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Identification of Environmental Impacts from Copper Usage in Solar and Offshore Wind Energy Systems

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KEYWORDS

Life cycle assessment, sustainable copper utilization, renewable energy

ABSTRACT

The development and operation of solar and wind renewable energy systems depend on the use of critical metals, including copper. While the unique properties of copper make it irreplaceable in the renewable energy technologies, the scarcity of copper raises environmental concerns. Copper extraction, processing and transportation have a significant impact on the local and global environment. This study comprehensively assesses the environmental impacts of copper usage in renewable energy systems, using the cradle-to-grave life cycle assessment (LCA). The results of the assessment show that solar energy system generates a larger impact in all 18 categories considered in the study except in the mineral resources scarcity. Furthermore, the study identifies and quantifies the potential of the transition from non-renewable energy sources (such as natural gas) to renewable energy to neutralize the global warming potential (GWP) contributed by copper. Results show that offshore wind requires a transition of 0.86% to 2.63%, while solar requires a more substantial 10.12% to 15.65% replacement to reach GWP neutralization. This suggests that initiating renewable energy deployment with small offshore wind projects, due to their lower replacement percentages, can be defined as a strategic entry point in energy policy development concerning the environmental impact of copper.

INTRODUCTION

In response to the pressing challenges of climate change, there is a global shift towards sustainable energy solutions. This has directed the world's focus towards the immense potential of renewable sources. Among these, offshore wind farms and solar farms have gained a reputation for their cleaner energy. The use of renewable energy in electricity production started to gain momentum in the early 2000s. The share of renewable energy in electricity production in the UK has increased from 3.4% in 2000 to 43.4% in 2020 (IEA, 2020). The UK government plans suggest that the future growth of the energy sector is primarily focused on renewable energy with major expansions.

However, as we dive deeper into the path of renewable energy adoption, it is important to examine the underlying environmental costs and benefits, especially when considering the often-overlooked role of critical materials. Copper, a vital component in the renewable energy infrastructure, is one such critical material whose significance in electricity systems cannot be understated. Previous research has shown that copper usage in renewable energy technologies can be 2 to 7 times higher than traditional fossil fuels (International Energy Agency, 2019). Furthermore, the amount of commercially extractable copper is limited and copper is documented as a scarce material. This emphasizes that an increase in copper demand at current rates might deplete the current reserves within the next few decades (Sverdrup et al., 2014). As such, this raises concerns about the sustainability of copper flow in offshore wind farms and solar farms. Furthermore, copper production is a highly energy-intensive process with a significant environmental footprint (Hong et al., 2018).

These concerns underline the immediate need to explore strategies for reducing copper demand and optimizing copper utilization in the renewable energy systems, particularly solar and offshore wind. Hence, it is important to understand the material flow of copper throughout the entire life cycle of renewable energy systems and quantify the environmental impacts of copper usage within these systems. This insight is fundamental for designing sustainable renewable energy systems. This paper makes a significant contribution to this current debate by (1) providing an in-depth evaluation of environmental impacts associated with copper usage in solar farms and offshore wind farms, and (2) determining the extent of the reduction in fossil fuel utilization for electricity generation required to counterbalance the negative environmental impacts of copper usage.

In related work, the environmental impacts of copper extraction and production have been assessed in many published studies such as (Hong et al., 2018) where the significant environmental impacts of copper extraction and production have been identified with a cradle to gate scope. Furthermore, several other works assessed the environmental impacts of renewable energy technologies such as offshore wind farms and solar farms including (Kouloumpis and Azapagic, 2022) and (Fu et al., 2015) identifying major environmental impacts associated. While these works have identified the material requirements in solar and offshore wind farms, a comprehensive evaluation of environmental impacts linked to individual critical materials such as copper in solar and offshore wind farms is rarely discussed. Nevertheless, the available literature regarding life cycle assessments of material usage in renewable energy technologies is relatively limited. Harpprecht et al. (2021) examined the environmental performance of several essential metals within renewable energy technologies and suggested a potential decrease in their impacts over time. While their analysis provides valuable insights into the environmental impacts of copper usage in renewable energy systems, the work is limited by its focus on the cradle-to-gate scope of the assessment. Viebahn et al. (2015) analysed the critical material requirements for the wind energy sector in Germany, considering different wind turbine technologies, and identified copper as one of the two most critical materials in wind turbines due to its high demand concerning its current availability. However, this study is limited to Germany. Yuan et al. (2023) focused on a single material and analysed the significance of the steel industry in terms of global warming potential in the context of floating offshore wind farms. But this study was limited to steel.

A comprehensive cradle-to-grave life cycle assessment specifically addressing the role of copper (from the extraction of copper to usage of copper in renewable energy components to end of life disposal management) within solar and offshore wind farms is lacking in the current literature. Our study is focused on contributing useful findings by combining the impacts of extraction and production of copper with copper deployment in solar and offshore wind farms. This paper aims to find answers to the following research questions: (1) What is the magnitude of environmental impacts associated with copper utilization across the entire life cycle of renewable energy technologies such as solar and offshore wind farms? (2) What proportion of electricity generation from fossil fuels needs to be substituted by offshore wind and solar farms to counterbalance the negative environmental effects linked to copper utilization?

METHODS

The life cycle assessment method is a standardized technique for assessing the environmental impacts of a product or a service. This study adopts the ISO 14040/44 framework for the LCA methodology (ISO, 2015). This methodology consists of four major steps: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) interpretation of results.

Goal and scope definition: The goal of this work is to carry out a comprehensive life cycle environmental impact assessment associated with copper usage in renewable energy technologies i.e. solar farms, and offshore wind farms in the UK. The scope of this assessment is cradle-to-grave. The functional unit is defined as “the copper consumption for average electricity generated by a renewable energy plant, per lifetime, per kilowatt hour”. The assessed life cycle process consists of two major sections: the cradle-to-gate process of copper extraction and production, and the gate-to-grave process of copper usage in renewable energy plants including transportation, usage stages, and end-of-life stages. The usage stage includes only the copper usage data. Figure 1 illustrates the cradle-to-grave system boundary. In this study two renewable technologies are considered: the silicon photovoltaic farms and the offshore DDSG (Direct Drive Synchronous Generator) wind farms. The DDSG wind farm contains 100 wind turbines with a 3 MW power rating with a substation, export and inter-array copper-based cables. According to Kouloumpis and Azapagic (2022), the wind farm was assumed to operate for 8760 hours annually with an average capacity factor of 44.37%. The study also considered a distance to shore of 30 km, a total export cable length of 60 km with a type of 132kV - 1000 mm2, an inter-array cable length of 61 km with a type of 33kV - 400 mm2, and a substation weight of 2,480,000 kgs.

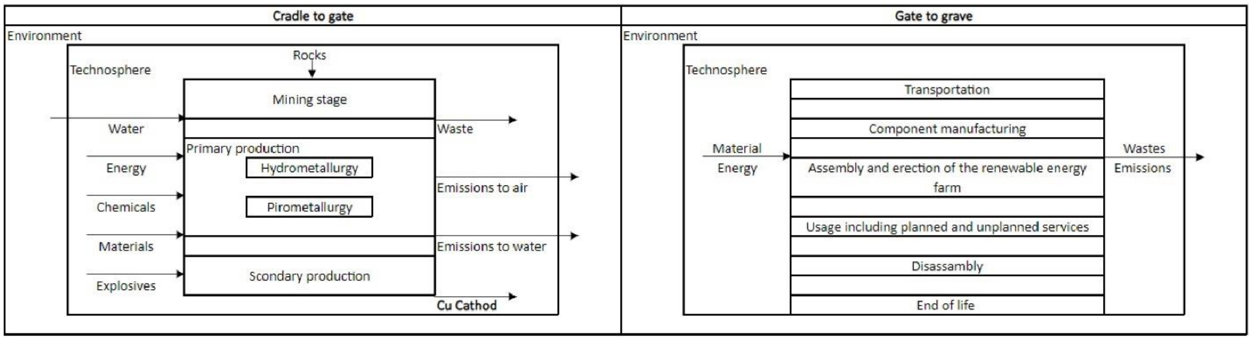

Figure 1: System boundary (cradle to grave)

The solar farm has a capacity of 1 MW and an average Si PV module with 187.5 Wp/m^2 ((PVPS), 2020), with an area of 5333.33 m^2. The annual yield of sunlight for the UK was 1128 kWh/m^2 and an average efficiency of 18.75% was estimated ((PVPS), 2020). The total weight of an unframed module was 11 kg per square meter ((PVPS), 2020) and the total weight of the module to produce 1 MW was calculated to be 58666.66 kg. The copper consumption was given as 0.93% ((PVPS), 2020). The total copper weight was 545.6 kg. The copper-consuming components are; Si Solar modules, inverters and transformers, and cabling. The specifications of Cu consumption are described in Table 1.

Table 1: Copper using components and their consumptions

Components	Total weight (kg)	Cu weight (kg)	Cu weight percentage (allocation factor)
Offshore wind farm			
DDSG wind turbine	300,720	14,980	4.98%
Substation	2,480,000	83,080	3.35%
Inter array cable (1km)	32,000	8,680	27.125%
Export cable (1km)	85,400	2,020	2.37%
Solar farm			
PV module	58,666.66	545.6	0.93%
Inverters and transformers	20,049	2,277	11.36%
Cabling	5,973.32	3,413.33	57.14%

Life cycle inventory analysis (LCI): Data were collected for each life cycle stage in Figure 1. In the process, the Ecoinvent data library was used as a reliable data source. Ecoinvent contains data on inputs and outputs such as materials and energy requirements, and emissions of a wide range of processes. Research articles, and experts were used for more specific data collection. For the offshore wind and solar farms, all components were estimated to be built in Europe (Kouloumpis and Azapagic, 2022). The copper source mix for Europe was estimated to be: 50% secondary copper and 50% primary copper (Soulier et al., 2018). The copper sources considered in the current research are summarized in Table 2. The copper production data (primary and secondary) were obtained from the Ecoinvent database, version 3.9. Data gaps were filled with relevant expert opinions, considerations, and literature sources.

Table 2: The mix of copper sources

Method	Percentage	References
Secondary copper from Europe	50%	(Soulier et al., 2018)
Primary copper from Europe	16%	(Statista, 2021)
Primary copper from Latin America	17%	(Eurostat, 2023)
Primary copper from globe (China, USA, Australia, RoW)	17%	(Henckens and Worrell, 2020)

The next stage of the life cycle process was transportation. The transportation distances and methods were calculated depending on the locations of supply sources and only copper weights were considered for transportation in impact calculation. At the production of components stage, the copper usage in the production process of renewable technology components is assessed, and a copper usage efficiency of 80% was assumed (it was noted that renewable energy manufacturing industries operate with high copper efficiencies). Thereafter, the manufactured components are transported to assembly points in the UK and the transportation methods were decided accordingly. Then the operation and maintenance stages were considered. Afterward, the decommissioning was done followed by end-of-life disposal stage. A 90% (Kouloumpis and Azapagic, 2022) of copper collection for recycling from all copper-containing components was considered while the remaining 10% would be incinerated as it is inseparable. To account for only copper usage impacts an allocation factor was used in component manufacturing, assembly, operation and maintenance, and decommissioning stages which is provided in Table 1. The specifications of renewable energy technologies and detailed inventory are available upon request.

Life cycle impact assessment: The life cycle impact assessment was conducted employing SimaPro LCA software, version 9.4.0.3. The calculation method encompassed all impact categories of the ReCiPe mid-point (H) (2016) methodology (PR´e Sustainability, 2023).

RESULTS

Figure 2 presents a comparison of environmental impacts associated with copper usage in solar and offshore sources across 18 impact categories, each measured in its respective unit per kilowatt-hour (kWh). The primary focus of this study was to find environmental impacts associated with copper usage in solar and offshore wind sources and identify key areas where the two technologies differ.

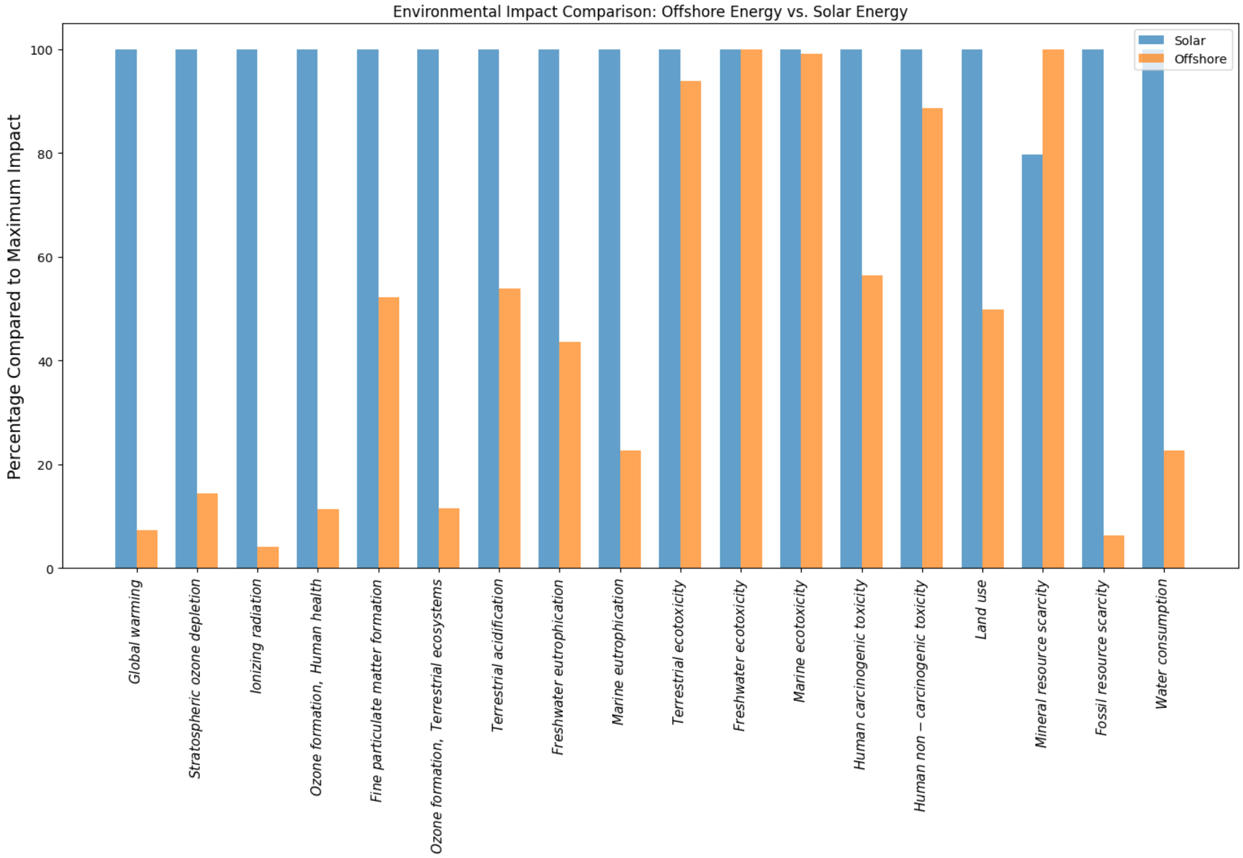

Figure 2: Comparison of copper usage impact in solar farms and offshore wind farms

The results demonstrate a remarkable distinction in their environmental performances. The most notable contrast between Solar and Offshore wind energy technologies is in their Global Warming Potential (GWP). Solar exhibited a significantly higher GWP with 4.67 g CO_2 eq./kWh, which is nearly fourteen times higher than the value for offshore wind energy which is only 0.34 g CO_2 eq./kWh. This is important in the context of addressing climate change and reducing greenhouse gas emissions (in copper usage). Furthermore, the stratospheric ozone depletion followed a similar pattern with solar energy having almost seven times higher value of 2.52E-06 g CFC11 eq per kWh than the value of 3.64E-07 g CFC11 eq per kWh in offshore wind energy. This indicates that using copper on offshore wind energy sources rather than solar energy sources to produce 1 kWh would preserve the ozone layer more. Ionizing radiation also follows the trend with solar energy sources having 1.15E-03 kBq Co-60 eq which is almost twenty-five times larger impact than 4.64E-05 kBq Co-60 eq of offshore wind energy sources. A similar trend can be seen throughout most of the impact categories with solar energy having a higher impact in terms of copper usage in them compared to offshore wind farms. The environmental impact category of freshwater ecotoxicity has almost the same impact value of 1.38 g 1,4-DCB in both sources. The environmental impact category of mineral resource scarcity follows a different trend by having a higher environmental impact on copper usage in the offshore wind rather than solar energy sources with 6.16E-2 g Cu eq in solar and 7.7E-2 g Cu eq in offshore wind energy. These numerical findings show the differences in environmental impacts associated with copper usage between the two technologies. While offshore wind energy excels in mitigating climate change and displays a better environmental performance, solar energy offers better environmental performances in one area of terrestrial ecotoxicity. This underscores the importance of considering a broad spectrum of environmental impact categories when evaluating the sustainable copper management. These findings guide policymakers and environmentalists towards informed choices.

DISCUSSION

With worldwide net zero commitments, a significant increase in critical material usage is expected, raising concerns about the sustainability of these materials. However, in a broader context, a possibility for trade-offs lies among the negative environmental impacts of copper usage and the environmental benefits of renewable energy replacing traditional non-renewable energy technologies such as natural gas power plants. The electricity generation process from offshore wind farms and solar farms does not involve GHG emissions thus making usage of these technologies to displace non-renewable energy sources environmental benefits. Analysis of the UK's electricity mix revealed increased contributions from renewable energy technologies throughout the years. However, the average contribution of natural gas exhibited a consistent pattern, fluctuating around 40%, reaching a maximum of 40.3% in 2021 (IEA, 2023). As a non-renewable energy source, natural gas has not shown any signs of decreasing. As such, natural gas was chosen for the trade-off calculations. The GWP of offshore wind farms in the UK was estimated to range from 6.4 to 19.5 g CO2 eq/kWh (Kouloumpis and Azapagic, 2022) and for solar farms to be from 75 g CO2 eq/kWh to 116 g CO2 eq/kWh (Parliament, 2019). These ranges were used to calculate trade-offs between the negative environmental impacts of copper usage and the environmental benefits of displacing non-renewable energy sources - natural gas power plants as shown in Figure 3. To account for the limitations (comparison of LCAs), the trade-off was calculated using GWP intensities (per kWh) compared to natural gas power plant (Riva and D'Angelosante, 2006).

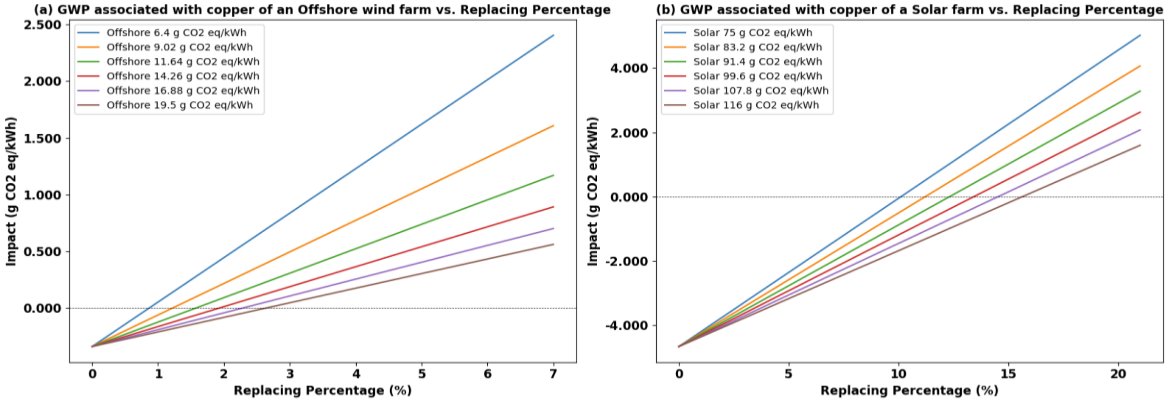

Figure 3: Trade-offs between negative and positive impacts (Solar and Offshore Wind)

On both sides (solar and offshore wind) six different scenarios are considered (from 75 gCO2eq/kWh to 116 gCO2eq/kWh in solar and from 6.4 gCO2eq/kWh to 19.5 gCO2eq/kWh in offshore wind energy). The results highlight that a gradual increase in replacing percentages in a single scenario (for example offshore wind 6.4 gCO2eq/kWh line in Fig. 3 (a)) reduces negative environmental impacts and push the negativity towards a positive environmental impact (important: a negative impact have a harmful effect on the environment while a positive impact has beneficial). The results indicate that in offshore wind energy, this replacing percentage required to neutralize the harmful effects of copper usage is a very low value for the scenarios considered which ranges from 0.86% to 2.63%. Similarly, for the solar energy, this replacement percentage was found to be ranging from 10.12% to 15.65%. The fact that the GWP of copper usage in offshore wind energy becomes environmentally beneficial when replacing 0.86% to 2.63% of natural gas power plants is remarkable. This indicates that even a modest transition to offshore wind energy (in terms of copper usage) can yield significant environmental advantages (in terms of GWP). On the other hand, solar farms require a relatively higher replacement rate of 10.12% to 15.65% for copper usage to be environmentally beneficial. As such, it can be concluded that offshore wind energy can be used as a starting point for sustainable copper usage, and a slight shift towards offshore wind energy would be enough to offset the GWP of copper mining, processing, and usage in the offshore wind industry. Furthermore, this implies that copper usage in offshore wind farms leads to environmental benefits despite early stages of adoption. However, solar needs large-scale adoption to offset copper's high greenhouse impact. Policymakers should consider the adoption of solar energy not as an isolated endeavour but as a collective effort. Both technologies have unique roles in mitigating climate change. While offshore wind farms are beneficial from the start, solar energy requires a more extensive commitment in terms of copper.

CONCLUSIONS

The environmental impacts of using copper in solar and offshore wind energy deployment in the UK considering the cradle-to-gate scope of copper is comprehensively assessed in this study. The study identifies the environmental impacts of copper usage in both technologies across 18 environmental impact categories. The comparison of values concludes that copper usage in offshore wind energy systems to produce 1 kWh in the UK is more environmentally beneficial than solar energy. Further, this study identified the potential of neutralizing the GWP associated with copper usage in both technologies through the replacement of natural gas power. The findings conclude that offshore energy can be a starting point for sustainable copper usage as it requires a modest transition of 0.86% to 2.63% of replacement and on the other hand, solar energy requires a replacement of 10.12% to 15.65% to reach a neutralization of GWP in terms of copper usage. The outcomes of this study will offer valuable insights into resource planning for strategic decision-making regarding the deployment of solar and offshore wind farms in the UK. These findings highlight the need for tailored policies and investments to maximize the impact of different renewable energy sources on mitigating environmental impacts associated with copper utilization. Future work would focus on refining this unique range and strategies to overcome the challenges associated with it.

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