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Impacts generated by the materials used in offshore wind technology on Human Health, Natural Environment and Resources

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ABSTRACT

Offshore wind energy (OWE) shows rapid growth in reducing CO_2 emissions. Although OWE is considered renewable several used materials in their activities, such as manufacturing, installation, maintenance, and dismantling of the wind farms, generate negative impacts on human health, the natural environment, and natural resources. To provide a better insight into these impacts on the OWE industry, this research generated the first detailed relationship between the main activities of the OWE industry, the turbine components, the main used materials, and the environmental impacts according to LCA's impact categories. Also, this study synthesized information about the impacts and energy consumption reported for the OWE industry, but also published for other industries about materials used in OWE. Their impacts have not been properly considered in the previous research. The results revealed that there is not enough information about LCA's assessment of the environmental effects generated in manufacturing some turbine components and during operation-maintenance activities. The results evidence that Steel is one of the main materials with the highest negative impacts and energy consumption, followed by Concrete, and petroleum-based materials. The findings of this research highlight the need for establishing strategies to replace the most contaminant materials with less harmful ones.

CRediT author statement

Juan Gabriel Rueda-Bayona, Ph. D: Writing - Original Draft, Conceptualization, Methodology, Software, Validation, Formal analysis, Juan José Cabello Eras, Ph. D: Writing - Original Draft. Tatiana R Chaparro-Chaparro, PhD: Writing - Original Draft.

1. Introduction

Renewable energy sources available in marine regions are one of the most promising opportunities for the current transition towards decarbonization and sustainability of the energy sector, great efforts are being made to develop technologies able to take advantage efficiently of their different forms. Technologies for the use of energy from waves and ocean currents are still in the initial phases of their development [1], although they have high potential, also the adaptation of technologies with great maturity in onshore applications to harness solar energy in large marine areas faces serious challenges and are at an early stage of their development [2]. The use of wind energy in the sea is the most mature and widespread to date [3] and in the future large marine energy clusters are envisioned applying the integrated use of all these sources in energy clusters [4] that would often be associated with the industrial production of green hydrogen for energy uses [5]. Although the marine energies are frequently considered clean and free of greenhouse emissions, they are not free from causing significant potential environmental impacts during their life cycle [6].

Wind technology is the second largest electricity generation source after hydro energy. Its total generation installed capacity in 2016 was almost 487 GW and is forecast to reach 800 GW in 2021, sharing a 64% growth in the following years [7]. All systems and products, although thought to be sustainable, provoke environmental impacts that must be assessed with holistic methodologies such as the Life Cycle Assessment (LCA). The LCA calculates the total environmental impacts generated by a system, process, or activity over an ecosystem or persons throughout its lifespan. The Intergovernmental Panel on Climate Change (IPCC) recommends to government stakeholders follow the LCA methodology to estimate the potential impacts derived from the utilization of new technologies [8].

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Wind energy technologies may be classified into two groups, onshore which are the most spread worldwide, and offshore wind energy (OWE). The OWE has several advantages: more available territory (sea), more persistent and stronger wind availability, less impact on the landscape, lower sound impacts, and avoiding conflict with ancestral inhabitants of the areas where wind farms are planned to be installed [9]. According to the fast growth of new OWE projects, in the forthcoming years, the OWE will be the world's most significant energy source [10].

Although OWE usually is considered a sustainable technology because it is green energy almost without greenhouse gases, it really generates environmental impacts, mainly during the extraction and transformation of raw materials for manufacturing and repairing electrical grids and wind turbines (40%–80%) [11,12], consequently efficient recycling and ending the life management of the OWE are one the main challenge of OWE industry for the transition to a circular economy [13,14]. Several studies point out that to mitigate the OWE environmental impact wind turbine dismantling is the most important stage, so usually in the building permits for OWE farms requirements for dismantling are mandatories, e. g, Scotland and Denmark ask for credits with sufficient financial funds for the project dismantling [15].

One of the current main concerns of the OWE industry is improving its perception as clean and sustainable, because renewable energies may not be "fully green" without cleaner production practices. The LCA may identify and quantify the impacts the offshore wind turbines (OWT) on Human Health, the Environment, and Resources. Many of the studies that applied LCA concluded that recycling at the end of life of wind turbines might reduce the pollution and greenhouse gas emissions between 80% and 100% [15–18]. [15], 25 years of wind turbine operation generates higher incomings, but comprises more maintenance activities, which is equivalent to the increment of structural failure risks that could affect human and environmental health.

Several countries have established guidelines and administrative directions for sustainable end-of-life of wind turbines. The Netherlands published an OWE law that demands the licensed project owner to dismantle and remove all structures and elements of the project within two years after the completion of the operation and finalization of energy production. Scotland law indicates to project owners to reserve economic bonus guarantees the project dismantling, and Denmark requires that this bonus be paid 12 years after the start-functioning of the wind energy project [15]. Additionally, recycling wind turbine blades has gained relevance in recent years because the first OWE projects are in the final stage of operation and a high quantity of residuals will be generated until 2050 [19].

There are two types of wind turbines according to their end of life, reusable and non-reusable. The reusables have a resale opportunity depending on the reconditioning potential. However, the recycling of these turbines have some barriers such as the elevated cost of dismantling compared to the profits of recycling Iron, Glass, and Carbon fibers [20]. The literature review revealed several methods of reusing and recycling blades of OWT, depending on the nature of its main materials. The Holcim company developed a recycling method in Europe, which recovers the potential energy of polymers through a high-temperature incineration process, using the oven of the Concrete plants. Also, the company repowered blades before a visual and eco-graphic inspection, [16]. In 2010 the Global Fiberglass Solutions company used recycled winds turbines blades for manufacturing rail tie-downs, subway tie-downs, garden rails, jersey barriers, bollards, and utility poles [17].

[21] assessed the recycling potential of fiberglass, one of the most used materials in wind turbine manufacturing. The study reported that residuals of the fiberglass combined with aluminum dust might be utilized for lightened geo-polymeric mortars (foams) production, where the fiberglass enhanced the mechanical performance of the foams without affecting their isolation properties. Also, the addition of fiberglass could result in 23–30% extra flexural and compression resistance to the mortars. Other benefits of using recycled fiberglass mixed with fly ash were shown by Ref. [22], which evidenced the carbon footprint reduction during concrete production [23]. highlights the need to improving the recycling of glass and carbon fiber because some mechanical properties of these materials are worsened. In this sense, some recycling techniques reported by Ref. [24]proposed the use of D-Limonene, a natural substance extracted from citrus peels. The research pointed out that using the D-Limonene kept the traction resistance of the recycled fiberglass up to 85% compared to the virgin fiberglass. Rubber is a recyclable material with several applications for the building industry, such as concrete with enhanced mechanical properties and pavements [25]. performed an LCA of rubber residuals derived from pneumatic tires for manufacturing green roofs for edifices. The study highlighted the advantages of using rubber because of its lower environmental impacts compared to conventional flat roofs.

According to Ref. [26], recycling permanent magnets of turbines would reduce over 80% of the total impacts derived from the direct-drive permanent magnet synchronous generator (DDPMSG) turbines. However, they warned of the challenge of recycling because the magnets reduce their potential after 20 years of service. Also, it is mentioned that producing electronics and permanent magnets with rare earth extracted in the United States or Australia instead of China would reduce the environmental impacts between 20 and 33% because of the more effective environmental laws and control entities of the United States and Australia, and the informal-illegal mining activities carried out in China. Also, the rare earth extracted in Australia had less Strontium (0.89% Sr) compared to the extracted in the United States (4.9% Sr), which becomes more attractive the use of the Rare Australian earth more because of its lower impacts on LCA categories such as Resources depletion (Minerals, Fossil fuels, and renewable energies).

The OWT is growing fast worldwide, and although environmental impact analyses are carried out and have to be approved by the authorities, the studies are mainly focused on assessing environmental impact and their mitigations in the wind farm areas will be located [27,28]. However, because of the great expansion that is predicted and its significance for the energy transition, a better understanding of its environmental impact throughout its life cycle is necessary to make the best decisions in its development. Although the LCA has been applied to OWE projects in the specialized literature, there are not numerous reports on this subject, so they are still incipient and do not give definitive conclusions.

Considering that sustainable OWE projects must follow the fundamentals of circular economy, identifying the main materials used and their impacts on human health, the natural environment, and resources is necessary. At the moment, several LCAs have reported the impacts of various materials and activities of the OWE industry [29], but gaps and lack of information about some materials have been identified. This study gathers, analyses and organizes qualitative-quantitative details on the environmental impacts assessed of the materials used in OWE in terms of LCA and energy consumption, to estimate the impact of several materials not included in the reported LCA assessment for OWE. The reports of other industries have been used, to establish a clear relation among the most used materials with the main activities of the OWT (i.e, manufacturing, installation, maintenance, and dismantling), and how these activities impacted the Mid- and Endpoint categories of LCAs.

2. Methods

The rapid rise of data generation (e.g databases, research articles) worldwide exceeds the capacity of humans to read and capture key information. Hence, emerging methods and approaches (e.g Big data analytics, Data Mining) becomes valuable tool for extracting relevant information hidden behind the enormous amount of data [30]. A systematic literature review as part of Data Mining differs from the traditional literature review because the derived results not only report state of the art [31], but generate new scientific information when data cross, combined and merge producing a new construct.

In this research, a systematic literature review focused on the applications of LCA in OWE and other industries is carried out to study the materials used in OWE environmental impacts. The literature review was carried out considering a searching systematic cycle integrated by four stages [32].

1 Input

This is the first stage of the cycle where were performed three main activities:

1.1 Problem

The research problem for this study is defined by three main questions. What are all the materials used in the OWE industry? which of the materials used in OWE industry have not been assessed by LCA? What are the environmental impacts generating these materials in other construction and maintenance sectors?

1.2 Database selection

The most robust scientific repositories such as Scopus, Web of Science (WoS), Science Direct, Springer and ASCE, and the Scielo Latin American database to verify advances in the development of OWE in America were mined.

1.3 Searching strategy

In this stage the keywords for searching are defined, then, for the first Literature review cycle the words were the offshore wind and OWE, life cycle assessment, and LCA with the following searching combinations: "offshore" AND "LCA" OR "life cycle assessment" AND "offshore wind"; because the high number of results, the search only considered research articles.

2 Processing

For this phase, searching strategy was applied to the databases, the process is described in Fig. 1. Initially, a full search was carried out (see raw 1 in Fig. 1), and found 606 papers related to the keywords. Second, the titles of all the papers were analyzed and seventy documents more closely related to OWE materials and LCA assessment of its environmental impact were selected (see raw 2 in Fig. 1). Third, the repeated articles in the databases were eliminated, leaving forty-one documents (see raw 3) whose summaries were carefully reviewed. Finally leaving 33 articles for their complete study, of which eighteen provided the required information about all the materials used in the OWE industry and the environmental impact of which had been evaluated by LCA.

5 Output

This is the final stage of the cycle which gathers 18 selected documents after the screening. The revised articles utilized several recognized and trusted LCA databases, primary data, and secondary data from the literature, where 16 of the 18 analyzed articles used Ecoinvent database (https://ecoinvent.org/). Two articles produced their own process-based LCA data following the ISO 14044 standard, and one used the Ecoinvent + U.S.Life Cycle Inventory (LCI) data sets. The most applied LCA software was the SimaPro (https://simapro.com) 7, 7.1, 7.2.4, 7.32, versions and Gabi 4 (www.thinkstep-anz.com). These selected articles were carefully read (Analysis of final selected documents) to establish the milestone of the research problem (Generation of the big picture), consequently identifying all materials used in the OWE industry and the lack of information about their environmental impact assed by LCA whose reduction is the main contribution of this study (Identification of literature gaps). As a result, several materials used in OWT facilities were identified and classified according to the main sections of the turbine and the associated engineering activities (construction, transportation, operation, and maintenance). The environmental impacts of these materials were analyzed according to the Midpoint and Endpoint categories of the LCA.

New search: As the conditions of the OWE industry are very different from the other industries taken as reference the results compiled for these materials could have a higher uncertainty than materials dealing in OWE specialized literature.

3. Results

In the eighteen documents finally studied, the impact according to LCA of the majority of materials used in OWE industry is reported. A frequency analysis to establish how many times each material is mentioned in each paper is described in appendix 1. The analysis found

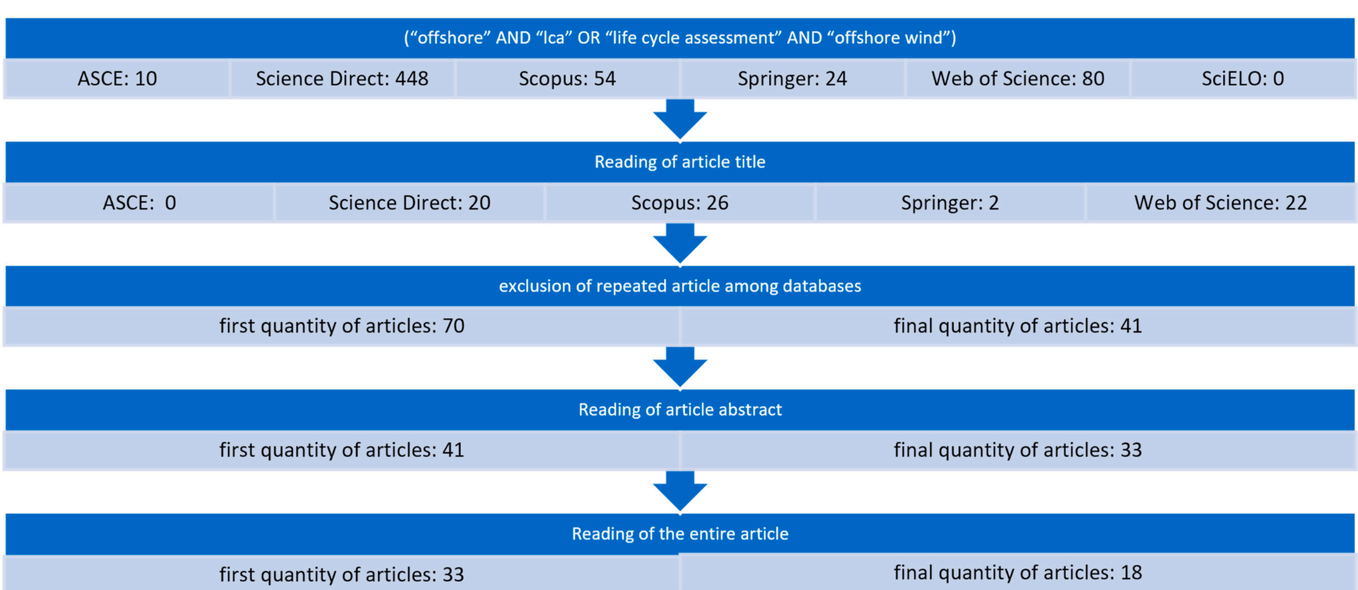

Fig. 1. Screening for the first searching cycle.

that Steel and Fiberglass are the most studied materials, utilized in foundations, hub and blades. Metallic materials (Aluminium, Copper, Iron) were mainly reported in the turbine's tower, junctions, and inner parts. Plastic and hydrocarbon derivatives were mentioned in auxiliary parts of the turbine and lubricants. The less studied materials were Zinc, Rare earth and Carbon fiber, where Rare earth is used for manufacturing generators with permanent magnets and carbon fiber is commonly required for blades.

Since the majority of the material used in OWE is also used in onshore win projects several papers about LCA for its are included in the study. Appendices 2 and 3 show the main findings of LCA studies applied to offshore-onshore wind farms, considering the technical characteristics as useful life, capacity, and foundation type among others. Appendix 2-3 pointed out that despite OWT having more factor energy capacity, the impacts according to LCA categories are higher, the same the energy consumption because the increment of distance to the coast and water depth rise the required materials for installation, operation, and maintenance of OWT. The results have been organized in materials used by OWE turbine sections and summarized in Figs. 2-5, the result of the material used for maintenance are summarized in Fig. 6.

3.1. *The environmental impacts of the most used materials according to main wind turbine sections*

The OWT are commonly divided into 3 sections from upper elevation to the seafloor (bottom): 1-Top which is integrated by Nacelle, Hub, Blades, Pitch system, Main Shaft, Gearbox, Generator, Control, Sensors, Converter, Transformer, Yaw system, Rotor, Canopy, 2- tower and 3-foundation [33,34]. In addition, the operation and maintenance activities of OWT require materials and transportation (Vessels, Helicopter) which use fossil fuels, also solvents, various types of paints, abrasive materials, etc. In this research, the main materials used in OWE industry for parts manufacturing and assembling, maintenance, and transportation were analyzed.

Since the OWTs' sections are very different in their configuration, materials, manufacturing, functions, location and assembling, the results are discussed in two parts, the top section independently and tower and foundation together. The parts that make up each section, the main materials which are used to manufacture each part, and the impact of each material on the middle point and end point of LCA are discussed in the next sections.

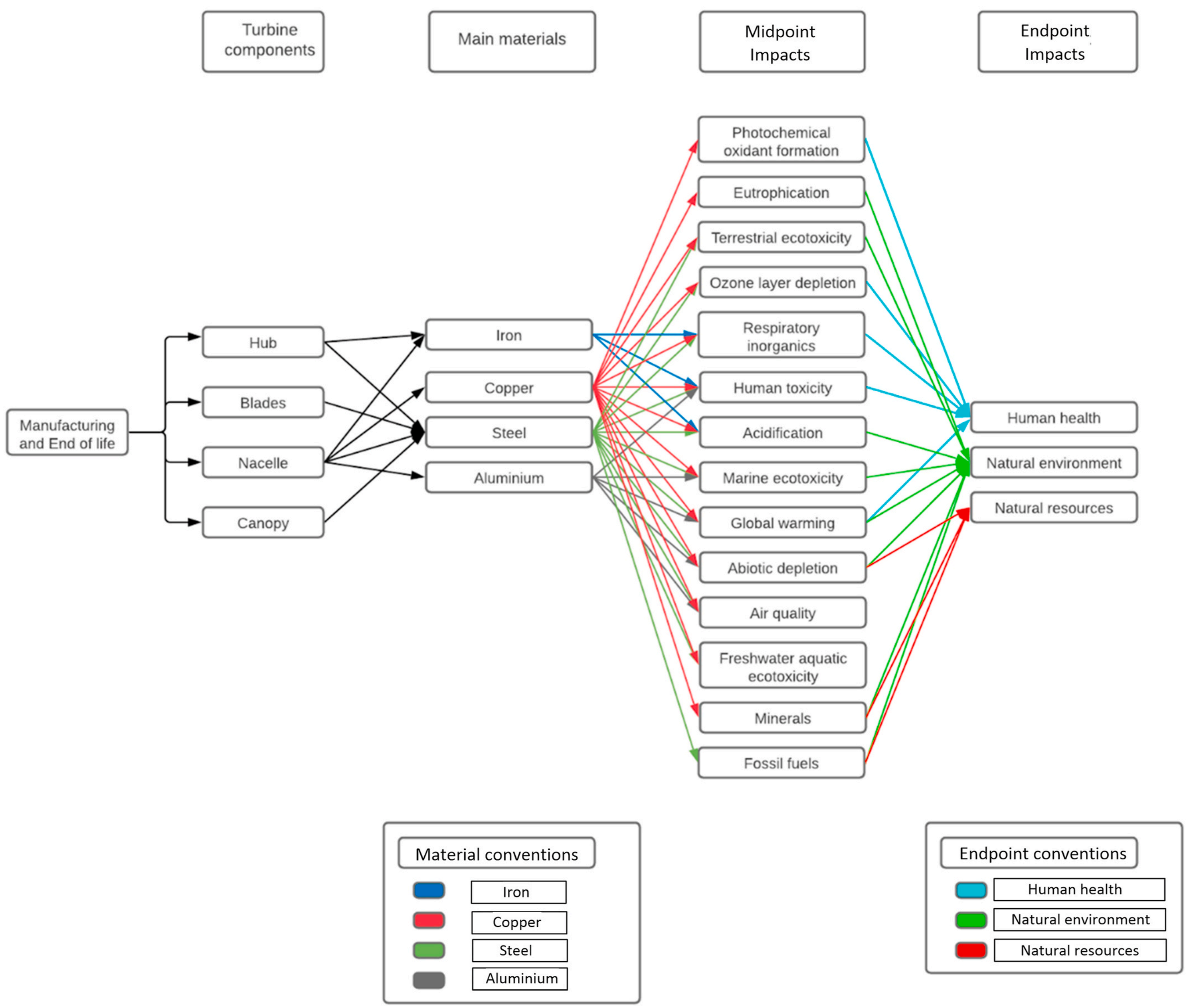

Fig. 2. Relation among main metallics materials of Top section and environmental impacts identified by LCA Mid-End points.

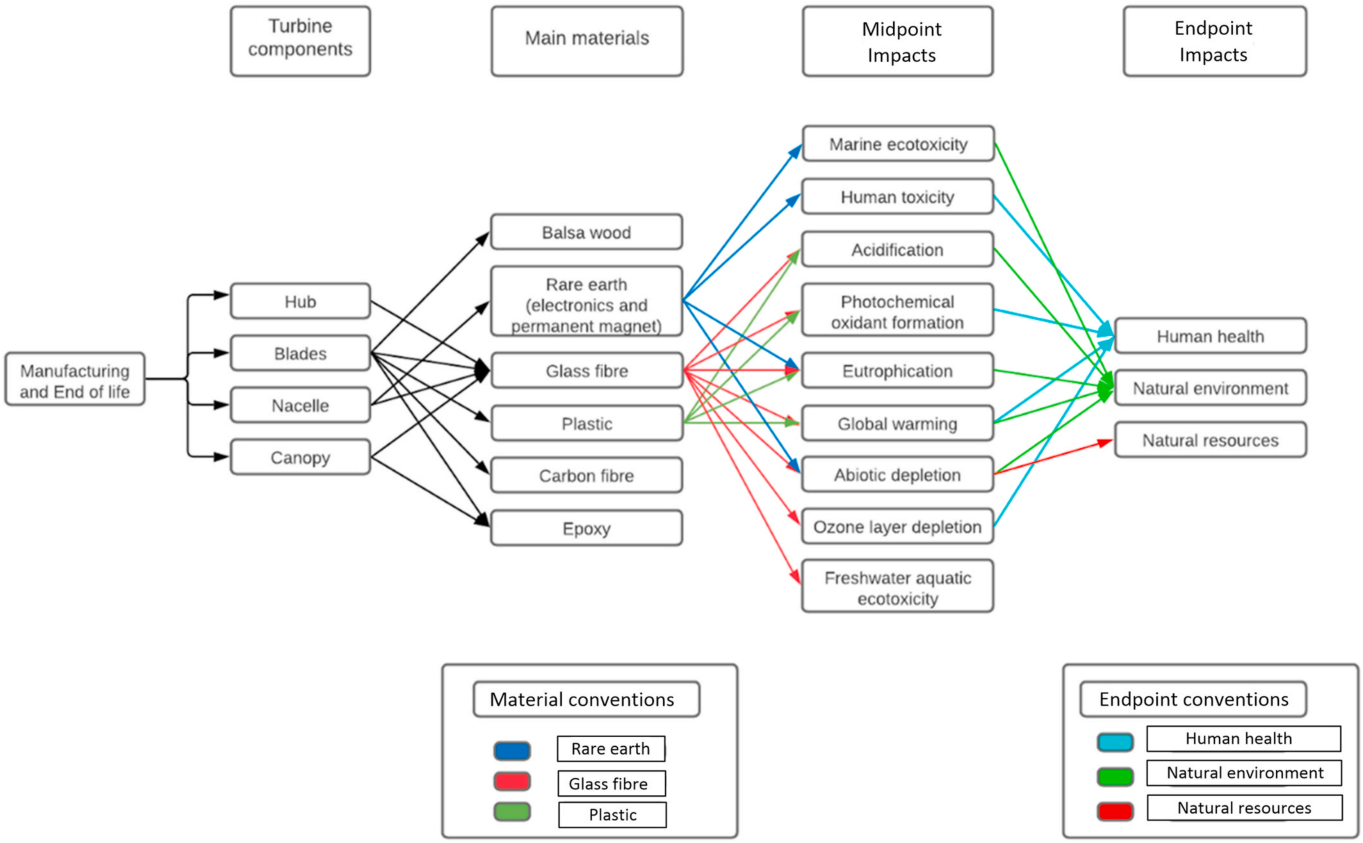

Fig. 3. Relation among main non-metallics materials of Top section and environmental impacts identified by LCA Mid-End points.

3.1.1. *Top section*

The parts of the top section: Blades, Hub, Canopy, and Nacelle require various metallic materials (see Fig. 2), which produce impacts in fourteen categories at the middle point. Then, the hazards to Human Health (Endpoint) come from toxicity, ozone layer depletion, photochemical oxidant formation, global warming, and respiratory inorganics, where the metallic materials have a strong contribution to these hazards because of the toxic residuals generated during their extraction and transformation.

Also in the parts of the Top section, several nonmetallic materials are used as can be seen in Fig. 3 which impact only 9 categories in the middle point, and their impact on human health come from human toxicity, photochemical oxidant formation, global warming, and ozone layer depletion; the impact on the natural environment from marine ecotoxicity, acidification, eutrophication, and abiotic depletion; and impact on natural resources come from abiotic depletion.

OWT demand a more complex fabrication compared to onshore turbines, because the OWT must be lighter and resistant to the sea environment [16]. As a result, the fabrication of offshore turbine parts generates more harmful emissions.

The literature review evidenced that the impacts to Natural Environment (Endpoint) were generated by acidification, Global Warming, abiotic depletion, marine ecotoxicity, fossil fuels, terrestrial ecotoxicity, eutrophication, and minerals (Figs. 2 and 3). These midpoints impacts were generated by the mining of metallics and rare earth, and due to the fabrication of wind turbine parts with fiberglass, and plastics. The natural resources (Endpoint) were affected by midpoints associated with abiotic depletion of the indirectly used materials (sand, clay, gypsum, limestone, fossil fuels and minerals), what evidence that the availability and quality of important natural sources of fresh water and atmosphere were impacted because of the associated mining and industrial activities. There were not found studies that linked Epoxy (utilized for blade covering), Balsa wood, and Carbon fiber to LCA Mid-End points, then, this research revised other studies conducted in different industrial sectors for finding potential impacts that can be linked to the OWE industry.

3.1.2. *Tower and foundation section*

The OWT tower is manufactured using laminated composites built with Carbon and fiberglass covered by epoxy resins. The review revealed that several towers were manufactured with Copper reinforced with Steel parts. Some towers were manufactured with Low alloy Steel because of the more weldability and formability, and in a fewer quantity, others towers were built in Concrete. The monopile, tripod, and jacket foundations were mainly manufactured with Steel, and Concrete was utilized for building Gravity based foundations. Floating foundations such as TLP or Ballast were built with Aluminium, Low alloy, Steel, and Zinc covering, and their mooring lines and accessories were manufactured with Aluminium, plastic, and Copper; Aluminium was the most frequent metallic material used in the tower, cables, busbars, and foundations (see Fig. 4).

The literature review noticed that metallic materials such as Steel, Copper, Aluminium, Zinc, and Iron (Fig. 4), reported more impacts to Midpoints compared to other materials, where Freshwater aquatic ecotoxicity, Marine ecotoxicity, Acidification, and Eutrophication were environmental hazards generated mainly by industrial wastewater discharges. Minerals and compound materials such as Concrete, fiberglass, and Rare earth impact Midpoints related to the hydrological cycle and air quality (Fig. 5). The impacts of the mentioned above materials reverberate over human health, abiotic depletion, and the environmental sustainability of ecosystems.

3.1.3. *Operation and maintenance activities*

The OWT requires supervising for a proper operation, where the

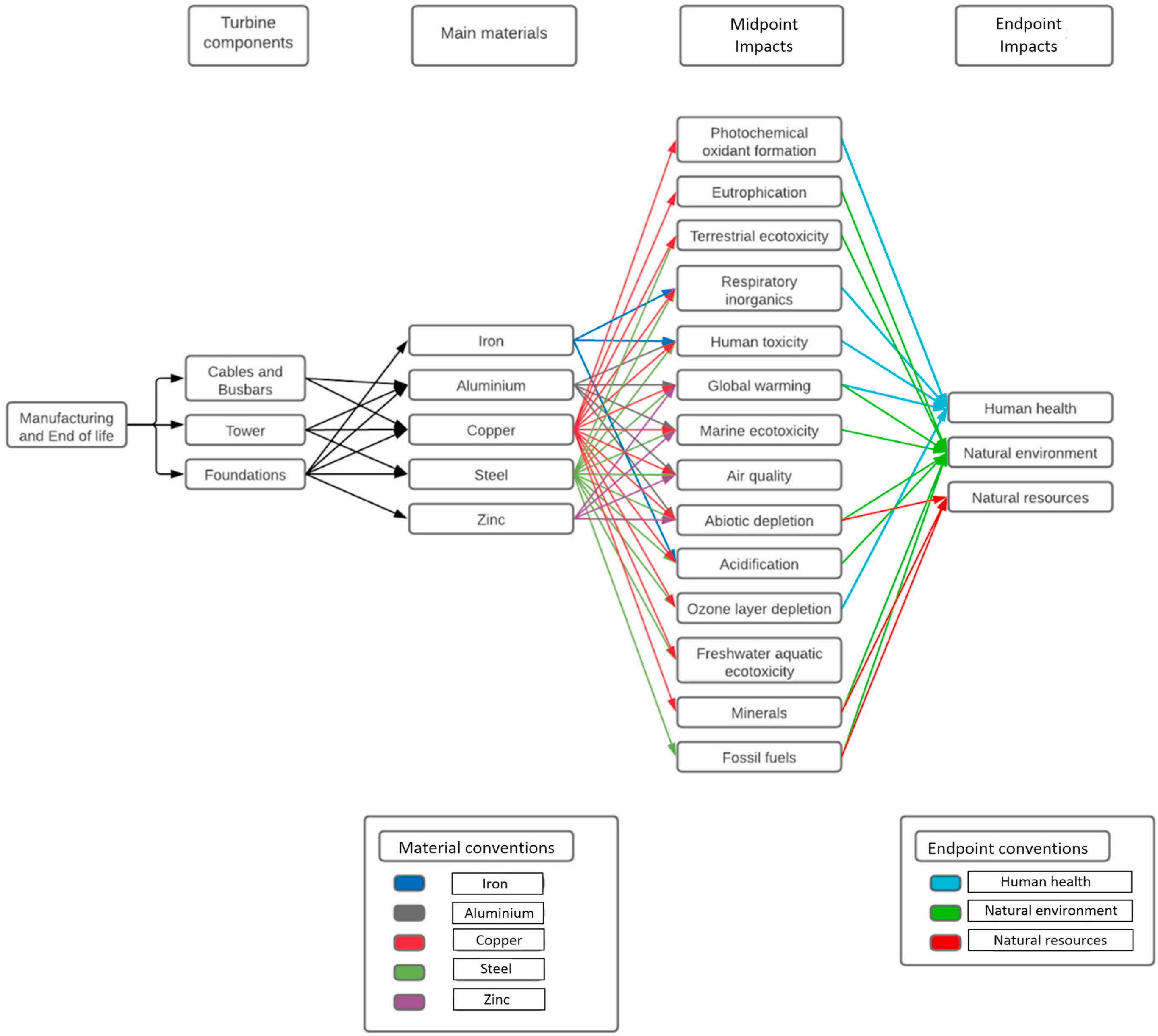

Fig. 4. Main metallics materials of Tower-Foundation section and environmental impacts identified by LCA Mid-End points.

corrosion, humidity, and environmental forces such as waves, currents, wind, earthquakes, ice, and collisions, affect the structural security of the system. Then, several materials are required for the maintenance of the wind turbines, being the lubricants and grease paint (oil derivatives). For the repairing of wind turbines is commonly used the Zinc covering, Copper and Rubber. These oil and mineral derivatives after their utilization become pollutants due to wind and rain transport into the ocean, what is considered punctual pollutant discharges.

4. Discussion

4.1. Main groups of materials according to their impacts

The identified materials used in OWE industry were linked above to the Midpoints and Endpoints related to an LCA (Figs. 2–6), for identifying the impacts and hazards to Human and Environmental Health and Natural resources. Then, this study grouped these materials according to their main composition: metals, concrete, laminar compounds, fiberglass, plastics, epoxy resins, rubber, oil derivatives (lubricants), Rare earth, and oil (fuel). The metallic material group is integrated by Aluminium (Al), Iron (Fe), Zinc (Zn), Copper (Cu), and Steel (Iron–Carbon alloy). These materials are the most contributors to the negative impacts in the Mid-End points of the LCA, because demand a high quantity of abiotic resources (land) and freshwater during the extraction, and generate important industrial wastewater discharges during the fabrication and alloy of wind turbine parts. In this sense [35], pointed out that Al, Fe, Cu, and Steel are the most generators of Human Toxicity.

During the fabrication of these metallic materials, significant CO_2 emissions are generated [36]. [37] pointed out that the residual removal process produces industrial wastewater that contributes to the eutrophication of freshwater bodies. Several studies reported that metals have a recycling potential between 80% and 90% at the end of life, which is an opportunity to reduce the impacts of the LCA [38], (Elginoz et al., 2017), [18,40]. In Steel manufacturing, pig Iron contributes up to 20% of the greenhouse gas emissions (GHG) during the wind turbine life cycle [41]. Also, fossil fuels are required to provide thermal energy to the alloying process which produces toxic inorganic emissions, which

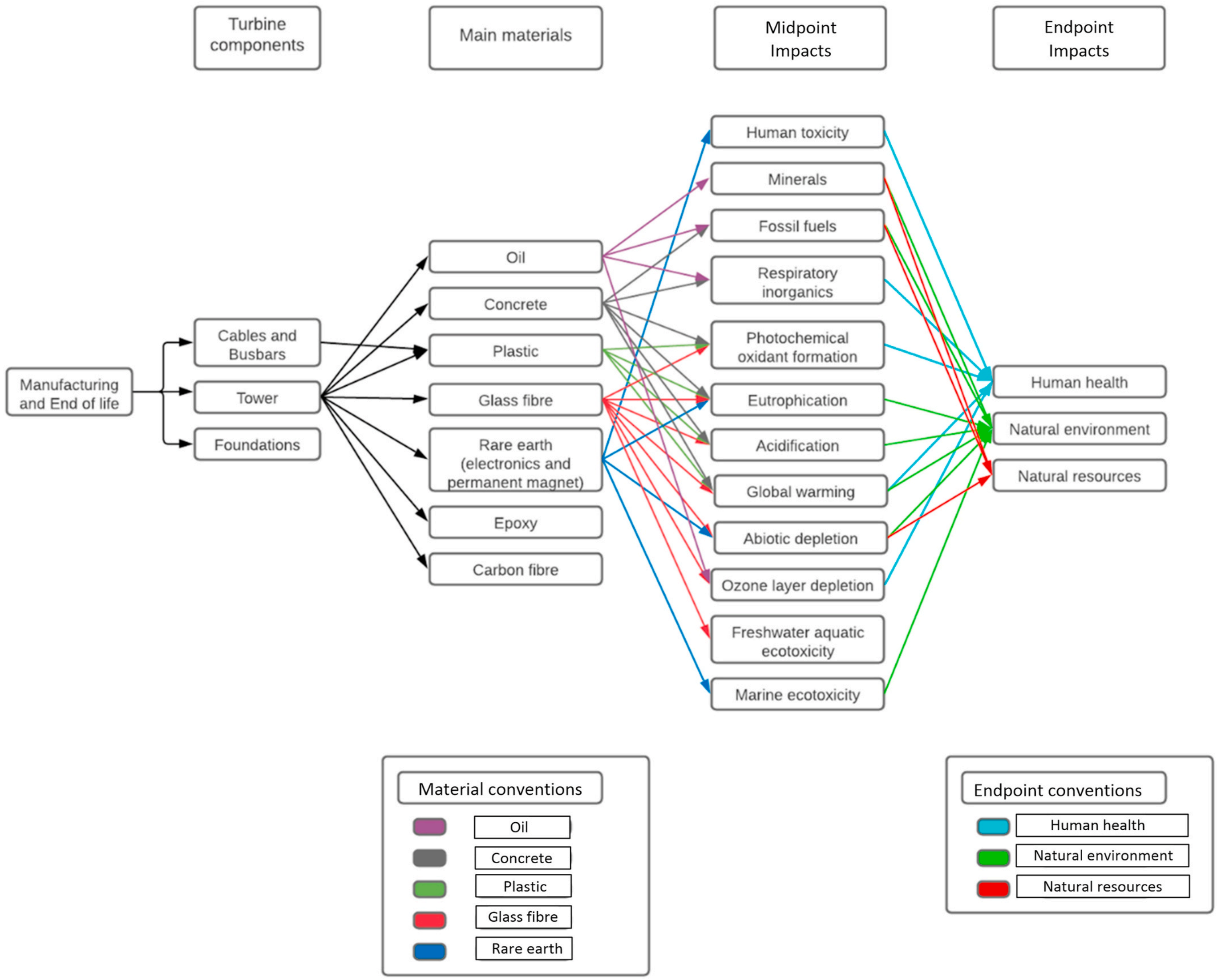

Fig. 5. Non-metallics materials of Tower-Foundation section and environmental impacts identified by LCA Mid-End points.

are dangerous for the ozone layer reduction, deteriorates the air quality, and raise global warming because of the CO_2 emissions from fossil fuels [16,42]. New efforts to modify the Steel production processes and reduce the amount of it (replacing it with new materials) for the OWE industry, would be an important strategy to reduce GHG [43].

In the study of [44], an LCA with a hypothetic Steel recycling (25%, 50%, and 90%) at the end of life is carried out, concluding that the residuals generated during manufacturing provoked aquatic toxicity and abiotic exhausting [18]. mentioned that 90% of Steel recycling would generate a reduction of 20% of the impacts of this material over the LCA Midpoints. Various studies mentioned that Copper is the most contaminant material in the OWE industry because it impacts almost all categories of LCA Midpoints (Figs. 2–6) [45]. compared a horizontal axis wind turbine against a vertical one and found that the vertical axis kind generated fewer impacts in all the LCA categories (Midpoints). That study revealed that the increment of Copper usage for manufacturing the wind turbine, starting from extraction (mining) to deposition and the end of life, generated the most adverse effect on human health [39]. showed that the elimination of Copper using incineration provokes toxic emission that affects freshwater resources [18]. pointed that the toxic emission of Copper affects the Ozone layer which generates an increment of UV-B radiation over the Earth surface.

Aluminium use was identified in the cables, busbars, tower and foundation of the OWT (Fig. 4), but it was not found in specific studies related to the significant negative impacts of this material over the Midpoints of LCA. [46], reported that vertical axis turbines generated lesser impacts in all LCA categories because the main axis was built with Aluminium contrary to the main axis horizontal kind which was built with copper, which suggested that Aluminium generated fewer negative impacts compared to Copper. Iron as metallic material is commonly used in the hub and some kinds of foundations, and there was not sufficient evidence in the reviewed literature that this material contributed to significant negative impacts of the LCA [43]. reported that Iron with Steel contributed to a high value of the impacts of acidification, and [46] identified that melted Iron and Steel are the most contributors to the impacts over inorganic respiratory of the LCA. The floating turbines are commonly covered by Zinc which impacts on Global warming (Midpoint), air quality, marine ecotoxicity, and abiotic depletion. As seen in the manufacturing of towers and foundations (Fig. 5) and the maintenance and repair (Fig. 6), Zinc impacts directly Human Health, Natural Environment, and the Natural resources of the LCA.

Concrete is a compound material integrated by Portland cement, gravels and sands, with some additives that could gather toxic chemical components and resins. This material is used for building Gravity based foundations and some kinds of monopile up to 30 m of depth. The use of Concrete for OWT foundations reduces the environmental loads of the

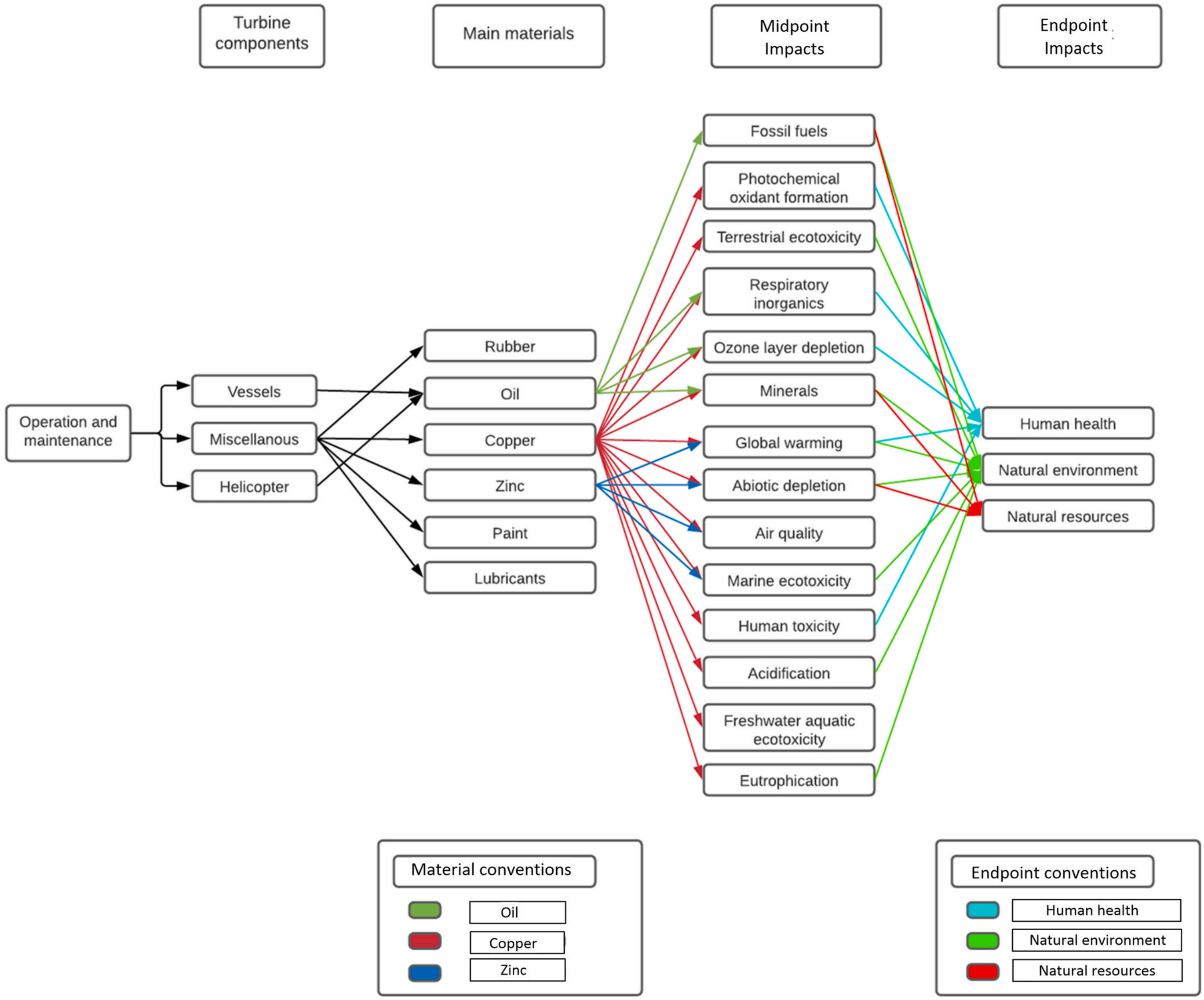

Fig. 6. Relation among operation-maintenance activities and environmental impacts identified by LCA Mid-End points.

OWE projects [47], where the replacement of Steel with Concrete avoids sulfur dioxide emissions (SO_2) and reduces the energy demand because of the alloying process of the Steel [48]. compared monopile and jacket OWTs built in Steel against gravity-based turbines (Concrete foundations), and showed that these Concrete foundations generated less GHG emissions [43]. reported that Concrete foundations impact less the LCA categories because they emitted less GHG emissions compared to metallic foundations (Steel). In this sense [46], reported that a Concrete tower shows fewer environmental hazards despite the impacts generated by Concrete production [40]. informed that the production of Clinker for Concrete and the generation of pig Iron due to Steel contributed to 20% of total GHG, including the CO_2 emissions because of the transportation activities.

Synthetic Laminar compounds such as Glass and carbon fibers reported several impacts in Midpoints, contrary to the natural compound Balsa wood whose impact has not been reported over the LCA (Figs. 3 and 6). The Glass fiber is widely used in different parts of the top section and tower, which is compounded by Silicon dioxide (SiO_2) known as Silica, and impacted Human and Environmental Health because of the air suspended particles and wastewater discharges during its production [39]. performed an LCA to a multipurpose offshore platform with a hybrid wind-wave energy generation, and concluded that Glass fiber and Steel used for the mobile parts were the most contributors to ozone layer depletion and Global warming. In this sense [40], mentioned that the final deposition of Glass fiber is carried out by incineration provoking impacts on the aquatic ecotoxicity of water resources.

The Carbon fibers are used for the blades and tower reinforcement, and this study could not find evidence in the literature review that this material affected the LCA categories (Figs. 3 and 5). In addition, the balsa wood required for covering the external layer of the wind turbine and the core of the blades did not report impacts on Human and Environment Health or the sustainability of Natural resources. Other materials such as epoxy resins and rubber belong to the plastics wherein their end of life are incinerated, then, reuse of these plastic materials could reduce up to 80% of the negative impacts because of the non-consumption of fossil fuels which generates toxic emissions [16]. The epoxy resins are used for the blade manufacturing mainly in the exterior layer, wrap, and covering of the tower, and this material is linked to the Midpoints impacts such as Photochemical oxidant formation, Global warming, and Eutrophication which affects Human health and Natural Environment Endpoints [49]. reported that epoxy resins are 48 times more impact per Kg compared to Concrete, which generates enormous GHG emissions to the environment. Finally, this study found that rubber material did not show links to the Midpoints of LCA which suggests the need of researching this plastic material for an accurate assessment of the LCA's.

The oil derivatives used in the operation and maintenance activities of the OWT were grease, oils, lubricants, and paints, and there were not results of studies that mentioned impacts over the Midpoints. The transportation activities performed by vessels and helicopters for operation and maintenance consume fossil fuels [50], and [51] informed that the transportation for maintenance activities contributed to 85% of total GHG emissions, which impacted the Ozone layer reduction and consequently affect Human Health [18]. Electronic components and permanent magnets of the wind turbines are manufactured with Rare earths [52] [53], which are the neodymium (Nd) (17.5–157.1 t/GW), praseodymium (Pr) (5.8–52.4 t/GW), dysprosium (Dy) (1.7–30.4 t/GW) and terbium (Tb) (0,4–6,8 t/GW) [54]. The manufactured parts such as the electronic components impact over the Midpoints Human toxicity, Abiotic depletion, and eutrophication, and their deposition may increase the heavy metals concentrations that impact the Marine ecotoxicity. The screening results after the literature survey did not evidence that permanent magnets generated impacts over the Midpoints categories.

4.2. Materials whose environmental impacts have not been reported in the specialized literature about LCA in OWT

According to the literature review some of the utilized materials in the OWE such as Carbon fibre, balsa wood, epoxy resins, rubber, lubricants, and Rare earths did not evidence impacts on Human, Environment health, and Natural resources. Then, this study analyzed papers that have reported the impacts of these materials in other industries [55]. analyzed the use of Carbon fiber in the automotive industry and assessed this material through an LCA analysis. That study reported the use of Carbon fibers impacts LCA categories such as Non-renewable energy consumption, Global warming, Acidification potential, and Human toxicity potential. The research mentioned that reducing the use of Magnesium for producing Carbon fiber decrease the environmental impacts [56]. in their study linked the Carbon Fibre with high GHC emissions and recommended material deposition because the high required energy for incineration and recycling generated important CO_2 emissions [57]. reported that Carbon fiber dust (suspended particles) may provoke human toxicity and inflammatory reactions because of the neutrophil's activity, oxidative stress, granuloma formation, and fibrosis.

An LCA analysis of balsa wood in civil construction was performed by Ref. [58], who studied Pinus Pinaster wood and found that the use of that material impacted the primary renewable and non-renewable energy consumption and the Global warming categories. The most impacted category was the primary renewable energy and other categories such as Abiotic depletion, Ozone depletion potential, photochemical oxidation formation, acidification, and eutrophication potential were impacted by less than 1%. The study pointed out that forest exploitation for acquiring wood and its transportation impacted Global warming because of the affectation of the carbon cycle.

The impacts of Epoxy over LCA categories were evaluated by Ref. [59] who assessed the environmental loads and reported Abiotic depletion with 59.4 kg Sb eq., higher than the natural resin "SuperSad" that they studied (0.01 kg Sb eq.). The Global warming category was the most impacted by the Epoxy resin because it reported 6663 kg CO_2 eq and the natural resin showed 4079 kg CO_2 eq. The other categories such as Potential acidification, Aquatic ecotoxicity potential of freshwater, Terrestrial ecotoxicity, Eutrophication potential, Human toxicity potential, and Terrestrial ecotoxicity potential were the most impacted by the Epoxy resin compared to the natural resin. That study in their concluding remarks pointed out that the utilization of the natural resin reduced the Carbon footprint and did not affect the availability of food sources.

[60] assessed through an LCA the purest presentation of rubber in the market "Crepé". The study found that the manufacturing of this rubber required high quantities of fresh water and consequently produced industrial wastewaters, and the electrical energy demand for the producing process impacted the Global warming category by 89%, followed by the burning firewood (5%), the use of formic acid (4%) and others (1%). The study of [61] reported that 30–50% of oil derivated lubricants are compounds with non-biodegradable mineral oils with high toxic content compared to natural lubricants. The LCA results indicated that natural lubricant Colza oil (Brassica napus) impacted more than the soybean oil, affecting the categories Acidification potential, Carcinogenic, non-carcinogenic, Respiratory effects, Eutrophication potential, Ecotoxicity, and Photochemical smog. The traditional lubricants (minerals) were the most contributors to the impacts over the categories of Global warming and Photochemical smog, contrary to the natural lubricants which reported negative values of the LCA because of the assumption that CO_2 is captured during the soybean and colza farming. Despite the use of fertilizers for the farming of the natural oils, it generates impacts on Acidification and Eutrophication potentials. The energy sources savings and the reduction of GHC emissions associated with the manufacturing of natural lubricants are more advantageous compared to the impacts of the mineral oils.

The use of Rare earth for manufacturing permanent magnets for wind turbines shows an increment in recent years because these new kinds of turbines generate electricity during low wind speeds, are lighter, and require less maintenance which is attractive for OWE projects [62]. The research of [26] showed results of an LCA to 3 kinds of 3 MW onshore wind turbines as follows: 1- doubly-fed induction generator (DFIG), 2- direct-drive synchronous generator with electrical excitation (DDSG), and 3- direct-drive permanent magnet synchronous generator (DDPMSG). The study mentioned that the Steel and permanent magnets of the DDSG generated the most environmental impacts, followed by DDPMSG and DFIG. According to the study, the most used Rare earth for manufacturing permanent magnets was the Neodymium (NdFeB magnet) with 67% of total consumption, Praseodymium (27%), and Dysprosium [63]. mentioned in their study that Rare earth impacted the Midpoint LCA categories, Acidification, Ecotoxicity, Eutrophication, Global warming, Ozone layer depletion, and consequently impacting the Endpoint on Human Health.

In Appendix 4 an inventory of the material impacts reported in other industries and engineering applications is shown. The LCA impacts were generated by several materials reported by other studies, where the main or the max-min values of each impact were extracted from the tables and graphs of each research. Because the utilized units of each LCA impact vary within the same material and LCA categories, and some studies reported mean or interval values of these impacts, we grouped the impacts in the following figures (Fig. 7, Fig. 8, and Fig. 9).

Fig. 7 shows that Petroleum based-epoxy resin (PBER) highly affects the Abiotic depletion and Eutrophication potential of LCA's. Steel impacts the acidification potential in terms of NOx and human health in terms of fine particulate matter (PM2.5). It was observed that Aluminium generated a higher impact on Human toxicity potential, and the Ozone layer depletion was highly affected by the Reinforced Concrete (RC) and the Steel Concrete Composite (SCC).

According to Fig. 8 metallic materials such as Steel, Aluminium, and Iron reported the highest impacts on the Global warming – Greenhouse Gas emission category. The Cement clinker (at the plant) and the Resin and Fibre-Glass (ReFG) also reported significant impacts.

Regarding the energy demand of each material reported in the LCA's (Fig. 9), it was observed that Steel, Magnesium, Carbon Fibre Reinforced Polymer (CFRP), Timber, Reinforced Concrete (RC), Steel Concrete Composite (SCC), Resin, and Fibre-Glass (ReFG) and Diesel, are materials that generate the highest energy consumption.

New materials that could replace the traditional ones in the OWE industry, not only may reduce the LCA impacts but also they might improve the Annual Energy Production (AEP) [64]. noticed that a rise in the AEP had reduced 18% of the standardized cost of energy (LCOE) in the last 15 years [65]. tested natural fiber/S-glass and

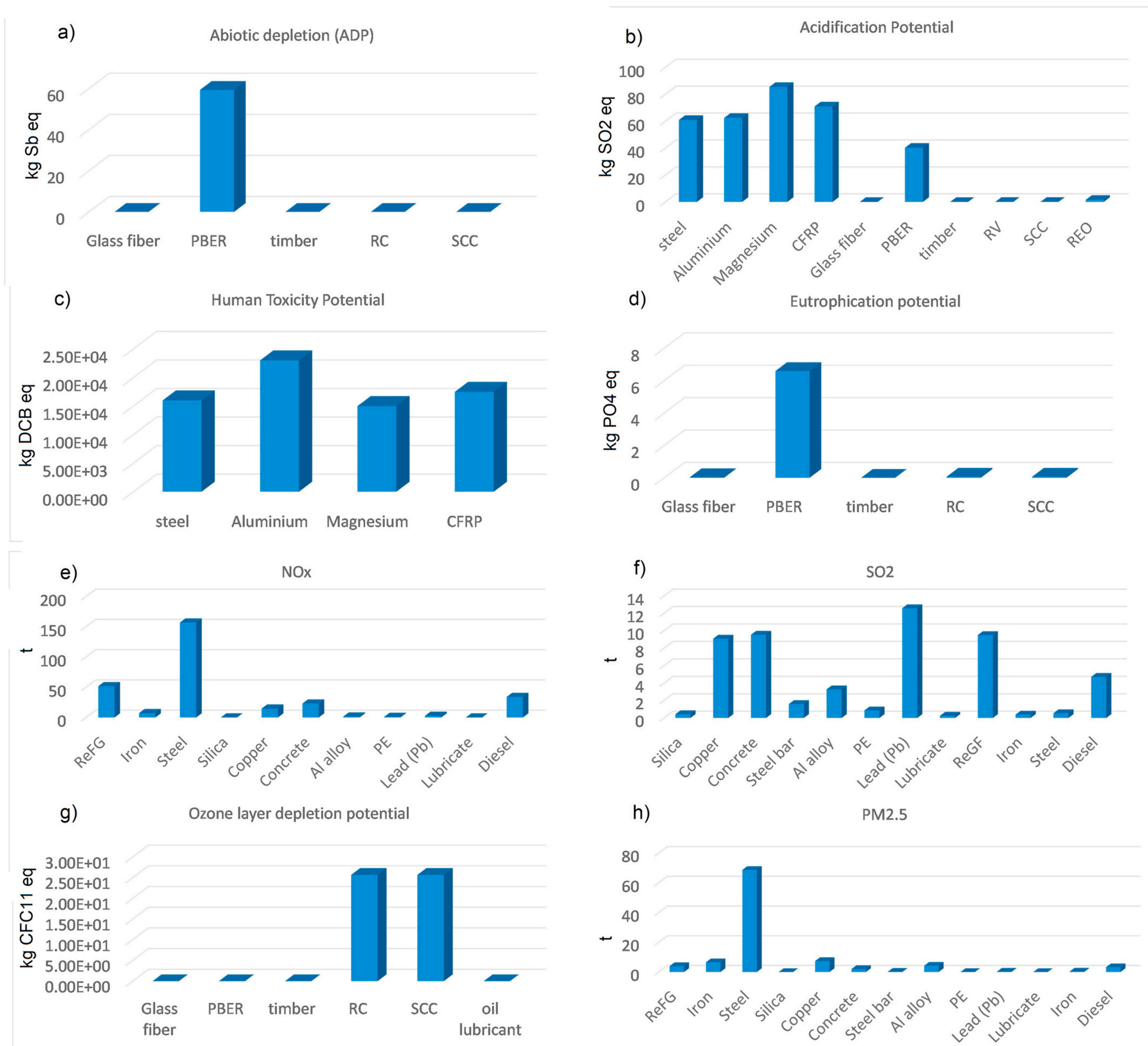

Fig. 7. LCA material impacts in wind energy and other industries. Appendix 4 lists detailed information about each material.

natural-fiber/Carbon fiber hybrid composites and pointed out that these emerging materials produce stiffer blades with better mechanical properties what improve the site AEP.

The cited above authors recommend the use of natural fiber reinforcements and polypropylene (thermoplastic polymer) to increase the recyclability of the OWT's blades and suggest chemical treatments to improve the mechanical properties. However, the utilization of new materials must be evaluated through LCAs because natural fibbers may require the use of toxic substances that might provoke negative impacts as PBER did in abiotic depletion, acidification potential, and eutrophication potential (Fig. 7). Also, composite materials such as thermoplastic polymer might need significant energy consumption in their manufacturing and utilization as seen by the ReFG in the primary energy consumption of Fig. 9, which reported the second highest GHG emissions after the Steel material (Fig. 8). In this sense, the use of new composite and eco-friendly materials as Timber must be carefully revised before replacing the traditional materials with the highest GHG emissions as Iron, Concrete, Steel and Aluminium, because Timber reported the highest primary energy consumption from non-renewable sources what is directly linked to the GHG emissions (Fig. 9b).

Considering the findings and gaps about the material impacts of OWE industry on Human Health, the Natural Environment, and Natural resources it is necessary to perform further research. The OWE is showing increasing interest and large investments worldwide projects are being done, however, the impacts generated during the manufacturing of wind turbines, and their associated activities (maintenance, repairing, dismantling) should be evaluated to reduce pollutant residuals through a cleaner production of new and enhanced materials. In this sense, the OWE industry if revising carefully the impacts of its materials and establishing sound strategies focussed on circular economy (re-use, recycling, and reduction) might be sustainable and clean energy as expected.

5. Conclusions

This research performed a data mining and a systematic literature

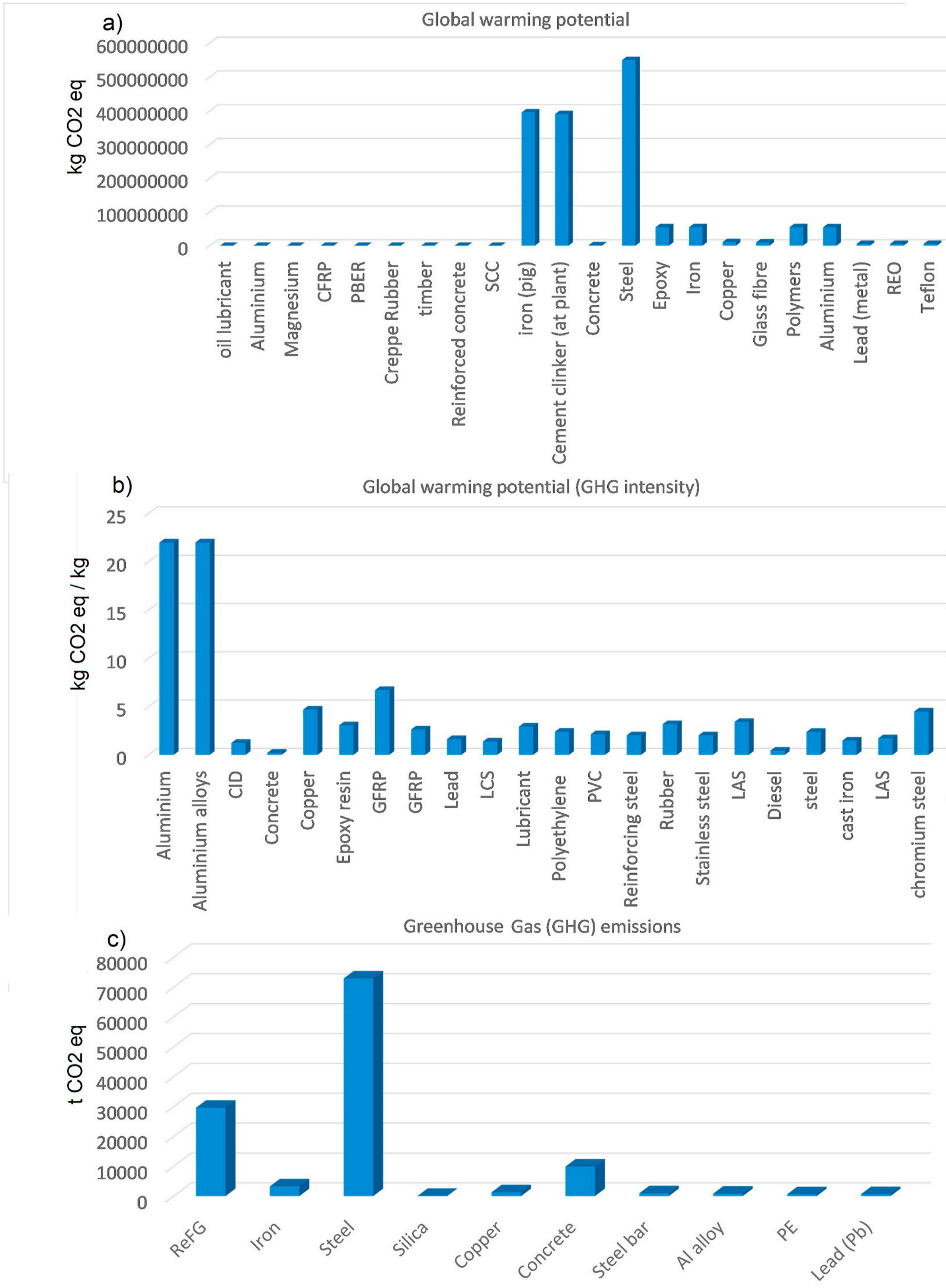

Fig. 8. Material Impacts of Global warming – Greenhouse Gas emission category reported in wind energy and other industries. Appendix 4 lists detailed information on each material.

review to produce the first detailed relationship among the activities of manufacturing, repair-maintenance and transportation of the OWT and their impact over the Human health, Natural Environment and Resources categories of LCAs. The relationship allowed extracting qualitative information that revealed the most used materials in the OWE (Appendix 1), relevant results of LCA assessments in real (Appendix 2) and theoreticals projects (Appendix 3). Appendix 4 synthesizes and organizes scattered quantitative data of material impacts of OWE industry on LCA categories.

The synthesis and analysis of LCA data performed in this research, revealed that the materials used for the OWTs and the OWE activities (building, operation, maintenance-repair, and dismantling), not only revealed high LCA impacts in the Mid- and Endpoint categories, but also significant energy consumption because of transportation (Vessels and Helicopters). The results of this study evidenced which materials provoked the most important impacts over the LCA and which are not assessed yet for the OWE industry. The metallic materials, Petroleum based kind, Concrete, Resin and Fiber-Glass showed the highest LCA impacts, and Steel was identified as a material with the highest energy consumption. The most impacted LCA categories were: Abiotic depletion, Acidification Potential, Human Toxicity potential, Eutrophication potential, NOx, SO2, Ozone layer depletion potential, Global Warming

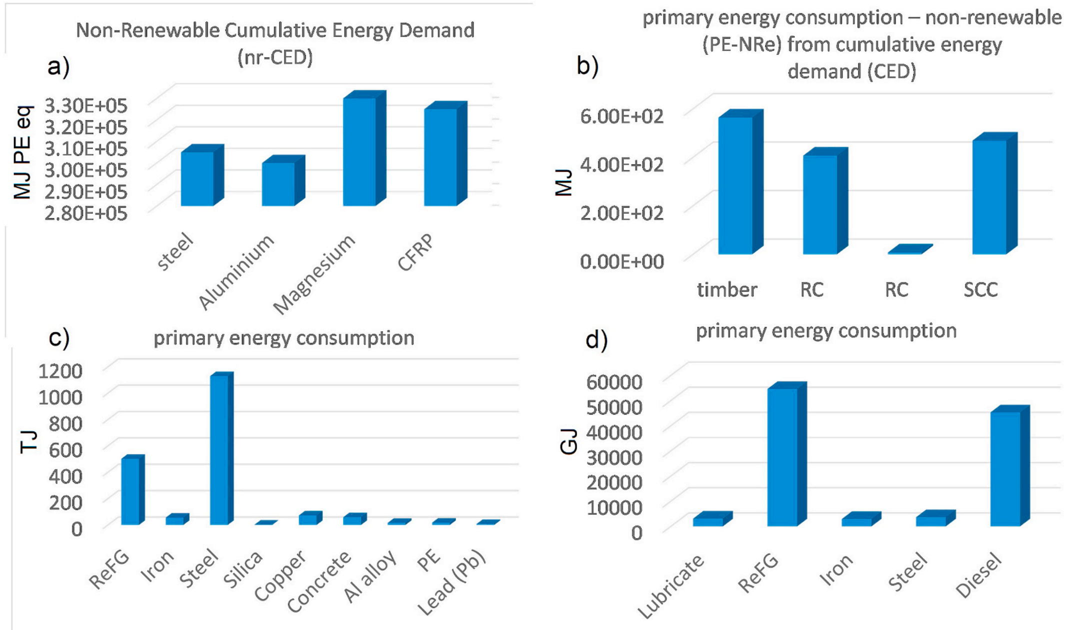

Fig. 9. Energy demand of each material in LCA's performed in wind energy and other industries. Appendix 4 lists detailed information on each material.

potential and PM 2.5.

The utilization of metallic materials such as Magnesium revealed the highest impact on the acidification potential (85.5 kg SO2 eq) followed by CFRP, Aluminium and Steel. Aluminium reported the highest impacts on human toxicity with a mean value of $2.30 \cdot 10^4$ kg DCB eq. However, the use of Aluminium for manufacturing the main axis of vertical OWT is less contaminant compared to the use of Copper for manufacturing the main axis of horizontal OWT. In this sense, OWE industry could revise the manufacturing processes between the horizontal and vertical OWT to converge in the most sustainable configuration of the technology.

The use of petroleum-based materials (PBER) reported the highest impact on Abiotic depletion (59.4 kg Sb eq) and Eutrophication potential (6.6 kg PO 4 -eq) and high impact on acidification potential (40.3 kg SO2 eq). Timber may be considered a promising material for replacing metallic materials for manufacturing wind turbine parts such as blades and towers, but it reported the highest primary energy consumption ($5.64 *10^2$MJ) of non-renewable sources, hence, the suppliers of Timber must consider a faster energy transition to the Renewables.

The findings revealed the need to increase LCA's studies to the materials with the highest impacts and how they could be replaced by less harmful materials such as biodegradables (e.g D-Limonene) or reusables (Rubber) with natural compounds. The aforementioned must be considered a priority for the OWE industry because several offshore wind farms are reaching their final operation period, and the residual materials due to the dismantling will generate more negative impacts. This research considers the rare earths as a sensitive material because their extraction not only affects Midpoint impacts (Human-Marine ecotoxicity, eutrophication, abiotic depletion), but also their extraction face environmental and political controversies seen between the USA and China, what makes Australia an alternative option for their production.

In General, the metallic materials negatively led the LCA categories, the GHG emissions, and energy consumption, hence, the OWE industry must explore new materials that could replace the traditional ones and should reduce the consumption of fossil fuels in the OWE support activities. While it happens, the industry must strengthen strategies for the transition to a circular economy, considering the recycling and reuse of materials and the reduction of fossil fuels through co-generation strategies.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.125223.

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