Can tidal power technologies be considered fully green?

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I. INTRODUCTION

Tidal energy is a renewable energy able to be used for decreasing the dependence on fossil fuels which are the main emitters of greenhouse gases (GHG) to the environment (Rashedi et al., 2022).

According to Rashidi et al. (2022), as well as Walker and Thies (2022), tidal energy technologies have the capacity to generate part of the electricity for the world energy demand; tidal energy is easily predictable because ocean currents are driven by the gravity forces induced by the moon and the sun. Although tidal energy has the potential to generate electricity, it technologies might not be without environmental impact, because some of its manufacturing processes, such as the acquisition and transformation of materials, installation, operation, maintenance and dismantling, provoke environmental impacts (Walker & Thies, 2022 and Rashedi et al., 2022). To mitigate these impacts, some studies recommend the implementation of recyclable materials, and others suggest incineration and landfilling (Walker & Thies, 2022).

Despite the progress in the tidal stream technology, it is at an early stage of development yet. So far, scarce research has been conducted on the environmental impact of materials used in turbine blades, including those that can be recycled and those that cannot and limited studies are available related to other industrial sectors (Walker & Thies, 2022).

This paper reviews the potentials of the most used materials in turbine construction by determining their contribution in eighteen (18) impact categories using life cycle analysis (LCA) assessment. The scope of the method includes five stages of the process: manufacture of materials, installation, operation, maintenance, and dismantling. Then, the LCA results of tidal energy are compared with the results other technologies in the offshore industry.

II. METHODOLOGY

A. SYSTEMATIC LITERATURE REVIEW

To comprehensively analyze the environmental impacts stemming from tidal energy technology, we conducted a systematic literature review that primarily focused on Life Cycle Analysis (LCA) applications in the tidal energy sector. This methodical review involved a thorough analysis of the environmental effects associated with the technology. The review process followed a structured approach, integrating three distinct stages (Rueda-Bayona et al., 2022).

B. DATABASE SELECTION

The secondary data for this study was retrieved from the most recognized scientific repositories, such as Scopus, Web of Science (WoS), ScienceDirect, Springer and ASCE. We utilized a range of predefined keywords to refine and narrow down the search to the precise topic of interest.

C. SELECTION OF RELATED ARTICLES

The articles used in this work were carefully selected by directly checking whether keywords were included in the title and abstract of each article. In addition, it was ensured that each selected article furnished detailed information regarding the materials employed in tidal energy and their subsequent evaluation using the LCA methodology.

Each selected article underwent a thorough examination to identify the materials extensively utilized in tidal technology. We meticulously assessed the impact generated by each material at different stages of the tidal energy process. Consequently, the materials used in the industry were identified and categorized according to the relevant engineering activities, encompassing manufacturing, construction, operation, maintenance, and decommissioning. Subsequently, we conducted a comprehensive analysis of the impacts associated with each material using the LCA method.

The following sections of this document present a detailed discussion of the materials used in tidal energy technology and their associated environmental impacts through various stages. The life cycle assessment (LCA) of tidal energy is also compared with that of other technologies commonly used in the offshore industry. This comprehensive approach allows us to take an in-depth look at how tidal energy technology impacts the environment and its sustainability within the broader energy landscape.

III. RESULTS

A. MATERIALS MOST USED IN TIDAL ENERGY

Among the materials that have the greatest impact on the eighteen categories evaluated in LCA, steel was the most contributor to global warming, ozone formation, human health, ozone formation, terrestrial ecosystem, human carcinogenic toxicity and mineral resource scarcity. Copper is responsible for more than half of the impacts to freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, aquatic ecotoxicity and non-carcinogenic human toxicity. Glass Fiber Reinforced Polymer (GFRP) mainly impacts stratospheric ozone depletion, marine eutrophication, fossil resource scarcity and the impact of water consumption (See Figure 1).

According to Rashedi et al. (2022), Steel is the main material constituting more than 70% of the total turbine mass, therefore, its contribution to impacts such as global warming and carcinogenic human toxicity is to not clear, due to the large amount of Steel required today (Paredes et al., 2019).

Copper is used in smaller proportions compared to other materials such as steel (Rashedi et al., 2022), however, it is the most negative contributor in acidification, eutrophication, and toxicity. Copper manufacturing emits a variety of materials such as phosphate that can generate eutrophication due to algal blooms caused by dumping, and tailings that generate toxicity effects due to poor management (Rashedi et al., 2022).

The production of glass fiber reinforced plastic (GFRP) composite materials has negative environmental impacts, such as fossil fuel depletion and air pollution. Carbon fiber is considered a lightweight alternative for manufacturing turbine blades, which could reduce the environmental impact. However, carbon fiber production generates more greenhouse gas emissions than fiberglass (Rashedi et al., 2022).

Although steel and carbon fiber composites have higher environmental impacts than fiberglass composites, recyclable and bio-based products offer lower environmental impacts. In addition, bio-based fibers represent an alternative option to replace carbon or glass fibers. These natural fibers have the lowest greenhouse gas emissions compared to the other options considered, and have relatively low environmental impacts on all evaluated measures (Walker & Thies, 2022).

Turbine blades are composed mainly of GFRP and some cases with GFRC, which are the least recycled parts, mostly disposed in landfills or incinerated. However, the study evaluated by Walker & Thies (2022), stated that recycling metallic and bio-based materials generate less impact compared to incineration or landfill.

In Figures 2 and 3, the final impacts were determined for the 18 categories mentioned. This was achieved with the help of specialized literature and a study using the ReCiPe method, which provides representative characterization factors on a global scale. These factors make it possible to model the impact pathways from the midpoint to the endpoint. In the figures, three categories characterizing this final impact can be observed.

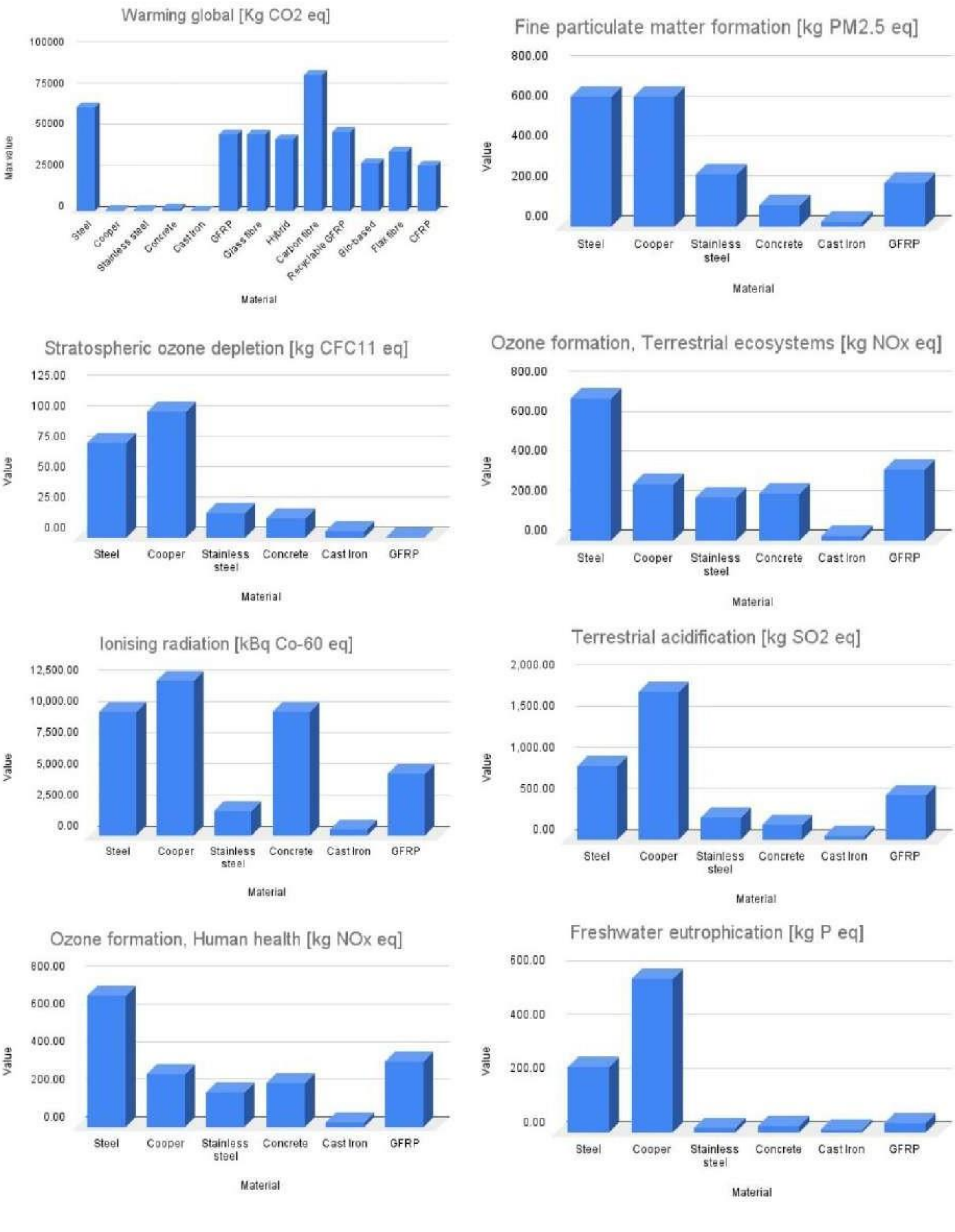

Fig. 1a. *Materials implemented in tidal energy turbines evaluated in 18 LCA categories.*

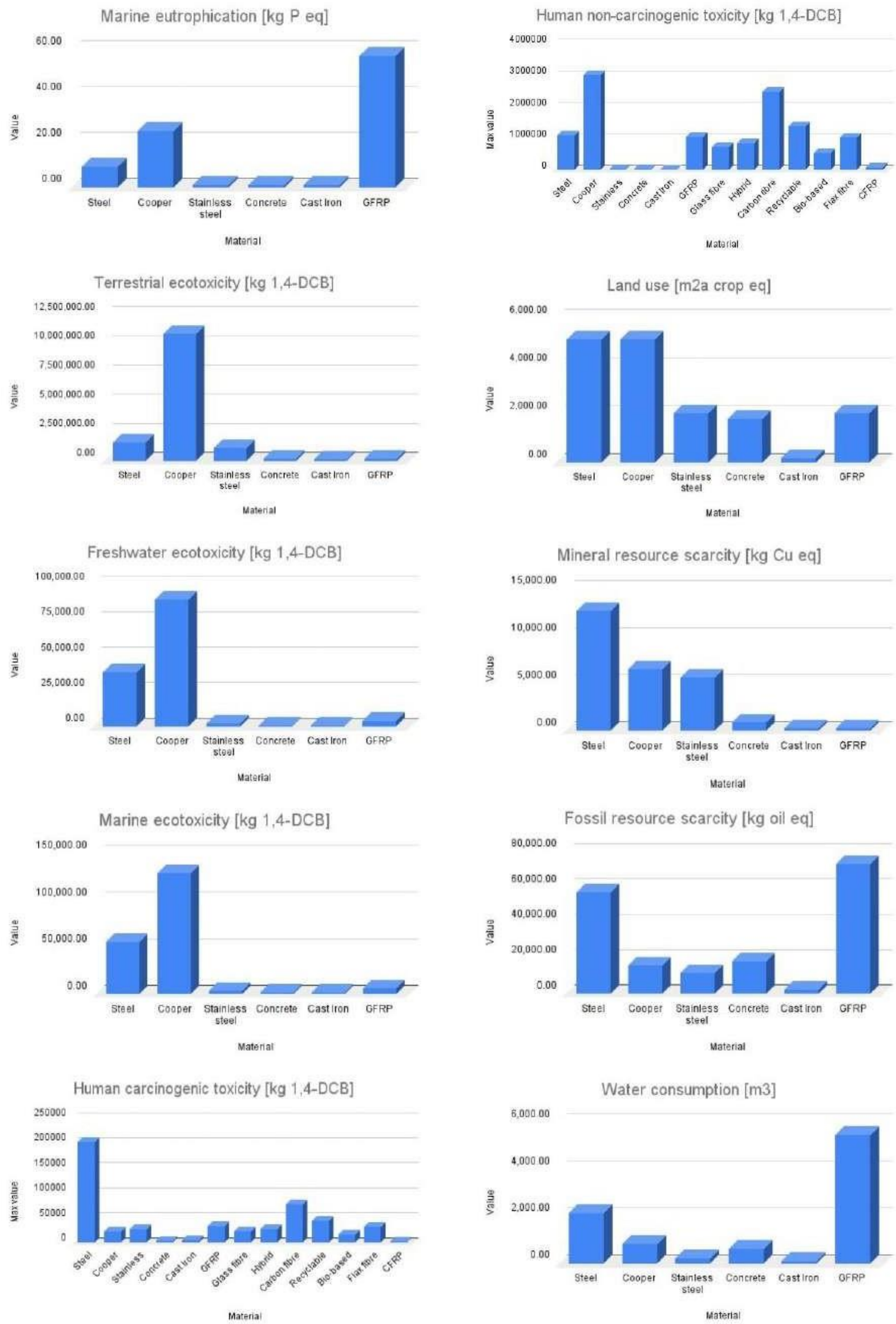

Fig. 1b. *Materials implemented in tidal energy turbines evaluated in 18 LCA categories.*

Fig. 2. *Relationship between major metallic and non-metallic materials and the environmental impacts identified by the 18 midpoint and endpoint impact categories.*

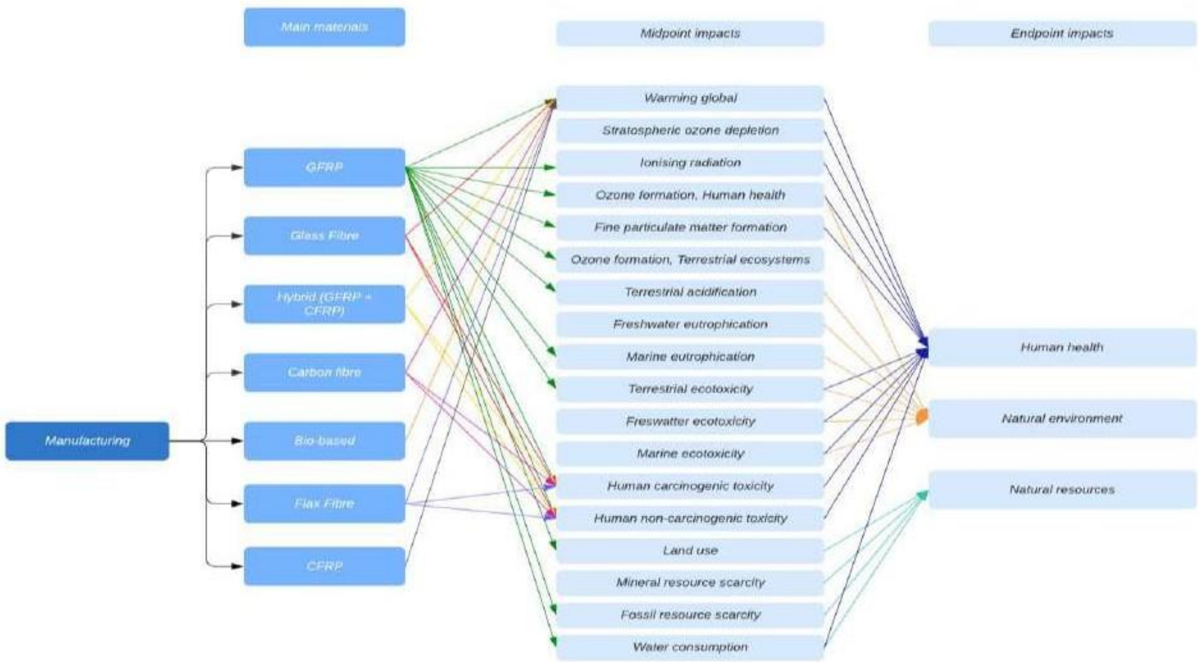

Fig. 3. *Relationship between major biological and composite materials and environmental impacts identified by the 18 midpoint and endpoint impact categories.*

B. MATERIALS USED PER ITEM

A summary of the articles used in this work is presented in Table 2. Each article details the materials that were mentioned and were relevant to this study.

Table 1. Summary of the technologies considered in this article.

Material	Number of referencing articles	Reference
Steel	**7**	**[1] [2] [3] [4] [5] [6] [7] [8]**
Copper	**4**	**[3] [4] [5] [7] [8]**
Stainless steel	**3**	**[2] [3] [4]**
Concrete	**6**	**[1] [2] [3] [4] [5] [6] [7]**
Cast Iron	**5**	**[1] [2] [3] [4] [5] [8]**
GFRP	**3**	**[1] [4] [5] [6]**
Glass Fiber	**1**	**[6]**
Hybrid	**1**	**[6]**
Carbon fiber	**1**	**[6]**
Bio-based	**1**	**[6]**
Flax fiber	**1**	**[6]**
CFRP	**1**	**[6]**

C. IMPACTS GENERATED BY INSTALLATION, OPERATION, MAINTENANCE AND DECOMMISSIONING ACTIVITIES.

According to the study by Paredes, Padilla-Rivera and Güereca (2019), it has been observed that, as in other impact categories, the remaining stages of the life cycle of ocean energy technologies, such as assembly, installation, operation and disassembly, have an almost negligible effect on global warming and in most categories evaluated, therefore, there is scarce information on the LCA of the aforementioned stages.

D. COMPARISON BETWEEN OFFSHORE TECHNOLOGIES

According to research by Yuan et al. (2023), copper is identified as the most important contributor to eutrophication and the performance of the technology described in their study, which focuses on floating wind power. The findings indicate that floating wind power generates the highest emission, especially in Asia compared to the United States. The latter country represents one of the main markets, which highlights the relevance of these results in a global context.

The article proposed by Yang et al. (2018), Burgess and Biswas (2021) and Brussa et al. (2023), also present Steel as the most contributing material in the generation of greenhouse gasses (GHG) and the highest energy consumption among the other materials. In the same way, it is presented as a material that addresses and contributes in all the categories presented by the Burgess and Biswas (2021) article.

On the one hand, in some phases of other technologies, the impacts of materials generated significant results in the eighteen categories evaluated. The graph in Figure 4 illustrates the impact of operation and maintenance (O&M) on abiotic resources. However, according to the literature, both operation and maintenance (O&M) and decommissioning stages (see Figure 5) can mainly contribute to the potential for ozone depletion (Yuan et al., 2023).

It should be noted that there is limited information about studies covering the life cycle analysis of the decommissioning stage.

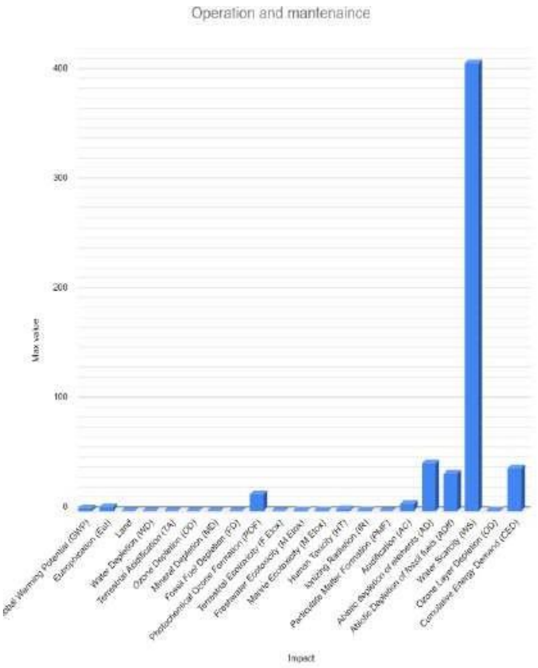

Fig. 4. Impact produced by the operation and maintenance stage in the LCA of different marine technologies (i.e. naval technology, floating offshore wind, wave energy conversion).

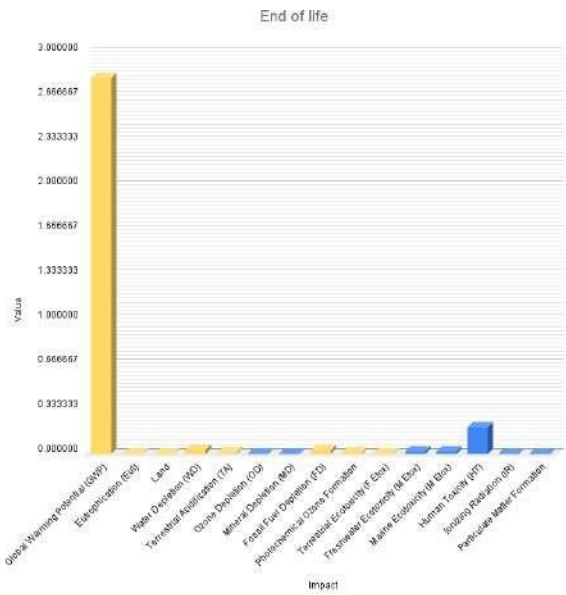

Fig. 5. Impact of endpoint stages on the LCA of wave energy conversion technology.

Note: The yellow bars indicate that the technologies evaluated in the Burgess and Biswas (2021) article are contributing to the reduction of the categories, while the blue bars indicate that the categories are contributing to the environmental impact.

IV. CONCLUSION

Partial results to date indicate that the materials manufacturing stage is the main critical point in the life cycle for all marine technologies. The most representative materials impacting different categories are Steel, Copper and GFRP.

It is important to note that although copper constitutes a smaller proportion of the total mass of turbines compared to steel, it is the main metal that can have negative impacts on freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, aquatic ecotoxicity and non-carcinogenic human toxicity.

On the other hand, biological materials are still under study, however, so far they have proven to be a viable alternative by producing lower emissions in some of the categories. Studies are also needed on the contribution of recycling materials, such as metals, which would allow for a large reduction in the production phase of these materials.

As for cast iron as a material, its contribution in all impact categories is less than 5%, so it is not attributed a significant participation in these categories.

The present study is still in the process of researching some of the items presented in the results.

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