Net Environmental Impact Classification of Copper, Zinc, and Lead in UK Offshore Wind Systems

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***Abstract*—Offshore wind renewable energy systems require substantial amounts of critical metals such as copper, zinc, and lead. The extent to which the displacement of fossil fuel–based energy offsets the environmental costs associated with increased material demand remains insufficiently quantified. This study introduces a net impact classification model to systematically assess whether the deployment of copper, zinc, and lead in offshore wind systems is environmentally justified. The method calculates category-specific displacement ratios using life cycle assessments. These ratios classify environmental justification into three tiers: detrimental, where the ratio is less than one; marginal, where the ratio is between one and two; and beneficial, where the ratio is greater than two. Detrimental categories indicate that the material impact cannot be offset by the environmental benefits of fossil displacement. Marginal categories show partial offset, and beneficial categories represent full environmental justification. Applied to copper, zinc, and lead in offshore wind systems, the classification shows that climate impacts achieve strong justification, with a displacement ratio of 21.5 for global warming potential. Eight other categories, including freshwater ecotoxicity (0.10) and mineral scarcity (0.44), remain unjustified despite complete fossil displacement. To validate this classification method's robustness, Monte Carlo analysis was conducted. The analysis confirmed that these tier assignments are statistically robust, with 72% classification stability and 78% of categories showing clear justification outcomes. The net impact classification was further used to analyze how changes in material supply chain parameters and material intensity within offshore wind components affect net impacts. Detrimental categories showed amplified net reductions, marginal categories dampened responses, and beneficial categories limited improvement.**

***Index Terms*—Life Cycle Assessment (LCA), Critical Materials, Offshore Wind, Sustainability Transitions, Environmental impacts**

I. Introduction

The global transition to renewable energy is accelerating. Offshore wind capacity reached around 83 GW by the end of 2024 and is projected to increase by approximately 350 GW over the period 2025–2034 [1]. This expansion is central to achieving net-zero emissions targets, as renewable electricity generation displaces fossil fuel combustion and its associated greenhouse gas emissions [2]. However, renewable energy infrastructure is highly material-intensive, requiring 2–7 times more critical materials (such as copper, zinc, and lead) than fossil fuel systems [3]. Offshore wind turbines alone demand approximately 8 tonnes of copper per megawatt [3], alongside significant quantities of other metals for cables, foundations, and electrical systems. As deployment scales expand, the demand for critical materials rises, posing significant challenges for their environmental sustainability.

Life cycle assessment (LCA) studies indicate that the environmental impacts of critical material production are substantial and increasing, driven by this rapid expansion. For example, copper extraction and refining exhibit high impacts on terrestrial ecotoxicity and mineral resource depletion compared to many other industrial metals [4]. In offshore wind systems, the largest environmental impacts occur during production stages, dominated by material supply chain impacts. Recent studies show that these production stages alone can account for around 70% of total global warming potential [5]–[7]. These capital infrastructure components—particularly critical material-intensive elements like copper cabling and zinc coatings—contribute disproportionately to toxicity and resource depletion impacts beyond their climate footprint [7]. These findings have prompted calls for circular economy interventions, including improved material efficiency, increased recycling rates, and expanded secondary material supply [8], [9]. Analyses indicate that enhancing material efficiency can substantially reduce these environmental impacts [10].

While the production of renewable energy technologies include notable material impacts, their deployment is widely justified by the environmental benefits gained through fossil fuel displacement. System-level LCA comparisons consistently demonstrate net climate advantages when renewable electricity replaces coal or natural gas generation [11], [12]. Beyond climate mitigation, fossil displacement reduces air pollutant emissions—particularly particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), and sulfur dioxide (SO_2)—yielding substantial public health benefits [13], [14]. Water consumption associated with thermoelectric cooling is similarly avoided, reducing stress on freshwater resources in water-scarce regions [15], [16]. These displacement effects form the primary justification for aggressive renewable deployment policies globally, with the UK targeting 50 GW of offshore wind by 2030 and 100 GW by 2050 [17].

However, existing assessments typically evaluate benefits at the system level. They compare total renewable infrastructure impacts against total fossil impacts, without isolating the contributions of specific material flows [18], [19]. At the material level, these displacement benefits are not assigned to the specific materials that enable renewable technologies. Without this attribution, assessments may misrepresent the sustainability of renewable technologies by masking critical material-specific trade-offs. This raises an important question: to what extent can the environmental benefits of fossil fuel displacement justify the impacts of extracting critical materials such as copper, zinc, and lead required for renewable infrastructure? Researchers have raised concerns that accelerated renewable deployment may compromise critical material sustainability and increase environmental impacts in non-climate categories [20], [21]. However, these discussions have mostly been qualitative or focused on system-level impacts rather than on individual materials. The degree to which fossil fuel displacement benefits can offset the environmental burdens of individual materials, however, has yet to be quantitatively demonstrated.

Answering this question requires moving beyond climate-centric assessments to capture the full environmental consequences of renewable deployment. While fossil fuel displacement provides clear climate benefits, renewable energy systems can simultaneously generate significant impacts in other categories, such as resource scarcity, toxicity, and land use [18], [22]. This category-level heterogeneity suggests that assuming uniform displacement benefits for all impacts may be misleading. When evaluating renewable technologies at the material level, it becomes clear that some critical materials may generate substantial impacts in certain categories that are not fully offset by fossil fuel displacement. Consequently, assessing multiple environmental impact categories is essential to accurately quantify trade-offs and avoid overestimating the sustainability of material-intensive components.

This study addresses this gap by developing a net impact classification method to assess the environmental justification of copper, zinc, and lead use in offshore wind systems. The method quantifies whether their extraction remains environmentally acceptable. The method quantifies category-specific net impacts across 18 life-cycle categories for these materials in UK offshore wind infrastructure. Environmental justification is then classified into three tiers based on the displacement ratio (β_i): detrimental ($\beta_i < 1$), marginal ($1 \leq \beta_i \leq 2$), and beneficial ($\beta_i > 2$). Probabilistic analysis (N=10,000) quantifies classification robustness (72%) and justification confidence (78% unambiguous). Results show that climate-related categories achieve strong net justification. However, eight categories including terrestrial ecotoxicity and mineral resource scarcity remain unjustified despite complete fossil displacement.

II. Methodology

A. Analytical method

To systematically evaluate whether fossil fuel displacement can justify critical material extraction from an environmental perspective, a category-specific net impact quantification method was constructed. This approach evaluates the relationship across multiple environmental dimensions rather than focusing solely on climate outcomes. For each impact category i and material m, the net impact $NI_{i,m}(r)$ captures the difference between the material production impact and the displacement benefit of substituting fossil-based electricity with renewables.

A negative $NI_{i,m}(r)$ indicates that fossil displacement effects outweigh material extraction impacts, representing environmentally justified extraction. Conversely, a positive value denotes persistent impacts, indicating unjustified extraction even after accounting for avoided fossil generation. The replacement ratio r scales the level of fossil displacement, ranging from 0 (no displacement) to 1 (full displacement).

B. Mathematical Formulation

The net impact formulation is defined as:

$$NI_{i,m}(r) = I_{m,i} - \alpha_{m,i} \cdot r \cdot (I_{gas,i} - I_{wind,i}) \quad (1)$$

where $I_{m,i}$ is the material extraction impact, $\alpha_{m,i} = I_{m,i}/I_{wind,i}$ is the allocation factor, $I_{gas,i}$ and $I_{wind,i}$ are the per-MWh impacts of natural gas and wind generation respectively. Recognizing that wind farm impacts comprise both material and non-material contributions:

$$I_{wind,i} = I_{m,i} + I_{rest,i} \quad (2)$$

where $I_{rest,i}$ represents all other wind farm impact sources (concrete, steel, assembly, operation, decommissioning). Substituting this decomposition and defining the displacement ratio $\beta_i = I_{gas,i}/I_{wind,i}$:

$$NI_{i,m}(r) = I_{m,i} - \frac{I_{m,i}}{I_{m,i} + I_{rest,i}} \cdot r \cdot (I_{gas,i} - (I_{m,i} + I_{rest,i})) \quad (3)$$

Simplifying:

$$NI_{i,m}(r) = I_{m,i} \cdot [1 - r \cdot (\beta_i - 1)] \quad (4)$$

This formulation reveals that net impact scales linearly with material impact $I_{m,i}$, modulated by a factor $[1 - r \cdot (\beta_i - 1)]$. When $\beta_i > 2$ and full displacement occurs ($r = 1$), this factor becomes negative, indicating net environmental benefits. Conversely, when $\beta_i < 1$, the factor exceeds unity, amplifying material impacts. Based on this, a category-specific sensitivity factor can be introduced ($S_i(r)$):

$$S_i(r) = 1 - r \cdot (\beta_i - 1) \tag{5}$$

This sensitivity factor quantifies the net impact response to changes in material impact ($I_{m,i}$). Values $S_i > 1$ indicate amplified response (proportional net impact reduction exceeds material impact reduction), $0 < S_i < 1$ indicates dampened response, and $S_i < 0$ indicates that reducing material impacts worsens the net impact.

C. Sensitivity Analysis

To identify categories where impact reductions most effectively improve net outcomes, the sensitivity of net impact with respect to the material impacts $I_{m,i}$ was derived:

$$\frac{\partial NI_{i,m}}{\partial I_{m,i}} = S_i(r) + I_{m,i} \cdot \frac{\partial S_i}{\partial I_{m,i}} \tag{6}$$

Since $\beta_i = I_{gas,i}/(I_{m,i} + I_{rest,i})$:

$$\frac{\partial \beta_i}{\partial I_{m,i}} = -\frac{I_{gas,i}}{(I_{m,i} + I_{rest,i})^2} = -\frac{\beta_i}{I_{m,i} + I_{rest,i}} \tag{7}$$

And thus:

$$\frac{\partial S_i}{\partial I_{m,i}} = -r \cdot \frac{\partial \beta_i}{\partial I_{m,i}} = r \cdot \frac{\beta_i}{I_{m,i} + I_{rest,i}} \tag{8}$$

The total sensitivity becomes:

$$\frac{\partial NI_{i,m}}{\partial I_{m,i}} = S_i(r) + I_{m,i} \cdot r \cdot \frac{\beta_i}{I_{m,i} + I_{rest,i}} \tag{9}$$

$$= [1 - r(\beta_i - 1)] + r \cdot \frac{I_{m,i} \cdot \beta_i}{I_{m,i} + I_{rest,i}} \tag{10}$$

Recognizing that $\alpha_{m,i} = I_{m,i}/(I_{m,i} + I_{rest,i})$:

$$\frac{\partial NI_{i,m}}{\partial I_{m,i}} = 1 - r(\beta_i - 1) + r \cdot \alpha_{m,i} \cdot \beta_i \tag{11}$$

$$= 1 + r[\alpha_{m,i} \cdot \beta_i - (\beta_i - 1)] \tag{12}$$

$$= 1 + r \cdot \beta_i(\alpha_{m,i} - 1) + r \tag{13}$$

This comprehensive formulation captures both the direct sensitivity (S_i) and the secondary feedback effect through β_i changes.

D. Approximation for Small Material Contributions

When material impacts are relatively small ($\alpha_{m,i} \ll 1$), higher-order effects can be neglected, yielding:

$$\frac{\partial NI_{i,m}}{\partial I_{m,i}} \approx S_i(r) = 1 - r \cdot (\beta_i - 1) \tag{14}$$

This approximation holds for most categories where critical materials contribute 2–15% of total wind farm impacts. The error from this approximation is:

$$\epsilon = r \cdot \alpha_{m,i} \cdot \beta_i \tag{15}$$

For typical values ($r = 1.0$, $\alpha_{m,i} = 0.10$, $\beta_i = 2.0$), the error is 0.20, or 20% of the base sensitivity, which becomes significant for high-β categories. Therefore, the complete sensitivity formulation (11) was used for quantitative analysis while using the simplified form (14) for conceptual discussion.

E. Category-Specific Sensitivity Regimes

The sensitivity factor $S_i(r)$ exhibits distinct behavior across category types:

- **Detrimental categories** ($\beta_i < 1$): Wind infrastructure is more intensive than gas generation. Here $S_i(r) = 1 + r(1 - \beta_i) > 1$ for all $r \in [0, 1]$. Reducing $I_{m,i}$ yields amplified improvements in net impact, with sensitivity proportional to how much more intensive wind is than gas (i.e., $1 - \beta_i$). Additionally, reducing $I_{m,i}$ increases β_i (7), creating a positive feedback that further improves net impact.
- **Marginal categories** ($1 < \beta_i < 2$): Gas is slightly more intensive than wind, but insufficient to overcome material impacts. Here $0 < S_i(r) < 1$, indicating reduced sensitivity to $I_{m,i}$ reductions, the displacement benefit partially offsets the material impact. However, reducing $I_{m,i}$ increases β_i, potentially pushing these categories across the $\beta_i = 2$ threshold into beneficial territory.
- **Beneficial categories** ($\beta_i > 2$): Gas is substantially more intensive than wind. When $r(\beta_i - 1) > 1$, $S_i(r) < 0$, indicating that the category already exhibits net favorable outcomes. Reducing $I_{m,i}$ paradoxically makes net impact less negative (weakens favorable outcomes), though the absolute magnitude remains favorable. These categories exhibit diminishing marginal returns from material interventions.

III. Data and Implementation

The analytical method was conducted using inventory data representative of UK electricity generation systems. Environmental impacts were quantified using the ReCiPe 2016 midpoint method, implemented in SimaPro 9.4 with Ecoinvent v3.9.1 as the background database. All results are reported per unit of electricity delivered (1 MWh) to ensure consistency across system boundaries.

A. System Definition

Three systems were considered: offshore wind electricity generation, natural gas electricity generation, and the extraction and use of three critical materials (copper, zinc, and lead) within offshore wind infrastructure. Natural gas was selected as the reference fossil source to represent the UK's current and projected energy mix, where gas-fired power continues to provide a substantial share of dispatchable generation capacity.

For offshore wind, the life cycle model includes raw material extraction, component manufacturing, installation, operation, maintenance, and decommissioning stages. The corresponding natural gas system includes process stage impacts.

B. Impact Quantification and Critical Material Dataset

Environmental impacts were quantified across 18 ReCiPe categories. The key parameters in (1) $I_{m,i}$ (material-specific), $I_{wind,i}$ (total wind generation), and $I_{gas,i}$ (gas generation) were expressed per megawatt-hour (MWh) of delivered electricity.

A distinct feature of this analysis is the high-resolution dataset developed for critical materials. The values of $I_{m,i}$ were not taken from generic database entries, but derived from a cradle-to-grave LCA model built specifically for this study and presented in [10]. This model integrates detailed supply chain data for copper, zinc, and lead used in offshore wind components, capturing variations in:

- Primary and secondary production shares, recycling rates, and usage efficiencies (reflecting circularity potential),
- material intensity across major turbine components (nacelle, tower, and cabling),
- infrastructure lifetime and distance to shore.

This granularity enables direct sensitivity analysis on how improvements in circular economy parameters or infrastructure parameters affect $I_{m,i}$ and, by extension, the overall net environmental justification.

IV. Results and Discussion

TABLE I
SYMBOLS AND DEFINITIONS

Symbol	Definition
Fossil	Fossil resource scarcity
GWP	Global warming
OF-T	Ozone formation, Terrestrial ecosystems
OF-H	Ozone formation, Human health
OD	Stratospheric ozone depletion
IR	Ionizing radiation
Water	Water consumption
Min-Scar	Mineral resource scarcity
Land	Land use
M-Eut	Marine eutrophication
PMF	Fine particulate matter formation
TA	Terrestrial acidification
H-NonCarc	Human non-carcinogenic toxicity
FW-Eut	Freshwater eutrophication
T-Etox	Terrestrial ecotoxicity
H-Carc	Human carcinogenic toxicity
M-Etox	Marine ecotoxicity
FW-Etox	Freshwater ecotoxicity

A. Net Environmental Contrasts

This section calculates the net environmental impacts for the three metals. Fig. 1 presents these net impacts under three replacement scenarios: r=0.0 (no displacement, baseline impacts), r=0.5 (partial displacement), and r=1.0 (full displacement, current policy assumption). The heatmap illustrates two contrast regions, revealing that displacement benefits are not uniformly distributed across environmental categories.

Climate-related categories—including global warming potential exhibit a progressive shift toward blue as the replacement ratio (r) increases. This indicates that fossil displacement strongly outweighs material extraction climate-related impacts.

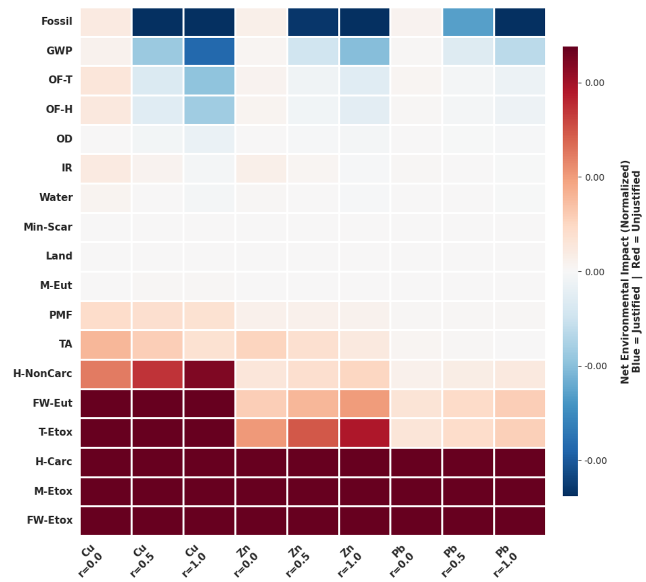

Fig. 1. Environmental Contrasts: Material Extraction vs Fossil Displacement. (See Table I for category abbreviations)

This happens due to the large emission difference between offshore wind (16.4 kg CO_2-eq/MWh) and natural gas systems (352.7 kg CO_2-eq/MWh) [7]. When this large displacement benefit is attributed to the materials, the avoided fossil CO_2 emissions substantially offset the material production emissions. As r increases from 0 to 1.0, this net benefit strengthens proportionally, intensifying the blue shade.

In contrast, toxicity and ecotoxicity-related categories display an opposite trend: red intensity increases with higher replacement ratios. These impacts, particularly freshwater ecotoxicity and human carcinogenic toxicity, are inherently higher in offshore wind infrastructure relative to natural gas electricity generation. For example, offshore wind exhibits 4.53 kg 1,4-DCB-eq/MWh of freshwater ecotoxicity compared to 0.44 kg 1,4-DCB-eq/MWh for natural gas [7]. Consequently, displacing natural gas with wind increases the total ecotoxicity. When this worsening is attributed to critical materials, these categories remain environmentally unjustified under complete fossil displacement (r=1.0). The intensifying red shade reflects this amplification effect.

This category-level divergence demonstrates that fossil displacement justifies material extraction in climate dimensions while simultaneously failing to justify non-climate environmental pressures. The environmental justification for critical material extraction is therefore impact-specific, not universal.

B. Sensitivity and Prioritization tiers

Fig. 2 shows the sensitivity factor (S_i) as a function of displacement ratio (β_i), clearly showing the three distinct regions. Each impact category's position on the curve is determined by its β_i value. It governs whether material impact reductions are amplified, dampened, or counterproductive. The S_i quantifies the magnitude of net impact change.

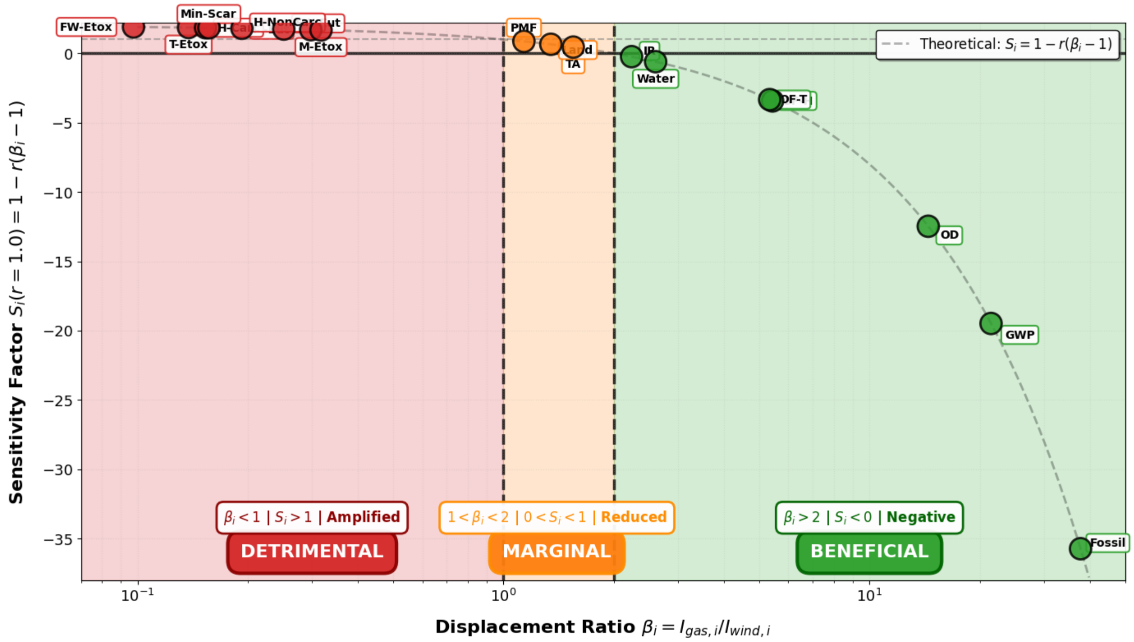

Fig. 2. Sensitivity Factor as Function of Displacement Ratio

*a) **Tier 1 – Detrimental Categories** ($\beta_i < 1$):* Eight categories—including freshwater ecotoxicity and mineral scarcity exhibit more intensive impacts in offshore wind than the gas generation it displaces. Material extraction in these categories remains environmentally unjustified even under complete fossil displacement ($r = 1.0$). A key finding is that these categories show $S_i > 1$ ($S_i = 1.68$–1.90). This means each unit of material impact saves deliver $1.68 - 1.90$ units of net impact reductions on these categories.

*b) **Tier 2 – Marginal Categories** ($1 < \beta_i < 2$):* Three categories (fine particulate matter, land use, and terrestrial acidification) occupy a transition zone where natural gas is only slightly more intensive than wind. These categories exhibit dampened sensitivity ($0 < S_i < 1$), requiring large reductions in $I_{m,i}$ to achieve small net impact improvements. The strategic objective here is to "shift" these categories from impacts to benefits by crossing the $\beta_i = 2$ threshold through aggressive material impact reductions, converting them to beneficial status.

*c) **Tier 3 – Beneficial Categories** ($\beta_i > 2$, $S_i < 0$):* Seven categories—including global warming potential (GWP) already deliver overwhelming net benefits. The negative sensitivity ($S_i < 0$) indicates diminishing marginal returns from material interventions; for GWP with $\beta_i = 21.5$, material reductions yield negative returns compared to $17 - 19\%$ improvements achievable in Tier 1 categories. Changes to material impacts of these categories yield lower net impact returns compared to Tier 1 categories.

C. Intervention Strategy

Having established the three-tier framework, this section examines how different intervention pathways influence net environmental outcomes. Two intervention types are analyzed: (1) critical material supply chain improvements (recycling, efficiency, secondary sourcing) and (2) material intensity parameters in offshore wind components that directly effect $I_{m,i}$ (Fig. 3 and Fig. 4).

The figures reveal dramatic variation in intervention effectiveness. Beneficial categories ($\beta_i > 2$) exhibit large negative values (up to -400%), indicating that while material impact reductions still lower total impacts, their marginal improvement to the net balance is limited where fossil displacement benefits already dominate. Detrimental categories ($\beta_i < 1$) exhibit amplified positive leverage, where a 10% reduction in $I_{m,i}$ yields 17-19% net impact improvement through $S_i > 1$ amplification. Marginal categories show dampened responses near zero.

This distinction enables targeted intervention strategies: material supply chain improvements directed toward detrimental categories deliver more environmental returns compared to direct material reductions. Simultaneously, material efficiency improvements could convert marginal categories to beneficial status, expanding the range of environmentally justified impacts. This category-weighted approach ensures that circular economy investments maximize net environmental improvements across the full impact spectrum.

While the sensitivity analysis examines all three materials (copper, zinc, and lead), the probabilistic validation focuses on copper as a representative case. Zinc and lead exhibit similar tier distributions, with all three materials showing eight detrimental categories, three marginal categories, and seven beneficial categories.

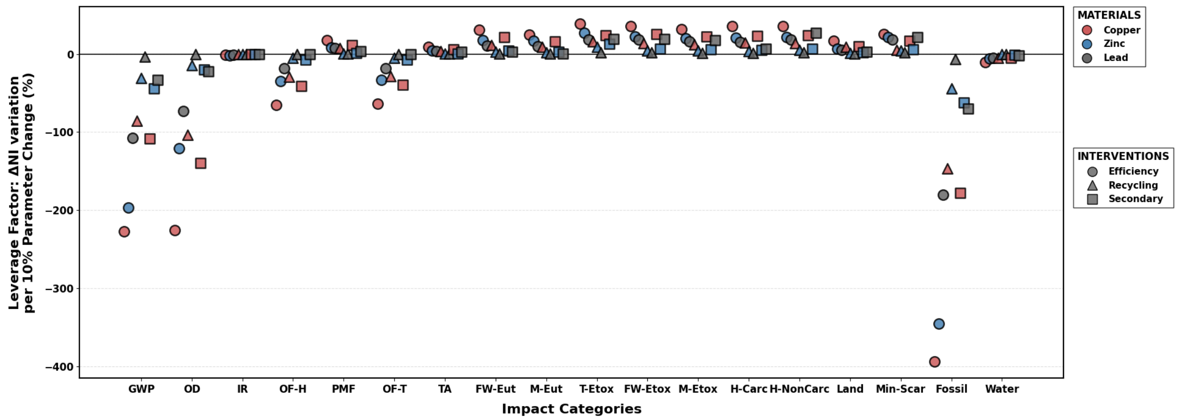

Fig. 3. Sensitivity of net impact to changes in material supply chain parameters

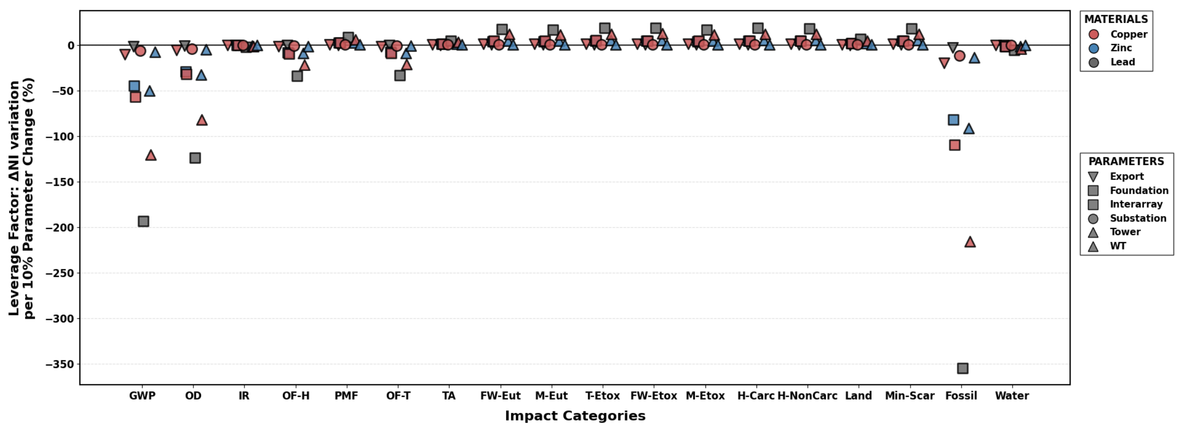

Fig. 4. Sensitivity of net impact to material intensity parameters

D. Probabilistic Validation and Justification Confidence

To quantify the robustness of the tier classifications and justification decisions under uncertainty, a probabilistic analysis was conducted using Monte Carlo simulation (N=10,000). In each Monte Carlo iteration, random values from the distributions (as defined by SimaPro uncertainty ranges) were sampled and β_i and $NI_{i,m}$ were calculated. This process generated probability distributions for both the displacement ratio (β_i) and net impact ($NI_{i,m}$), enabling the quantification of: (1) tier classification confidence, the probability that β_i falls within each tier's boundaries, and (2) justification confidence, the probability that $NI_{i,m} < 0$.

1) Tier Classification Robustness: Fig. 5 shows the probabilistic distributions of β_i across all impact categories. The analysis reveals that 13 of 18 categories (72%) exhibit robust tier classifications, with $> 95\%$ confidence in their assigned tier. Five categories show borderline tier assignments: water consumption (negative mean β_i with high variance), fine particulate matter formation ($\beta = 1.14$, straddling Tier 1/2 boundary), land use ($\beta = 1.33$), terrestrial acidification ($\beta = 1.56$), and ionizing radiation ($\beta = 2.25$, near Tier 2/3 boundary).

Notably, all eight Tier 1 (detrimental) categories maintain $> 99\%$ confidence in remaining detrimental despite uncertainty propagation, confirming that these impacts persistently exceed displacement benefits. Similarly, four of five Tier 3 (beneficial) categories show $> 99\%$ confidence, with only ionizing radiation exhibiting moderate uncertainty (61.7% Tier 3 probability).

2) Justification Confidence: While tier classification identifies intervention strategies, justification confidence quantifies decision certainty under uncertainty. The $P(NI_{i,m} < 0)$ (the probability that net impact is negative) was calculated for each category (Fig. 6). This metric indicates the confidence that a material extraction is environmentally justified.

The analysis reveals three distinct groups: (1) clearly justified categories ($P > 95\%$, n=5) where displacement advantages robustly exceed material impacts; (2) clearly unjustified categories ($P < 5\%$, n=9) where material impacts persistently exceed displacement benefits; and (3) uncertain categories ($5\% \leq P \leq 95\%$, n=4) where justification depends sensitively on actual values within the uncertainty range.

Importantly, tier classification and justification confidence provide complementary information. For example, fine par-

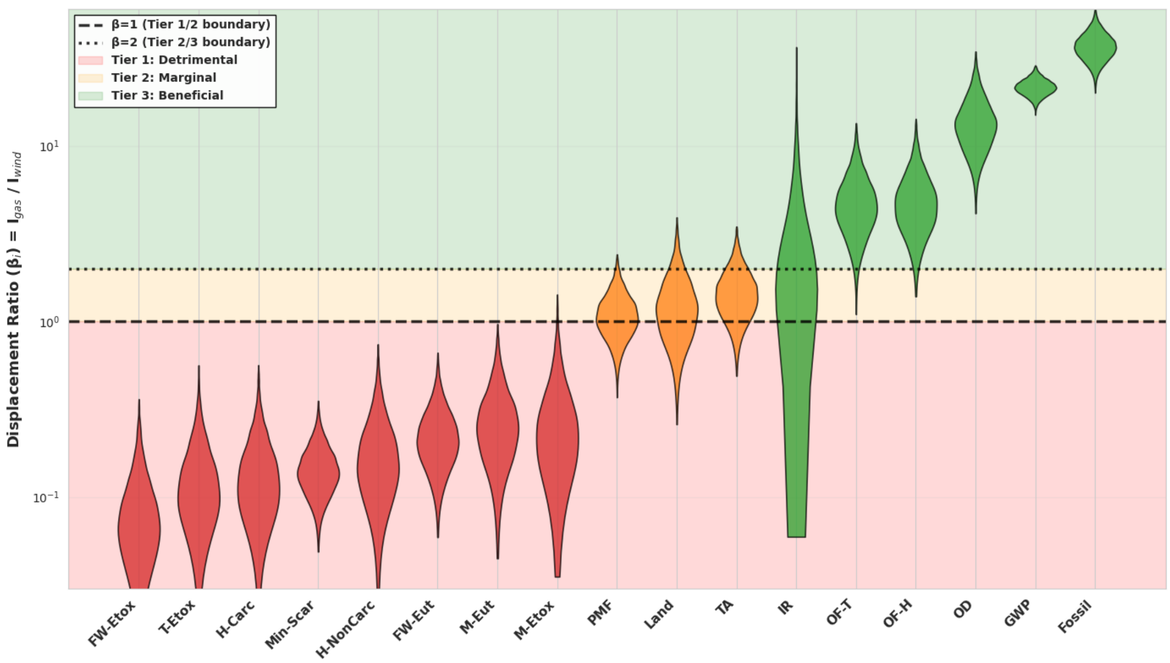

Fig. 5. Probabilistic Analysis: Distribution of Displacement Ratio β_i Across Impact Categories (Copper)

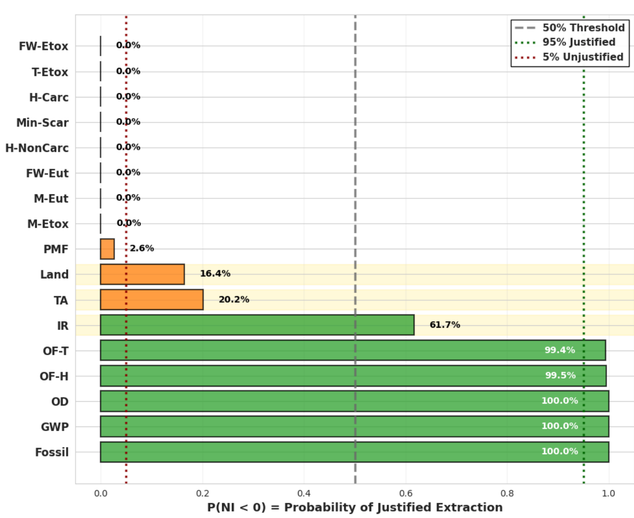

Fig. 6. Confidence that material extraction is environmentally justified (Copper)

ticulate matter formation is classified as Tier 2 (marginal, $\beta = 1.14$) but exhibits only 2.7% justification probability, indicating material impacts consistently exceed benefits despite the moderate displacement ratio. Conversely, ionizing radiation achieves Tier 3 classification (beneficial, $\beta = 2.25$) but only 61.7% justification confidence, highlighting a priority area for refined characterization.

Overall, 14 of 18 categories (78%) exhibit unambiguous justification status ($P > 95\%$ or $P < 5\%$), demonstrating that the tier framework remains robust under uncertainty while identifying specific categories requiring enhanced data quality or targeted interventions.

3) Policy Implications and Generalization: This priority system proposes four strategies for maximizing net environmental benefits of critical material usage in renewable energy deployment:

- R&D Prioritization: Direct research funding toward high-S_i categories (toxicity reduction) where interventions can deliver amplified environmental returns.
- Extended Impact Disclosure: Expand Environmental Product Declarations to include Tier 1 categories alongside GWP metrics, providing stakeholders with comprehensive environmental profiles for material-intensive components.
- Impact-Weighted Circularity Metrics: Complement tonnage-based recycling targets with S_i-weighted impact reduction metrics to align circular economy incentives with environmental outcomes.
- Cross-Technology Application: Extend the β_i-driven prioritization framework to other material-intensive technologies (solar PV, electric vehicles, batteries) exhibiting analogous trade-off patterns.

The probabilistic analysis (78% of categories show unambiguous justification status) confirms that these priorities are robust under uncertainty. Categories with $\beta_i < 1$ represent fundamental justification challenges that displacement advantages cannot offset, demanding direct and targeted interventions. Without this strategic reorientation, renewable energy deployment risks producing enduring non-climate environmental burdens even while achieving global decarbonization goals.

V. Conclusion

This study developed a category-specific framework to quantify whether fossil fuel displacement can environmentally justify the extraction of copper, zinc and lead used in offshore wind systems. By introducing the displacement ratio (β_i) and sensitivity factor (S_i), the method enables explicit differentiation between impact categories that are environmentally justified, marginally offset, or persistently detrimental.

The results show that while offshore wind delivers strong net climate justification (β_{GWP} = 21.5), eight non-climate categories including freshwater ecotoxicity and mineral resource scarcity remain environmentally unjustified even under full displacement. These categories correspond to Tier 1 ($\beta_i < 1$) regions where material impacts dominate despite the decarbonization benefit. Conversely, climate-related and air-quality categories fall in the beneficial range ($\beta_i > 2$), confirming the robustness of their environmental justification.

Sensitivity analysis shows that the factor S_i links material design choices and supply chain improvements to overall environmental outcomes. In categories with $S_i > 1$, reducing material impacts yields amplified environmental benefits, indicating that interventions such as recycling or efficiency improvements are particularly effective. Probabilistic validation confirms the statistical robustness of this tiered framework, with 78% of categories showing unambiguous justification status ($P > 95\%$ or $< 5\%$).

The findings highlight the need for a multidimensional sustainability perspective that complements climate mitigation with targeted reduction of non-climate burdens. The β_i-based framework provides a transferable basis for prioritizing interventions, guiding research and aligning circular economy metrics with actual environmental outcomes. Future work should extend this approach to solar PV, electric vehicles, and batteries to establish cross-technology comparability, and integrate regionalized displacement and material datasets to refine spatial differentiation in justification outcomes.

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