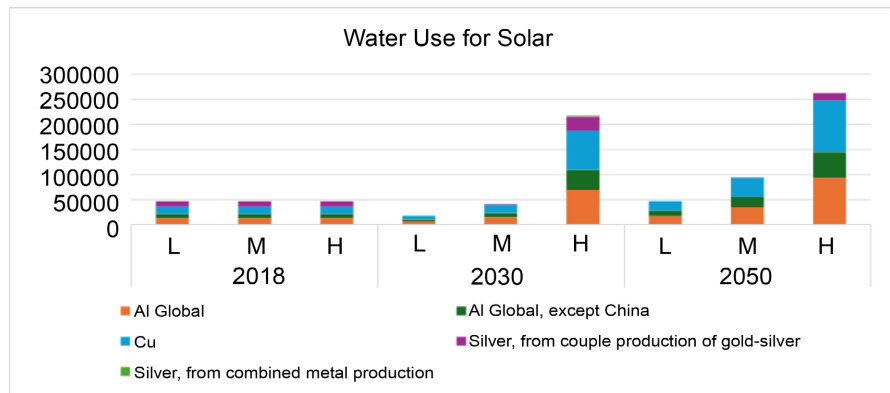


Figure 9. Water use for solar.

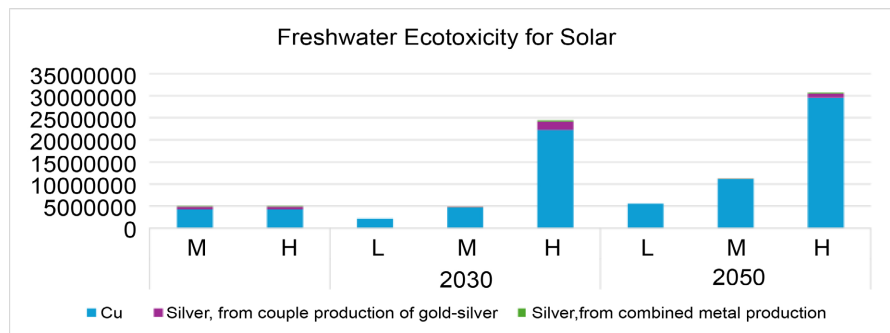


Figure 10. Freshwater ecotoxicity for solar.

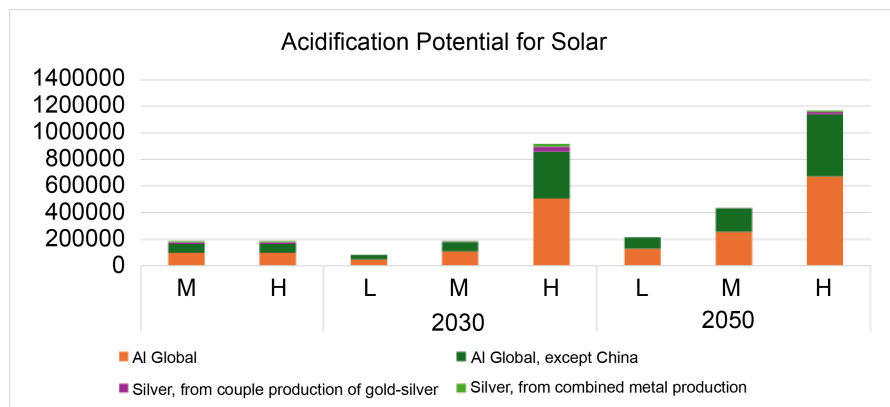


Figure 11. Acidification potential for solar.

A total of five different minerals are compared in **Figure 12**. These minerals are chosen because they are the only ones have available data and are present in the wind technology demand forecasted. From highest to lowest, the total annual CO₂ emissions are highest for zinc, copper, and aluminum. When comparing CO₂ emissions data for minerals extracted from different geographies, copper is chosen based on the available data. From **Figure 13**, it becomes evident that copper extracted from South Africa and USA has the highest total annual emissions [15].

Figures 14-17 present the associated environmental impacts (freshwater eutrophication, freshwater ecotoxicity, water use and acidification potential) for

solar [16].

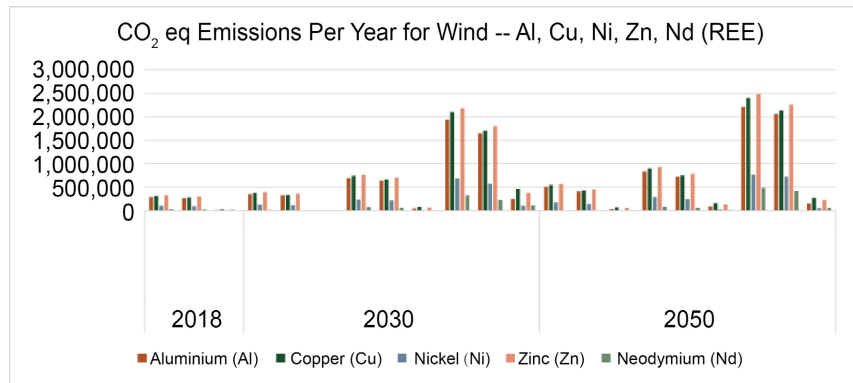


Figure 12. CO₂ eq Emissions per year for wind—Al, Cu, Ni, Zn, Nd (REE).

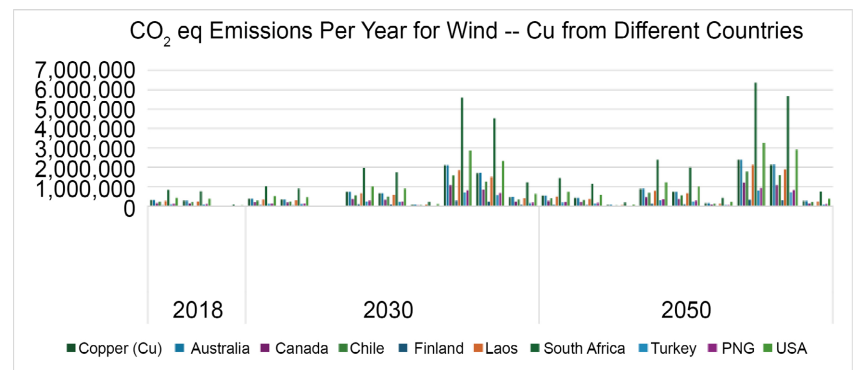


Figure 13. CO₂ eq emissions per year for wind—Cu from different countries.

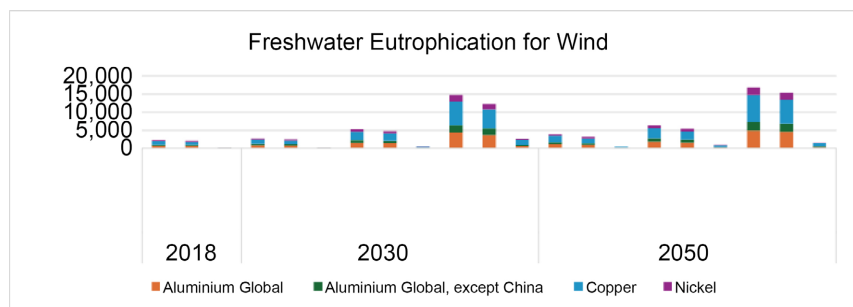


Figure 14. Freshwater eutrophication for wind.

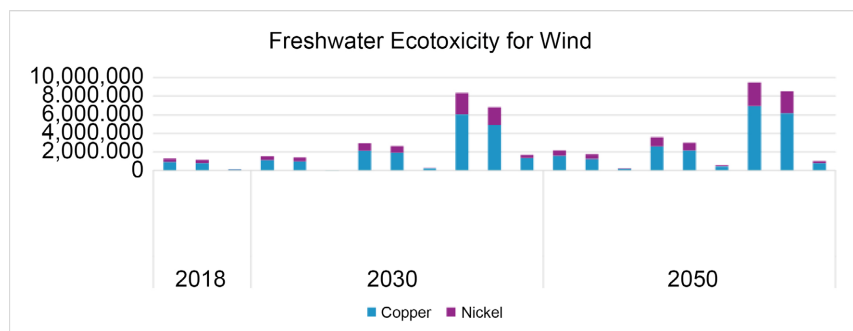


Figure 15. Freshwater ecotoxicity for wind.

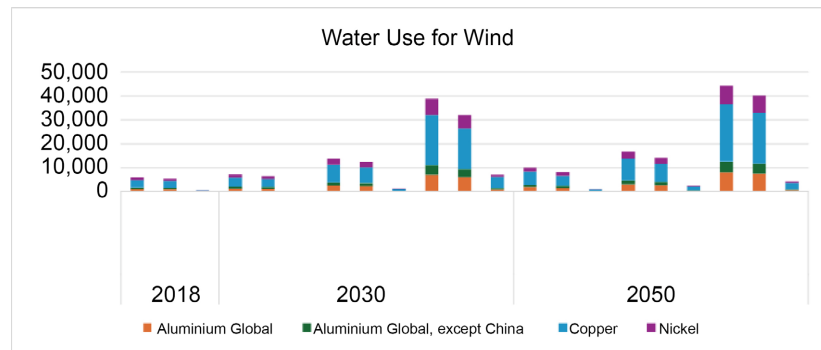


Figure 16. Water use for wind.

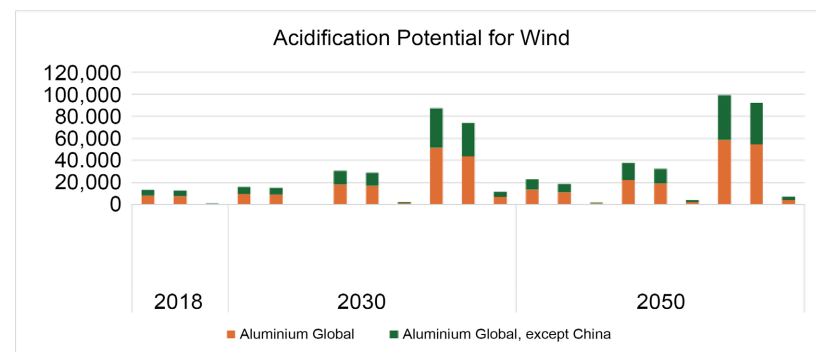


Figure 17. Acidification potential for wind.

4. Discussion

The results show that concrete and steel will be the materials most highly used for the deployment of solar and wind energy, across all the demand scenarios analyzed. When only considering critical minerals given the data available, aluminum and copper have the highest total $\text{CO}_{2\text{eq}}$ emissions based on future demand for solar. Silicon has the highest quantity demand in terms of technology-specific materials for solar. However, because no direct silicon related mining emissions data can be found, it is not possible to offer a conclusive result on its CO_2 emissions compared to CO_2 emissions from aluminum and copper.

For wind turbines, zinc, copper, and aluminum will be responsible for the highest total CO_2 emissions during the mining stage.

However, it is worth noting that when comparing the per unit CO_2 emission ($\text{tCO}_{2\text{eq}}$ per metric ton of materials), the ranking of emission changes. Neodymium has the highest CO_2 emissions per tons ($13.2 \text{ tCO}_{2\text{eq}}$ per metric ton of Neodymium oxide), which is about 11 times more compared to emissions from zinc ($1.18 \text{ t CO}_{2\text{eq}}$ per metric ton of zinc), 4 times more compared to copper global average ($3.2 \text{ t CO}_{2\text{eq}}$ per metric ton of copper), and 3 times more compared to CO_2 emissions from aluminum ($4.9 \text{ t CO}_{2\text{eq}}$ per metric ton of aluminum) (see Table 3).

While shifting from low demand to high demand scenarios in both year 2030 and 2050, CO_2 emissions increase 4 to 5 times across all minerals.

As the climate target becomes more ambitious, the increased demand for minerals leads to a significant rise in emissions. The total emissions are driven by the

higher quantity demand for minerals, rather than being solely influenced by the flat rate of CO_{2eq} emissions [17].

While conducting a comparative analysis between aluminum and copper demand in solar and wind technologies (Figures 18-20), several noteworthy observations have emerged. First of all, it is evident that the quantities of aluminum and copper required for solar substantially exceed those for wind in the baseline year of 2018. Upon applying the forecast factor, the discrepancy in required quantities between solar and wind becomes even more pronounced.

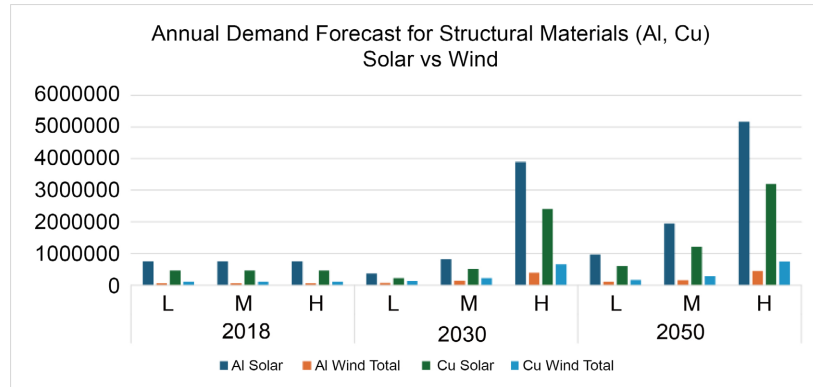


Figure 18. Annual demand forecast for structural materials (Al, Cu) solar vs wind.

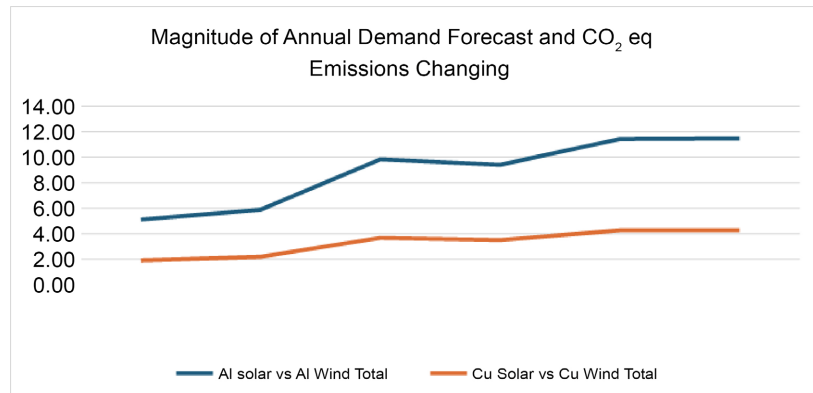


Figure 19. Magnitude of annual demand forecast and CO₂ eq emissions changing.

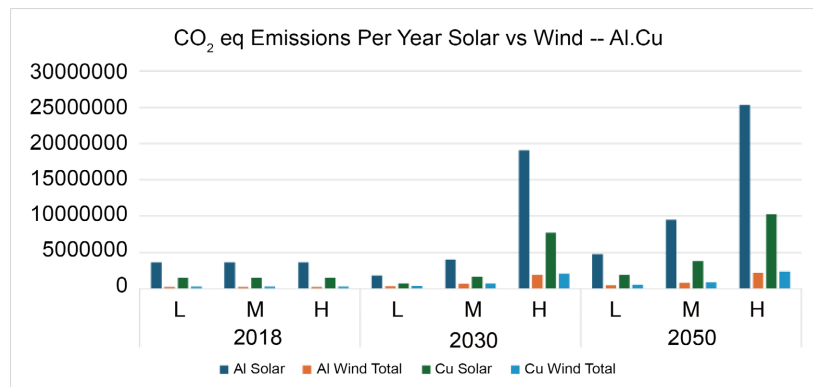


Figure 20. CO₂ eq emissions per year solar vs wind—Al, Cu.

Furthermore, when examining the scenarios within each target year, a distinct surge in demand is observed when transitioning from the Low Demand Scenario (LDS) to the High Demand Scenario (HDS). Overall, the rate of increase in aluminum demand exceeds that of copper. Importantly, as both the annual demand forecasts and CO₂ equivalent emissions experience concurrent changes (assuming a consistent flat rate of CO₂ emissions across all scenarios), it follows that CO₂ equivalent emissions will exhibit a more rapid escalation for aluminum due to its higher quantities demanded. In terms of freshwater eutrophication, aluminum exhibits the higher impacts (only similar to copper given the data available). This is especially pronounced when production from China is included, due to the high values estimated for this country. This indicates a heightened risk of eutrophication associated with Chinese aluminum mining activities. Additionally, aluminum also demonstrates the highest acidity potential based on global averages, excluding China. However, silver has higher acidification potential per unit than aluminum, which is 6.79 kg SO₂-equiv/kg silver from couple production of gold-silver and 3.98 kg SO₂-equiv/kg silver from other combined metal production respectively. The trend reverses for wind. In terms of freshwater eutrophication, copper has the highest values, with aluminum ranking on the second. This is because wind has a higher demand of copper than aluminum.

Meanwhile, copper stands out for its extensive water consumption and freshwater ecotoxicity in both solar and wind, making it a significant contributor to environmental impacts in these categories. Copper facilities alone withdrew over 1.3 billion cubic meters of water in 2006, reflecting the substantial water usage in copper mining operations. Additionally, the processing methods employed in copper production contribute to freshwater ecotoxicity concerns, highlighting the environmental challenges associated with this industry sector. It is important to note that copper has the highest total annual ecotoxicity after considering the demand forecast, but freshwater ecotoxicity for silver used in solar and nickel used in wind is much higher. The freshwater ecotoxicity per unit CTU_{eco}/kg for copper is 9.25, nickel 17.52, 330.61 for silver from gold-silver couple production and 54.03 for silver from combined metal production [18].

4.1. Implications

The findings of this study carry important implications for various stakeholders. For policy makers, it is crucial to strengthen regulatory frameworks and standards to encourage sustainable practices within the mineral extraction and processing industry. And it is especially important to consider how to incorporate these externalities when considering the environmental benefits of the energy transition. To control greenhouse gas emissions, it is important to implement carbon pricing mechanisms that incentivize emission reductions and promote the use of renewable energy sources for mineral operations. It is also important to enforce stricter environmental regulations that limit other air emissions and discharges to soil and water. For public utilities, accelerating investments in renewable energy infrastructure and modernizing grids are essential to meet the increased energy

demand associated with mineral extraction. It is also important to explore energy storage solutions to support the transition to cleaner energy sources and enhance grid stability. Utility companies should invest in cleaner production processes and energy-efficient technologies to minimize emissions throughout the mineral supply chain. Optimizing supply chain operations and enhancing transparency in reporting emissions data will further contribute to promoting sustainability in the industry [19].

4.2. Uncertainties

4.2.1. Analyzing Scenarios, Forecast Factors, Market Share, and Technological Mineral Intensities

The scenarios selected for analysis were derived from existing literature. Although the forecast factor was determined based on the market share of sub-technologies within solar and wind, it is important to note that market projections are subject to change. The choice of scenarios and the required installed capacity are likely to be directly influenced by policy stringency, while the market share of sub-technologies is contingent upon prevailing market conditions.

In addition, this examination encompasses changes in mineral intensities themselves, as well as the emergence of technologies that rely less on critical minerals. In both cases, it is possible to observe externalities arising from increased demand or, conversely, a reduction in externalities due to technological advancements and improvements [20].

4.2.2. Environmental Factors: Consistency Limitations, Limited Data, LCA Variations, and Global Scope

The environmental factors incorporated in this research are based on the most reliable and consistent data that is publicly available. It is important to note that the overall scope of the study and the data collection process extend beyond what was ultimately included in the calculations. During the data collection phase, it became apparent that there is a lack of robust data regarding the environmental impacts of many minerals. For instance, in the case of minerals like silicon and manganese, their impacts were estimated based on their alloy forms (e.g., Ferrosilicon, ferromanganese). Without further investigation, it becomes challenging to determine the precise environmental figures for silicon and manganese as individual entities.

Additionally, obtaining formal data for mining sources, particularly those located in developing countries, proves to be a significant challenge. Furthermore, the application of various life cycle assessment (LCA) methodologies can result in variations in the final impact estimations. Given these factors, this paper specifically focuses on the mining stage to ensure consistency, while other processing stages like refining are not considered [20].

5. Conclusion

This study has revealed the critical role that mineral extraction plays in the

deployment of renewable energy technologies, shedding light on both the environmental impacts and material demands associated with these technologies. Through detailed analysis of solar PV and wind energy systems across various future demand scenarios, it becomes evident that the transition to renewable energy, while essential for mitigating climate change, is not without its challenges.

Key findings highlight that structural materials such as concrete and steel dominate the demand landscape, while critical minerals like aluminum, copper, and rare earth elements present significant environmental concerns. The data underscores that the high quantities of these materials required, particularly in high-demand scenarios, lead to substantial increases in CO₂ emissions, freshwater eutrophication, and ecotoxicity. Moreover, the geographical origins of mineral extraction significantly influence these impacts, with locations such as South Africa and the USA demonstrating higher emissions rates for certain materials.

This analysis emphasizes the importance of addressing the environmental trade-offs inherent in the renewable energy supply chain. Policymakers, industry stakeholders, and environmental agencies must collaborate to promote sustainable mining practices, implement robust environmental regulations, and encourage technological innovation that reduces mineral dependency. Such measures are vital to ensure that the environmental costs of renewable energy technologies do not overshadow their benefits in combating climate change.

Ultimately, while renewable energy is a cornerstone of global decarbonization efforts, a holistic approach that accounts for the full life cycle of these technologies is crucial. Future research should extend beyond the mining stage to include processing and recycling phases, fostering a more comprehensive understanding of the environmental footprint and enabling more sustainable energy transitions [21].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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