Comparative life cycle assessment of copper, zinc, and lead in offshore wind renewable energy systems: computing the environmental trade-off for UK's energy transition.

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Abstract. The expansion of offshore wind energy in the UK is essential for achieving net-zero emissions. However, this transition also necessitates a thorough examination of its potential environmental drawbacks. A key area of concern is the use of critical materials and rare earth elements. This paper presents a cradle-to-grave life cycle assessment (LCA) evaluating the environmental impacts associated with the use of three metals—copper, zinc, and lead—across three offshore wind turbine technologies; Direct Drive Synchronous Generator (DDSG), Direct Drive Permanent Magnet Synchronous Generator (DDPMSG), and Doubly-Fed Induction Generator (DFIG). The study quantifies the environmental burdens linked to each metal's deployment, presents sensitivity analyses based on variations in manufacturing efficiency, and assesses the environmental trade-offs of fossil fuel displacement under three boundary displacement strategies. Results indicate that copper imposes the highest environmental burden, with terrestrial ecotoxicity approximately 1900% greater than that of zinc, while lead exhibits the lowest impacts across all categories. Sensitivity analysis reveals that a 10% improvement in manufacturing efficiency could lead to a corresponding 10% reduction in the Global Warming Potential (GWP) of copper by 2050. Additionally, fossil fuel displacement analysis shows substantial GWP reductions when offshore wind energy replaces natural gas—up to a 2049% decrease under a 100% displacement scenario.

1 Introduction

The escalating threat of climate change has spurred a global transition towards sustainable energy solutions, with offshore wind energy emerging as a key player. In the UK, policies like the Renewables Obligation in 2002 have been instrumental in driving the adoption of renewable electricity, which has surged from 3.4% in 2000 to 43.4% in 2020 [1]. This growth is set to continue, with the UK government targeting 100 GW of offshore wind capacity by 2050, as part of its commitment to achieving net-zero emissions [2].
However, the expansion of renewable energy necessitates a careful examination of its environmental implications, particularly concerning the use of critical materials. While offshore wind farms utilize materials like steel, aluminum, and polymers, the focus here is on copper, zinc, and lead due to their unique criticality [3]. These materials face supply challenges due to limited geological availability and increasing demand, resulting in declining ore grades [4]. Their importance and irreplaceability in renewable energy technologies like offshore wind pose potential supply limitations. Given current demand trends, Sverdrup et al. (2014) highlight the potential for copper reserve depletion.
The transition to renewable energy aims to decarbonize, but the resource demand raises sustainability concerns. For example, copper's extensive use in offshore wind cables and generators, and zinc and lead's vital roles, means renewable energy technologies require much more of these materials than fossil fuel counterparts [1]. This highlights the need to understand these material flows.
As has been emphasized by Mori et. Al (2021), isolating and assessing critical materials within LCAs is crucial for understanding their environmental impacts and informing sustainability improvements [5]. This is further supported by Mancini et al. (2015) [6], who highlight that the security of resource supply, especially for critical materials, is a growing concern, and that considering isolating critical materials in LCA enhances resource assessments and informs better decision-making. A focused approach that isolates critical materials provides targeted insights into their unique challenges and opportunities for sustainability improvement. By understanding their individual impact profiles, researchers and policymakers can develop more effective mitigation strategies and ensure a sustainable energy transition.
The existing research on the environmental impacts of critical material usage in offshore wind energy systems is still developing. While some studies have examined critical material demands for the global electricity sector [7, 8], these studies lay the groundwork by projecting increased material demand but do not assess the environmental impacts of this increased demand. Some attempts have been made to connect resource extraction and resource usage in renewable energy systems in terms

of environmental performance. For example, [9] presented material requirements and carbon footprints in electrical energy storage systems, and [10] analysed the environmental benefits of decarbonization strategies in the power sector, concluding that a shift toward mineral resource depletion is likely to occur. [11] and [12] highlighted the environmental impacts of metals and their variation due to demand increases in renewable energy systems, but these analyses were conducted as cradle-to-gate assessments.
However, the environmental impacts of critical materials in renewable energy systems, when coupled with fossil fuel phaseouts, have not been thoroughly examined. Studies such as those by [5] and [6] have emphasized the need to consider the entire life cycle of materials, from extraction to disposal, to gain comprehensive insights into their environmental sustainability. Furthermore, the phase-out of fossil fuels is a crucial component of the energy transition, as highlighted by [13], who noted that reducing fossil fuel use is essential for achieving climate goals and ensuring energy independence. Thus, this study goes one step further to assess the environmental impacts of critical materials in renewable energy coupled with fossil phaseouts to capture the true environmental sustainability of critical materials utilized in the renewable energy transition. By integrating the phase-out of fossil fuels into the assessment, this study aims to provide a more holistic view of the environmental trade-offs and benefits associated with the use of critical materials in the renewable energy transition.

This paper contributes to existing research through: (1) conducting a comparative cradle-to-grave environmental impact assessment of copper, zinc, and lead across three wind turbine technologies (DDSG, DDPMSG, DFIG) including the usage phase and transport distances providing a more comprehensive understanding of life cycle impacts; (2) Quantifying how manufacturing efficiency improvements affect environmental impacts across UK's net-zero timeline (2023-2050), showing material-specific responses (e.g., 10% GWP reduction for copper with 10% efficiency improvement); and (3) Revealing environmental trade-offs when offshore wind replaces natural gas, demonstrating significant GWP benefits (up to 2049% reduction) alongside increased terrestrial ecotoxicity (86% increase). These three contributions collectively provide decision-makers with critical insights into the environmental implications of material choices and efficiency improvements in offshore wind development, supporting more sustainable implementation of the UK's renewable energy transition.

2 Materials and Methods

This study employs the life cycle assessment (LCA) methodology, a standardized technique for evaluating the environmental impacts of a product or service. We adhere to the ISO 14040/44 framework [14]. The LCA consists of four key phases: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation of results.

2.1 Goal and scope definition

This section outlines a generalizable cradle-to-grave LCA framework for assessing the environmental impacts of critical material utilization in renewable energy systems, demonstrated through copper, zinc, and lead usage in UK-based offshore wind farm. The geographical scope of this assessment is worldwide. The functional unit is defined as critical material consumption per megawatt-hour (MWh) of electricity generated by a renewable energy plant over its lifetime. The analysis encompasses critical material extraction, distribution, usage in renewable energy system component production, assembly of renewable energy plant, use in renewable systems, and end-of-life disposal or recycling, as demonstrated in Fig.1. (The figure illustrates a general system boundary)

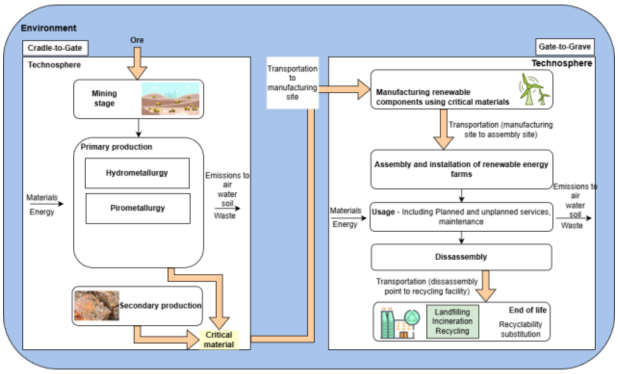

Fig.1. System boundary (cradle to grave)

The end-of-life phase employs the recyclability substitution method (0-100%) to account for the environmental benefits of material recycling. This method assigns credits based on the proportion of recovered and recycled materials, reflecting the avoided environmental burdens compared to virgin material production. The study considers three wind turbine technologies as scenarios [15].

1. Scenario 1: DDSG (Direct Drive Synchronous Generator) wind farms.
2. Scenario 2: DDPMSG (Direct Drive Permanent Magnet Synchronous Generator) wind farms.
3. Scenario 3: DFIG (Doubly Fed Induction Generators) wind farms.

The wind farm contains 100 wind turbines with a 3 MW power rating, resulting in a 300 MW total wind farm capacity, including export cables, inter-array cables, a substation, towers, and foundations that utilize critical materials. An annual 8760 operating hours and an average capacity factor of 44.37% are estimated [16, 17]. The average electricity generation throughout the lifetime of the offshore wind farm is calculated to be 23.32 TWh. The distance to shore is set at 30 km, the total export cable length is 60 km, and the cable type used is 132kV - 1000 mm^2. The inter-array cable length is 75 km, and the cable type used is 33kV - 400 mm^2. The weight of the substation is 2,480t [16]. A detailed inventory is available upon request. Table 1 shows the critical material using components and their weights.

Table 1. Offshore wind farm components and critical material weights

Component	Total weight (t)	Cu (t)	Zn (t)	Pb (t)
DDSG (per turbine)	299.22	13.5	0.22	0
DDPMSG (per turbine)	122.7	3.54	0.085	0
DFIG (per turbine)	162	1.76	0.115	0
Substation	2480	83	2.92	0
Interarray cable	2400.64	651.2	20.55	747.2
Export cable	5124	121.2	216.2	6
Tower (per 1)	146.7	0	1.5	0
Foundation (per 1)	600	0	149.7	0

2.2 Life cycle inventory analysis

Data were collected for each life cycle stage, as defined in the goal and scope definition, for copper, zinc, and lead. The Ecoinvent database (version 3.9) [18] served as a primary data source. Additional data was gathered from research articles, engineers, and industry experts.

All components of the offshore wind farm are estimated to be produced in Europe [16]. The study uses a mix of primary and secondary material sources from various regions. (Detailed sourcing compositions are available upon request) Metal production data (primary and secondary) were obtained from the Ecoinvent database. Data gaps were filled using expert opinions, relevant considerations, and literature. For copper, all necessary cradle-to-gate data were obtained directly from the Ecoinvent database. For zinc and lead, adjustments were made to the available cradle-to-gate datasets to align them with the study's specific conditions. Detailed inventory data, including energy and material requirements, can be provided upon request. Following the material production stage, transportation impacts were calculated based on supply source locations. At the component production stage, critical material usage efficiencies of 80% for copper, 75% for zinc, and 80% for lead were estimated.

Subsequently, manufactured offshore components are transported to assembly sites in the UK. The assembly of renewable energy technologies, along with operation and maintenance stages, was then considered (specifications available upon request). The end-of-life stage involves decommissioning, followed by disposal. To model the environmental benefits of recycling, this stage employs the recyclability substitution method. This approach accounts for the reintegration of recycled materials into the material mix, effectively reducing the demand for newly extracted materials and mitigating overall environmental impacts. Allocation factors, using mass-based allocation methods were applied to account for inventory data related to critical material utilization in component manufacturing, assembly, operation & maintenance, and decommissioning.

2.3 Life cycle impact assessment

The life cycle impact assessment was performed using SimaPro LCA software (version 9.4.0.3). The ReCiPe Midpoint(H) (2016) method was used, encompassing all its impact categories, including climate change. This method was chosen for its comprehensive coverage of environmental impact categories.

3 Results and Discussion

3.1 Comparative environmental impact assessment of critical materials in offshore wind infrastructure

This section details the cradle-to-grave LCA results (including the often overlooked renewable component manufacturing stage) of copper, zinc, and lead usage in a typical offshore wind farm in the UK for several impact categories as demonstrated in Fig. 2.

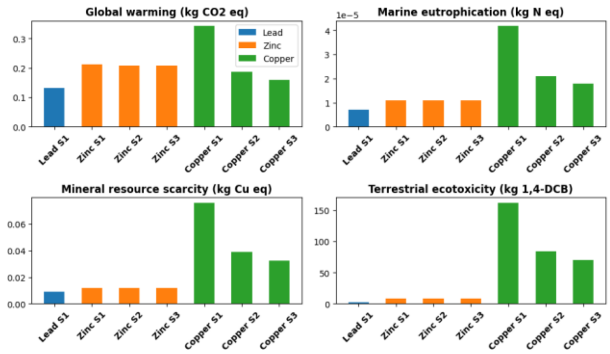

Fig. 2. Comparison of environmental impacts of critical materials across scenarios.

The comparative analysis of the environmental impact profiles across lead, zinc and copper reveals distinct patterns and significant variations in the environmental burden distribution. Copper exhibits the highest impacts across most categories, notably in Terrestrial Ecotoxicity, where its impact is substantially higher (approximately 1900% higher than zinc), and Mineral Resource Scarcity (approximately 532% higher than zinc). Zinc presents a moderate impact profile with relatively stable results across scenarios. Lead demonstrates the lowest impacts, though the analysis is limited to its use in cables.

Across scenarios, copper demonstrates significant impact reductions, with S3 showing approximately 54% lower GWP compared to S1. Similar proportional reductions are observed across all impact categories for copper, highlighting the crucial role of technological choices on environmental benefits across multiple impact dimensions. Zinc exhibits more modest reductions between scenarios, with improvements generally in the 2-3% range from S1 to S2, and only slight additional gains in S3 indicating zinc's environmental profile is less responsive to the scenarios interventions modeled. Lead shows the lowest absolute impacts in most categories but still presents significant concerns. Its relatively modest GWP (approximately 38% of copper's S1 value) suggests advantages from climate change perspective, but its toxicity underscores the importance of multi-dimensional environmental impact assessments. The results emphasize the need for material-specific mitigation strategies rather than generalized approaches to environmental impact reduction in renewable energy systems.

3.2 Environmental impact variation with usage efficiency

This section details how usage efficiency in component manufacturing affects environmental outcomes. The results are quantified according to the UK's net-zero plans for 2023 (13.6 GW), 2030 (50GW), 2040 (75GW), and 2050 (100GW) to better represent the severity of these impacts within the context of national climate goals.

The analysis reveals that improvements in usage efficiency generally reduce most environmental impact categories across all three materials. This trend is particularly evident in Global Warming Potential (GWP) for copper, as illustrated in Fig. 3 which shows the GWP across three scenarios (S1, S2, and S3) for the years 2023, 2030, 2040, and 2050. In 2050, Scenario S1 shows a decrease in GWP from 148.7 million kg CO2 eq. (with 72% usage efficiency) to 120.1 million kg CO2 eq. (with 88% usage efficiency) representing a 19.2% reduction in GWP. Furthermore, a 10% improvement in usage efficiency from the base value (80%) results in almost 10% decrease in GWP. Transitioning from Scenario S1 to S3 in 2050, decreases GWP by 62.5%.

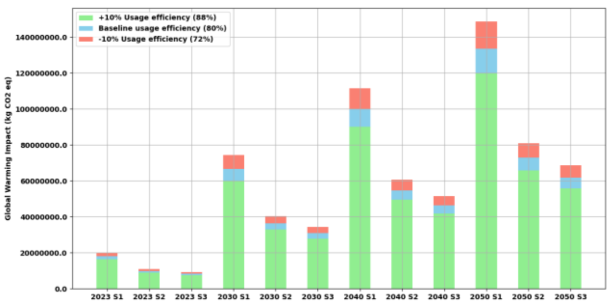

Fig. 3. Global Warming Potential (GWP) for copper across three scenarios (S1, S2, and S3) for the years 2023, 2030, 2040, and 2050.

A similar trend is observed for zinc as demonstrated by Fig. 4. In 2050, Scenario 1 for zinc shows a decrease in GWP from 90.4 million kg CO2 eq. (with 67.5% usage efficiency) to 74.5 million kg CO2 eq. (with 75% usage efficiency) representing a 17.6% reduction in GWP. Furthermore 10% improvement in usage efficiency from the base value (75%) would decrease GWP by 9.6%. Transitioning from Scenario S1 to S3 in 2050 yields a 19% reduction.

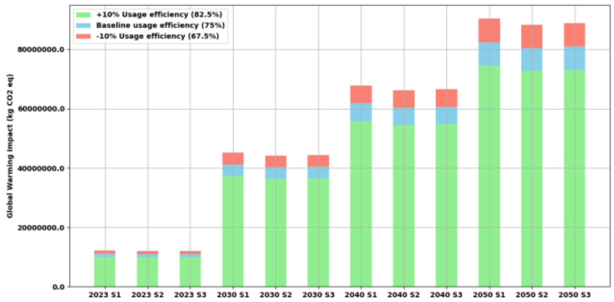

Fig. 4. Global Warming Potential (GWP) for zinc across three scenarios (S1, S2, and S3) for the years 2023, 2030, 2040, and 2050.

For lead (demonstrated in Fig. 5) in 2050, changing from 72% usage efficiency to to 88% usage efficiency reduces GWP by 11.6% and a 10% improvement in usage efficiency from the base value (80%) would decrease GWP by 5.8%. While the magnitude of the reduction varies across impact categories and materials, the overall trend of decreasing environmental impacts with increasing usage efficiency holds true for most categories.

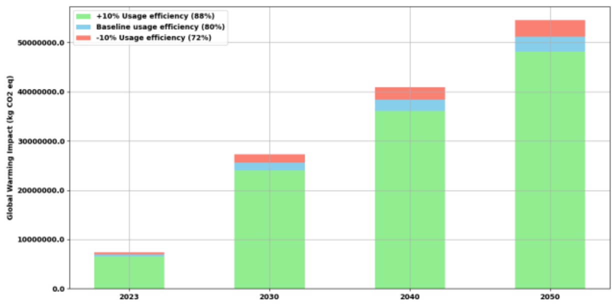

Fig. 5. Global Warming Potential (GWP) for lead across years (2023, 2030, 2040, 2050)

3.3 Environmental impacts trade-offs in fossil fuel displacement

The environmental impacts of critical material usage in offshore wind farms are typically quantified without considering the broader context of the renewable energy transition. As the UK rapidly expands its offshore wind capacity, these wind farms will displace some amount of electricity generation from fossil fuel sources. This displacement creates a trade-off between the negative environmental impacts of critical material usage and the positive impacts of reduced fossil fuel consumption. To better understand this trade-off, we examine scenarios with varying degrees of fossil fuel displacement. We focus on natural gas, as its contribution to the UK energy mix has remained relatively consistent in recent years, making it a key nonrenewable energy source for comparison.

It is important to note that this displacement is subject to many other factors, including economic, social, financial, and other issues. This study aims to provide an estimate of the environmental impact, acknowledging the complexity of the issue. Three levels of replacement were considered for two environmental impact categories (GWP and terrestrial ecotoxicity):

1. **0% Replacement:** This level quantifies the environmental impacts of critical material usage in offshore wind farms without considering any displacement of natural gas-generated electricity. This scenario serves as a baseline (the typical approach in current LCA studies on critical materials in renewable energy technologies) for comparison with scenarios that do consider the displacement of natural gas.
2. **50% Replacement:** This level assumes that half of the electricity generated by offshore wind replaces an equivalent amount of electricity that would have been generated by natural gas power plants (1 MWh offshore wind replaces 1 MWh natural gas).
3. **100% Replacement:** This scenario assumes that all of the electricity generated by offshore wind replaces an equivalent amount of electricity that would have been generated by natural gas power plants (1 MWh offshore wind replaces 1 MWh natural gas). It is important to note that this scenario represents a theoretical maximum for illustrative purposes. In reality, the actual displacement of natural gas may be limited by factors such as grid stability, energy demand fluctuations, and the role of other energy sources.

By comparing these three levels across the different target years, we aim to highlight the potential reduction or increase in overall environmental impacts of critical material utilization in offshore wind energy. The net environmental impact of this displacement is calculated as:

$$N_i = E_R * I_c - E_F * I_d \quad (1)$$

Where :

- E_R is the megawatt-hours of electricity generated by offshore wind.
- I_c is the environmental impact per MWh of electricity generated by offshore wind for the critical material.
- E_F is the megawatt-hours of electricity generation from natural gas that is displaced.
- I_d is the change in environmental impact attributable to the critical material, per MWh of electricity replaced by natural gas, due to the transition from fossil fuels. It is calculated as: $([I_{fossilOperational} - I_{Renewable}]*I_c/I_{Renewable})$

To provide a clearer focus, the following analysis will concentrate on Scenario S1 only. When considering the broader renewable energy transition, where offshore wind energy replaces natural gas-generated electricity, these impacts take on a new dimension. To illustrate this, the interplay between GWP and terrestrial ecotoxicity for copper is demonstrated in Fig. 6 and Fig. 7.

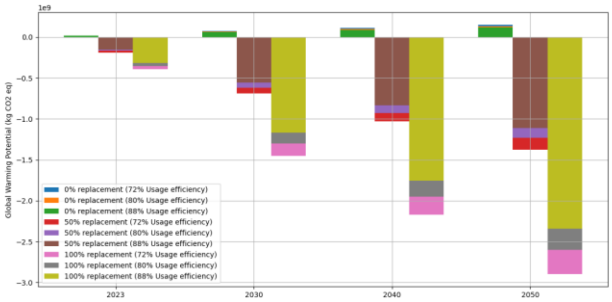

Fig. 6. GWP of copper across replacement levels for the years 2023, 2030, 2040, and 2050.

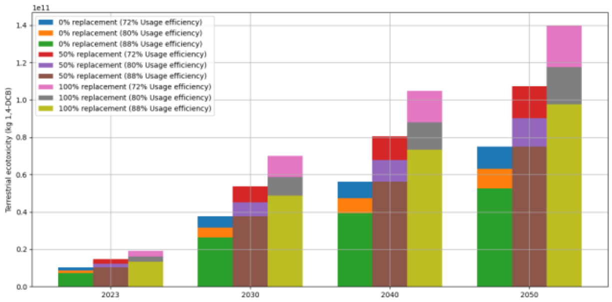

Fig. 7. Terrestrial ecotoxicity of copper across replacement levels for the years 2023, 2030, 2040, and 2050.

The data reveals significant impacts of natural gas replacement on both GWP and terrestrial ecotoxicity across all critical materials studied. Increasing natural gas replacement significantly reduces global warming potential (GWP). For instance, in 2023, displacing 100% of the natural gas leads to a 1944% reduction in GWP compared to the 0% replacement scenario for copper. Similar dramatic benefits are observed for zinc (1897% reduction) and lead (2049% reduction). This trend intensifies over time, with the 100% replacement scenario showing increasingly negative net impact values through 2050, highlighting the cumulative climate benefits of the renewable energy transition.

In contrast, terrestrial ecotoxicity (TE) increases with greater natural gas replacement. For all three metals, 100% replacement in 2023 results in a 86% increase in terrestrial ecotoxicity. The magnitude of this trade-off grows significantly over time, with the 2050 values showing approximately 7.3 times higher terrestrial ecotoxicity compared to 2023 levels under the 100% replacement scenario.

The results highlight a potential environmental trade-off specific to critical material usage in offshore wind: while offshore wind energy offers benefits in terms of global warming potential by displacing fossil fuels, it simultaneously leads to increased terrestrial ecotoxicity across all three critical materials. The distinct behavior of copper, zinc, and lead under various replacement scenarios underscores the need for material-specific mitigation strategies. Improving usage efficiency of these critical materials can partially mitigate the increase in terrestrial ecotoxicity, but the year-on-year accumulation of impacts remains significant. This cumulative effect emphasizes the importance of considering the long-term environmental consequences of expanding offshore wind capacity and integrating life cycle thinking into renewable energy planning. Further research is needed to develop comprehensive strategies to effectively manage these material-specific trade-offs between GWP and terrestrial ecotoxicity, along with other environmental impact categories, to ensure the sustainable utilization of critical materials in the renewable energy transition.

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