Ocean Engineering 266 (2022) 113031

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Evaluation of environmental sustainability matrix of Deepgen tidal turbine

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ARTICLE INFO

Keywords:
Life cycle assessment
Sustainability
Carbon footprint
Climate change
Renewable energy

ABSTRACT

Tidal energy is a reliable, consistent and abundant source of renewable energy. However, there are many concerns with different tidal energy devices relating to their environmental impacts over the lifetime. It is essential to address these issues by assessing the environmental impacts of these technologies throughout all phases of life cycle. In this context, a cradle to grave life cycle assessment (LCA) study is performed hereby on 1 MW Deepgen tidal turbine. ReCiPe LCA method has been used to evaluate 18 different environmental impacts; i.e., global warming in 100 years horizon, stratospheric ozone depletion, ionising radiation, ozone formation (human health), fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. According to the findings, steel, copper and glass fibre reinforced plastic (GFRP) carry the highest contributions across all impact categories. Steel contributes about 30%, on average, across all impact categories; copper contributes significantly to eutrophication and toxicity impacts while GFRP contributes significantly to marine eutrophication. Total global warming emission of the turbine stands at approximately 1 ktCO_2 eq which establishes the turbine as a lower GHG impact carrying solution. Findings from the study will serve as a benchmark to deploy more tidal power turbines around the world.

1. Introduction

Renewable energy sources will predictably supply up to two-thirds of global energy demand by 2050. Ocean energy is a promising renewable energy alternative to fossil-fuel based energy technologies that stand as major greenhouse gas emitters to the global environment. The two most common types of ocean energy are wave and tidal energy. It is estimated that worldwide 1 TW tidal energy and 2 TW wave energy can be captured from the ocean. Assuming a capacity factor of 40% for the installed devices, this leads to an annual output power generation of approximately 3500 TWh and 7000 TWh, respectively, while the world's current annual electricity consumption stands at about 25000 TWh in 2020 (Douziech et al., 2016). This means, majority of current power needs can be sourced from ocean (Douziech et al., 2016; Rashedi and Khanam, 2020; Harrison, 2015). Compared to wave energy, tidal energy generation can be well predicted as marine currents are driven by gravity rather than weather (Rashedi and Khanam, 2020). Despite the advantages, tidal stream technology is still in its early stage of development, implying that further research needs to be undertaken to transform this into commercially viable.

One such tidal energy device is Deepgen turbine which is developed by a UK based company, namely, Tidal Generation Limited (TGL) (Harrison, 2015). The device operates by the kinetic energy of ocean current, as caused by high tidal movement, which in turn generates electricity. The power output of the tidal stream device is highly sensitive to the velocity of tidal current and location of turbine (Harrison, 2015; Kumar, 2022). While there are several tidal stream devices available, the Deepgen turbine is a promising technology due to a number of notable features. Firstly, it consists of a nacelle simple in design, and convenient to transport. Due to the buoyancy of nacelle, it can be installed and retrieved in a single tidal cycle using small vessels, thus lowering the installation and maintenance expenses. Secondly, the nacelle uses a thruster that intelligently turns it into the direction of tide, thus allowing it in seamless management of ebb and flood tides while maximising the energy generation. Thirdly, it is designed with a three bladed pitch-controlled rotor that is useful to control the wave load on

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https://doi.org/10.1016/j.oceaneng.2022.113031
Received 1 August 2022; Received in revised form 12 October 2022; Accepted 27 October 2022
Available online 10 November 2022

the turbine by altering the blade pitch angle, thus enhancing the longevity of the device (Harrison, 2015). While such technological evolution continues, a proper environmental sustainability evaluation for it encompassing all life cycle phases is still limited. And there cannot be more pressing needs to evaluate the environmental sustainability matrix of the device based on the fact that these renewable energy technologies carry significant environmental impacts in cradle to grave life cycle phases, although major greenhouse gas emissions are avoided due to negligible to nil combustion of fossil fuels in their use or operational phase (Douziech et al., 2016; Rashedi and Khanam, 2020; Kumar, 2022). A holistic assessment of various environmental footprints is therefore necessary for such ingenious technologies.

Out of the various environmental assessment tools, life cycle assessment (LCA) offers a novel, quantitative and robust impact assessment pathway based on the latest scientific evidence and rigorously followed ISO standards (PRé, 2016; Sridhar and Tseng, 2013). LCA models the entire life cycle of a product starting from raw material extraction to manufacturing, transportation, use, maintenance to the end-of-life (EoL) phase including disposal and treatment of waste (Sridhar and Tseng, 2012a; Verma et al., 2022a). Life cycle approach implies that every phase spanning from cradle to grave has a role to play; that helps product designers, various service providers, and other stakeholders to make long term, sustainable choices in consideration of all environmental media, i.e., air, water, land/soil, and encompassing all life cycle phases. Life cycle approach also avoids shifting the environmental concerns: 1) from one life cycle stage to another, 2) from one geographic area to another, and 3) from one environmental medium (for example, air) to another (for example, water or land/soil). The LCA approach also guides in identifying the processes that carry high environmental pressure and compare alternatives to reduce this pressure, thus complementing the commercial viability of a product or technology.

Despite LCA being a powerful tool for assessing the environmental viability of various technologies, number of LCA studies conducted on tidal stream technologies is still very limited. A comprehensive literature review conducted based on Scopus database reveals only five articles relevant to the LCA of tidal stream technologies. These articles analysed eight different tidal stream devices. Table 1 summarises all these LCA studies performed on various tidal stream devices. In one such study, Douziech et al. compared the environmental performance of four tidal devices by ReCiPe method, such as, HS1000 turbine, Annapolis tidal station, SeaGen turbine and Morild Hydra tidal plant (Douziech et al., 2016). The study, however, did not include Deepgen in their comparison although the HS1000 carries some similarities with the design and working principle of the former. Earlier Douglas et al. conducted a LCA study on the SeaGen turbine assessing one energy based (embodied energy) and one environmental impact (carbon emission) (Douglas et al., 2008). Kaddoura et al. conducted a LCA on the Deep Green (DG500) tidal kite by seven environmental and energy impacts, such as, global warming, acidification, freshwater eutrophication,

Table 1
State of the art of published LCA articles on tidal stream devices.

Device	Year	Power Rating per device (MW)	Total number of devices	Project life (years)	Functional unit	Project Location	Scope	EoL method described	LCIA Method	Impacts Calculated
DG500	2020 (Kaddoura et al., 2020)	0.5	24	25	1 kWh	UK	Cradle-to-grave	Yes	ReCiPe	Aluminium, Cement, Copper, Iron, Non-Renewable Energy, Land Occupation, Global Warming, Acidification; Freshwater Eutrophication, Photochemical Ozone-Creation, Particulate Matter.
HS1000	2016 (Douziech et al., 2016) 2016 (Douziech et al., 2016) 2016 (Douziech et al., 2016)	1	3	25	1 kWh	Scotland	Cradle-to-grave	Yes	ReCiPe 2008	Agricultural land occupation, Climate Change, Fossil depletion, Freshwater ecotoxicity, Freshwater eutrophication, Human Toxicity, Ionising radiation, Marine ecotoxicity, Marine eutrophication, Metal Depletion, Natural land transformation, Particulate matter formation, Photochemical oxidant formation, Terrestrial acidification, Terrestrial ecotoxicity, Land use and Water depletion.
SeaGen		1.2	2	25	1 kWh	Northern Ireland	Cradle-to-grave	Yes	ReCiPe 2008	Same as above
HydraTidal		1.5	3	25	1 kWh	Norway	Cradle-to-grave	Yes	ReCiPe 2008	Same as above
Deepgen	2013 (Walker et al., 2015)	0.5	–	25	10 MW array	UK	Cradle-to-grave	Unclear	–	Embodied energy, GHG emission
OpenHydro	2013 (Walker et al., 2015)	2	–	20	10 MW array	UK	Cradle-to-grave	Unclear	–	Embodied energy, GHG emission
SR2000	2013 (Walker et al., 2015)	2	–	20	10 MW array,	UK	Cradle-to-grave	Unclear	–	Embodied energy, GHG emission
Flumill	2013 (Walker et al., 2015)	2	–	20	10 MW array	UK	Cradle-to-grave	Unclear	–	Embodied energy, GHG emission
SeaGen	2013 (Douglas et al., 2008)	1.2	2	20	–	Northern Ireland	Cradle-to-grave	Unclear	–	Embodied energy, GHG emission

photochemical ozone-creation, particulate matter, land occupation, and non-renewable energy consumption (Kaddoura et al., 2020).

In contrast, and despite having distinct advantages, the Deepgen turbine has received little attention.Based on Scopus and Web of Science database search, there is a single LCA study by Walker et al. devoted to Deepgen marine turbine which evaluated only two impacts (Walker et al., 2015). Herein, Walker et al. compared climate change and embodied energy for the Deepgen turbine. Moreover, the article did not consider any advanced life cycle impact assessment (LCIA) method for environmental impact assessment; rather it relied on generic equations to estimate the carbon footprint and embodied energy. Besides, the end-of-life (EoL) scenarios of the turbine were not adequately addressed in the article. It is also worth noting that none of the tidal stream devices included in Table 1 examined the environmental impacts in a material or process scale which offers the baseline impact results prior to introducing the sustainable manufacturing or life cycle processes. As a result, more research on the Deepgen device should be conducted, taking into account diverse environmental aspects, in order to further demonstrate its viability as a sustainable power source.

Accordingly, a comprehensive LCA study on the Deepgen tidal device is performed hereby addressing the research gaps mentioned above. To that aim, the ReCiPe method is used to assess the environmental impacts, which include 18 different midpoint impact indicators (Rashedi and Khanam, 2020; Goedkoop et al., 2013). The ReCiPe method finds its strength as one of the most recent and advanced methodologies with its broadest set of environmental impact categories and the impact calculation mechanism having a global scope (Goedkoop et al., 2013; Khanam and Jonkman, 2020). In addition, the EoL scenario and the inventory of materials and processes of the devices have been updated by including previously excluded materials and processes in relation to the only published LCA article on the Deepgen turbine. Furthermore, the article analyses the environmental impacts from the perspective of process based LCA, demonstrating how different materials and processes contribute to the total environmental impacts.

Overall, the novelty of the article is validated by addressing the following research gaps:

- assessing 18 environmental impacts using advanced LCIA method such as ReCiPe (none of the previous studies evaluated 18 impacts), and
- analysing process based life cycle impact contributions.

Four other sections follow this section of the article. Out of these, Section 2 focuses on the methodology of the LCA study together with goal and scope of the study, details of life cycle inventory and life cycle impact assessment procedure. Section 3 highlights the key results of the study together with hotspot analysis and major emission carriers along different impact categories. Section 4 focuses on areas of improvement i. e. key processes whereby the life cycle impacts can be reduced. Finally, Section 5 delivers a concluding overview of the article.

2. Methodology

This LCA study has been performed adhering to the 14,000 framework series of the International Standards Organization (ISO), specifically, ISO 14040:2006 and ISO 14044:2006 standards (ISO 14040, 2006; ISO 14044, 2006). The methodology stated by these standards consists of four phases which include the goal and scope, inventory analysis, impact assessment and interpretation of the results. The following sub-sections accordingly discuss the above-mentioned four phases of the LCA study.

2.1. Goal and scope of the LCA study

The purpose of the article is to evaluate the life cycle environmental profile of the Deepgen tidal turbine that is used to generate tidal power from ocean. All inputs and outputs of the turbine during its entire cradle to grave lifecycle were evaluated, ranging from raw material extraction for manufacturing to its process of decommissioning. A system boundary of the LCA study has been shown in Fig. 1. The Deepgen tidal turbine is entirely built on site, with all materials brought in. The first stage of the system boundary includes the extraction of raw materials with further processing and treatment required for the production of turbine blades, exterior structures, piled foundations, and other structural elements. In the second stage of the system boundary, the entire device, including the turbine blade, turbine, gearbox, rotor hub, casing, body, shafts, and electrical components, will be manufactured and assembled on-site. This stage also includes importing the materials with appropriate transportation from the vendors to the manufacturing site. In this stage, relevant assembly activities, such as, machining, sandblasting, flame-cutting, hot rolling, and crane use are considered. In the installation stage, the piled foundation is constructed first. The stage includes the drilling process and cable trench cutting for pile placement and cable laying, respectively. Once the foundation is completed, the device is installed on the foundation using cranes. Transportation of the piled foundation and other devices from the manufacturing site to the installation site is also included at this stage. In the operations and maintenance (O&M) phase, transportation to the installation site, repairs and replacement materials throughout the turbine's lifetime are included. The decommissioning process includes the towing of the device back to the shore and dismantling of the device. In this stage, the foundation and piles are separated from the seabed and concrete section. During the decommissioning phase, three different types of decommissioning processes, such as recycling, incineration, landfill, and reuse, are considered.

The turbine has a rated capacity of 1 MW and has an expected lifetime of 25 years (Harrison, 2015). The whole turbine with its expected operational life is taken as the functional unit of the study. Alternatively, the authors could have chosen 1 kWh as the functional unit. But with the change in wave height, sea current speed and the depth of sea across various installation site, the generation capacity of the turbine varies significantly which changes the life cycle impact accompanied with 1 kWh generated power in every hour. Moreover, different marine current devices have different capacity factors which means 1 kWh generated power does not necessarily reflect the actual life cycle impact of the devices. Therefore, the authors resorted to 1 MW based functional unit to nullify the effect of varying power generation.

Also, as the turbine does not generate any other form of material or energy except the tidal power, no allocation in input/output inventory is required. Recipe method was used to evaluate the full life cycle environmental profile of the Deepgen tidal turbine. This method transformed the long list of inventories associated to the turbine's life cycle into a limited number of environmental impact scores by means of characterisation factors. The characterisation factors ultimately determine the midpoint and endpoint factors. Midpoint scores express the relative severity of 18 different environmental impact categories, while endpoint scores show the damage scores to three major area of environmental protection. Endpoint scores usually suffer from uncertainties as it is obtained from the aggregation of midpoint impacts, hence, it was not evaluated in this study. This study evaluated total 18 different environmental impact categories according to ReCiPe (2016) v1.1 midpoint method (hierarchist version) (Goedkoop et al., 2013). The hierarchist version was used to consider the value choices with regards to the time frame and other issues based on scientific acceptance. The list of mid-point impact categories include global warming, stratospheric ozone depletion, ionising radiation, fine particulate matter formation, ozone formation (human health), ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human noncarcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption.

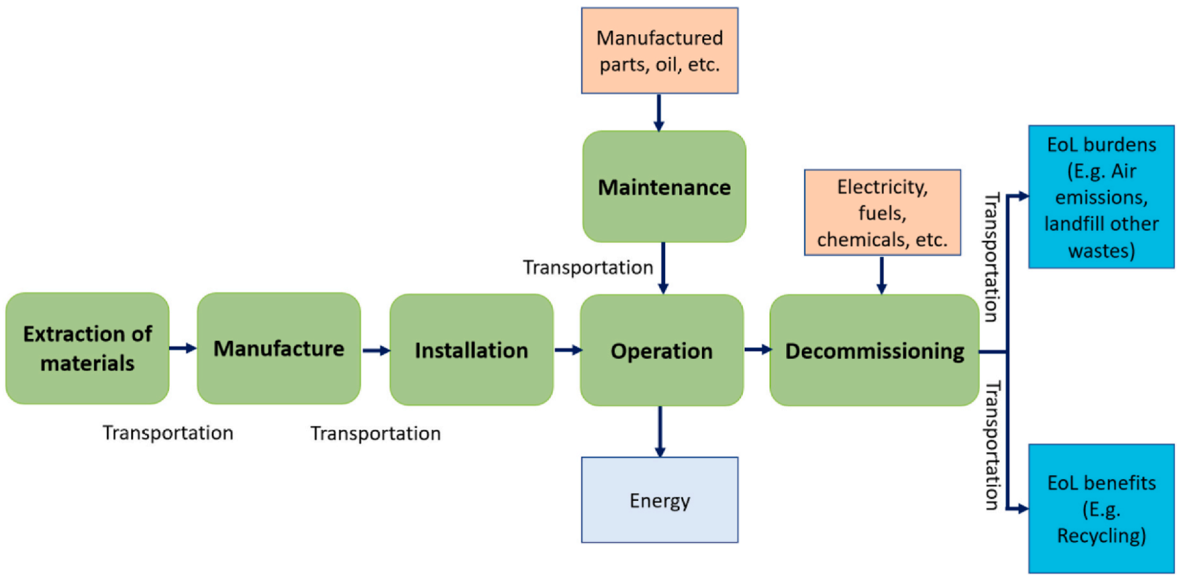

Fig. 1. System boundary of the LCA study on Deepgen turbine.

Some of the life cycle inventory (LCI) data have been gathered from the LCA study conducted by Walker et al. (2015); the remaining data has been sourced from other LCA studies, scholarly publications, and published Environmental Product Declarations (EPD). The LCI data of electricity generating devices have been sourced from the published EPDs of ABB devices (ABB, 2021a; ABB, 2021b). In addition, a well-defined transportation system has been considered. Some cabling system data has been upgraded in line with the industry standards. Overall, the study considers a 2% mass based cut-off criteria in sourcing its life cycle inventory.

The general construction of the Deepgen tidal turbine is shown in Fig. 2 together with its major components, such as, turbine, structure, support system, and foundation. Three turbine blades, rotor-hub, gearbox, generator, shaft, bearings, and casing make up the turbine. Plate steel makes up the structure, with welded steel pipe connecting the device to the piled base. The concrete and steel piles keep the device anchored to the bottom. A cable is attached to the device that transfers generated electricity to the shore.

2.2. *Life cycle inventory analysis*

The Deepgen tidal turbine is entirely assembled on site, with all materials brought in from the shore. The fully assembled device is transported 300 km by road to a port, where it is loaded onto a large ship and then transported for 3.16 km to the installation site (Walker et al., 2015). Before the device can be anchored, the piled foundation materials are transported to the installation site. Primary materials have been sourced for the LCA study without considering any recycled materials. Most of the assembly activities, including, machining, sandblasting, flame cutting, hot rolling, and crane use are considered in the study (Sridhar and Tseng, 2012a, 2013). The electricity consumed by the installation and maintenance phase is estimated to be 1200 kWh. Machine operations such as drilling and welding, however, are not part of this generalisation and has been separately estimated.

The pie chart in Fig. 3 depicts the LCI of the 365 tonne (t) Deepgen tidal turbine together with the most significant materials. Steel accounts for up to 80% of the overall mass (Walker et al., 2015). This is to be anticipated, given that the device's construction, mechanical parts, and cable safety are all made of steel. The remaining 20% is used in the

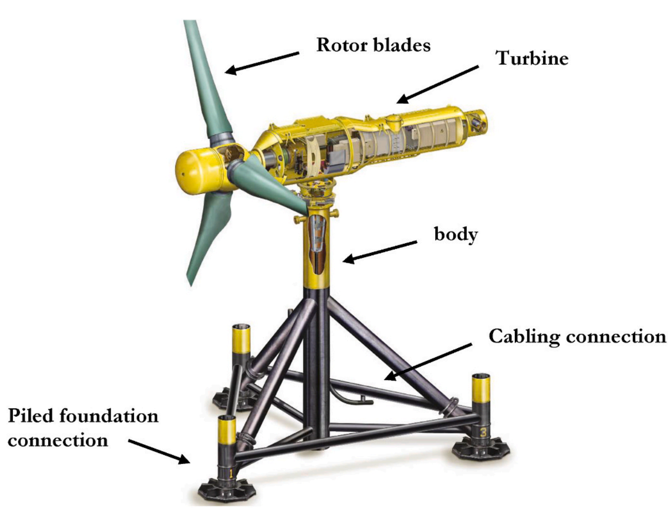

Fig. 2. Deepgen tidal turbine (Harrison, 2015).

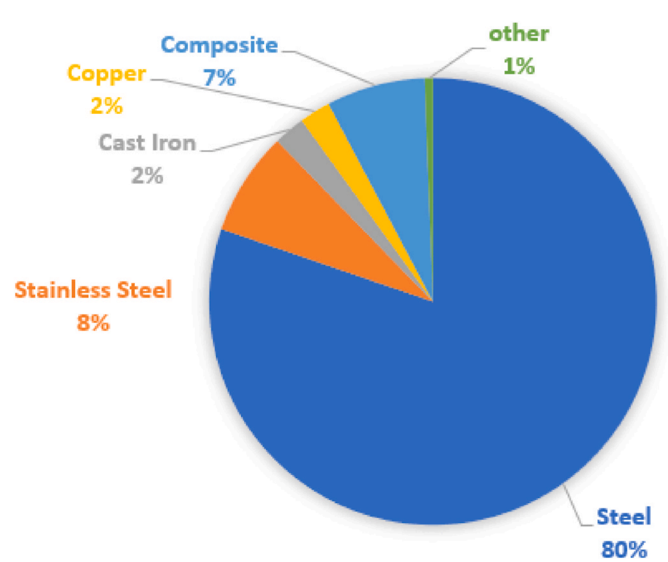

Fig. 3. Material breakdown for the Deepgen turbine (Walker et al., 2015).

turbine itself, which is primarily made of stainless steel and composite.

2.2.1. Structure

The structure of many tidal turbines, including the Deepgen turbine, is manufactured with steel (Harrison, 2015). The total mass of the welded steel pipe that supports the body and connects to the base is estimated to require 73200 kg of low-alloyed steel (Harrison, 2015). All processes and materials to create the structure is listed on Table 2. The loss of material due to handling and processing of the device is estimated to be 5% (Sridhar and Tseng, 2013; Douglas et al., 2008). Information on the type of paint used for the Deepgen is unavailable so the NORSOK M-501 paint has been considered as it complies with ISO 20340 standard regarding offshore paint applications (AkzoNobel, 2014).

2.2.2. Piled foundation

The Deepgen tidal turbine is anchored to the seabed using a piled base structure (Harrison, 2015). Low-alloy steel, cement, and water are among the materials used. The total mass of steel is estimated to be 75000 kg for one device (Walker et al., 2015). Three 10 m × 2 m steel piles will be used to anchor the device and will be set in concrete. A concrete mixture ratio of 1:0.45:1.5:3 is used for cement, water, sand and gravel, respectively (Raza et al., 2021). All materials and processes to create the foundation are listed on Table 3.

2.2.3. Electrical components

Cables are used to transport the electricity onshore. A 79 mm diameter armoured multi-core cable with a cross-linked polythene (XLPE) will be used (Harrison, 2015; Douglas et al., 2008). The cable is transported 300 km straight to the port. It will then be transported to the installation site to be set on the seabed. The materials required for the cable is listed on Table 4. Every copper wire has a cross sectional area of 70 mm^2 and is made of 4 mm armour steel wire with 3.4 mm polythene insulation (Nexans, 2021).

The LCI of the generator and distribution transformer has been sourced from ABB's EPD reports and is shown in Table 5. A 1 kW generator with a 25-year design life and a 315 kW distribution transformer with a 30-year design life are used in the inventory (ABB, 2021a; ABB, 2021b).

2.2.4. Turbine

The rotor-hub, gearbox, shafts, bearings, and casing form the critical components of the turbine and the LCI data of these is listed in Table 6. The three blades of the Deepgen turbine are all made of composite material (Harrison, 2015). As the specific details of the composite material has not been found, glass fibre reinforced polymer (GFRP) has been assumed for blade use due to its structurally robust properties as well as being a cheaper option. Mass of stainless steel for one turbine has been estimated to be 27400 kg (Walker et al., 2015). Lubricating oil has been excluded from the LCI as it would be used in a very small quantity during the whole lifespan of the turbine (Sridhar and Tseng, 2013).

Table 2
LCI of structure.

	Amount	Unit
Product		
Structure		
Materials	187100	kg
Steel, Low-alloyed (Harrison, 2015)	8	kg
Paint (AkzoNobel, 2014)		
Processes	20	m
Welding (Walker et al., 2015)		
Disposal (Sridhar and Tseng, 2013; Douglas et al., 2008)	9355	kg
Steel chippings		
Transport (Walker et al., 2015)	14968	tkm
Lorry, >32t (Steel to manufacture site)		

Table 3
LCI of foundation.

	Amount	Unit
Product		
Foundation		
Materials	75000	kg
Steel, Low-alloyed (Harrison, 2015; Walker et al., 2015)	147300	kg
Cement (Raza et al., 2021)	66285	kg
Water (Raza et al., 2021)	441900	kg
Gravel (Raza et al., 2021)	220950	kg
Sand (Raza et al., 2021)		
Processes (Walker et al., 2015)	30	m
Drilling for piles		
Disposal (Sridhar and Tseng, 2013; Douglas et al., 2008)	3750	kg
Steel chippings	7365	kg
Excess cement	4050.75	kg
Excess water	22095	kg
Excess gravel	11048	kg
Excess sand		
Transport (Walker et al., 2015)	262930	tkm
concrete mixing truck, >32t	6000	tkm
Lorry, >32t fleet average (Steel to manufacture site)	21375	tkm
Lorry, >32t fleet average (piles to port)	3008	tkm
Large ship >32t		

Table 4
LCI of cabling system.

	Amount	Unit
Product		
Cables		
Materials	6936.4	kg
Copper (Harrison, 2015; Nexans, 2021)	1223	kg
Polyethylene (Harrison, 2015; Douglas et al., 2008)	23990	kg
Steel, Low-alloyed (Nexans, 2021)		
Disposal (Sridhar and Tseng, 2013)	346.8	kg
Copper chippings	61.2	kg
Polyethylene chippings	1199.5	kg
Steel chippings		
Transport	9644.82	tkm
Lorry, >32t, fleet average manufacture to port (Cables to port - 300 km)	101.66	tkm
Large ship >32t, (3.162 km distance from port to installation site)		

2.2.5. Installation & maintenance

The foundation is constructed first in the installation phase. Here, drilling process is considered for pile placement and cable trench cutting is considered for cable laying (Harrison, 2015; Douglas et al., 2008). Once the foundation is completed, the device will be installed to the foundation using cranes. A total 262 h machining operations has been considered for the assembly and installation processes (Walker et al., 2015). In addition, there will be regular maintenance conducted in every two years with 100 h of maintenance per period.

2.2.6. End-of-life scenarios

The decommissioning process includes the towing of the device back to the shore and dismantling the device. The foundation and piles will be separated from the seabed and concrete section. The EoL scenarios of various materials are derived from various literature and listed in Table 7 (Walker et al., 2015; Witik et al., 2013; Norgate, 2013). The LCA study focuses on EoL recycling (avoided burden or closed loop) approach; as such, the recycling credits reduce the life cycle impact of the turbine, unlike the cut-off LCA modelling approach. Composite materials, used for the construction of the blades, are considered for landfill and incineration. Unlike other metals and polymers, recycling of composite materials is inherently challenging due to the intermixed structure of multi-materials. The recycling method for composites require multiple separation techniques including mechanical, thermal and chemical treatments. This complex recycling method is still at its

Table 5
LCI of the generator and transformer.

	Amount	Unit
Product		
Generator AC Machine type HXR 355, 1000kw power (25 years)		
Materials (ABB, 2021a)	5010	Kg
Electrical Steel	1440	Kg
Steel, low alloyed	3070	Kg
Cast iron	10	Kg
Aluminium	1280	Kg
Copper	40	Kg
insulation material	200	Kg
wooden packing material	60	Kg
impregnation resin (Epoxy resin)	40	Kg
Transport	892	Tkm
Lorry, >32t, fleet average (Device to manufacturing site)		
Product		
Distribution transformer 315kVA, 11 kV, 3 phase, ONAN (30 years)		
Materials (ABB, 2021b)	533	kg
Core Steel, low alloyed	340	kg
Transformer oil	324	kg
Steel (Tank), low alloyed	113.51	kg
Aluminium Wire	85.3	kg
Aluminium sheet	59.9	kg
Insulation material	11	kg
Porcelain		
Transport	117.3	tkm
Lorry, >32t, fleet average (Device to manufacturing site)		

Table 6
LCI of the turbine.

	Amount	Unit
Product		
Turbine blades (Harrison, 2015)		
Materials	26100	kg
Composite material (GFRP)		
Disposal	1305	kg
Excess composite		
Transport	2088	tkm
Lorry, >32t, fleet average Material to manufacturing site)		
Product		
Turbine (Rotorhub, gearbox, shafts, bearing, casing) (Walker et al., 2015)		
Materials	5230	kg
Cast iron (casing)	27400	kg
Stainless Steel (TGL)		
Disposal	261.5	kg
Iron scraps	1370	kg
Steel scraps		
Transport	2610.4	tkm
Lorry, >32t, fleet average (Materials to manufacturing site)		

developing stage and no consensus has been available for standard materials and treatment process (Witik et al., 2013). Therefore, recycling for GFRP is ignored in this study as assuming different recycling rates will lead to the uncertainty in LCIA results. The remaining materials are assumed to be recycled, incinerated, sent to landfill or deposited underground as per Table 7.

3. Results & discussion

The results and discussion section has three sub-sections: first sub-section highlights the total impact of the turbine by 18 different environmental impacts; the next sub-section contributes to a deep discussion on selected impacts, while the last sub-section discusses on the area of improvement.

Table 7
End-of-life scenario for all materials (Walker et al., 2015; Witik et al., 2013; Norgate, 2013).

Material	End-of-life Scenario
Steel	60% recycled, 40% landfill as inert waste
Stainless Steel	60% recycled, 40% landfill as inert waste
Cast iron	60% recycled, 40% landfill as inert waste
Aluminium	56% recycling, 44% landfill as inert waste
Copper	40% recycling, 60% landfill as inert waste
Concrete	40% recycling, 60% landfill as inert waste
GFRP	50% landfill, 50% incineration as municipal solid waste
Epoxy insulation	50% landfill, 50% incineration as municipal solid waste
Paint	50% underground deposition, 50% incineration as hazardous waste
Porcelain	100% landfill as inert waste
Polyethylene	50% recycling, 50% municipal incineration
Impregnation resin	50% underground deposition, 50% incineration as hazardous waste
Timber	50% industrial composting, 25% used for heat production at furnace, 25% landfill

Finally, the LCA model has been developed using SimaPro LCA software version 9.0.0.49 (PRé, 2016).

3.1. Total life cycle impact

The characterised results of cradle-to-grave LCA study of the Deepgen tidal turbine are shown in Table 8 by 18 different impacts. Contribution of major materials, processes, and modes of transportation in each of the 18 categories is highlighted in Fig. 4. Global warming, ozone formation, freshwater eutrophication, human carcinogenic toxicity, mineral resource scarcity, and fossil fuel scarcity impacts are mostly contributed by steel. Steel was the most responsible for human carcinogenic toxicity, accounting for 73 percent of overall emissions. Given the large amount of mass required to produce the turbine, this large contribution is to be expected. Steel is a common source of carcinogenic toxicity in humans, as high metal exposure can lead to cancer. Even at low doses, studies on metals and their environmental toxicity revealed a high risk to human health. Similarly, steel was the second-largest contributor to mineral resources scarcity, accounting for 46% of the total impact. Steel carries the largest mass composition of all materials in Deepgen turbine; therefore, this high impact is not unexpected. Steel contributed an average of 23 percent to the remaining categories, indicating that it delivers significant impact across the range.

GFRP carried large contribution in six of the 18 impact groups. Specially, with 43 percent, 58 percent, 32 percent, and 51 percent contribution, GFRP contributed the most to stratospheric ozone depletion, marine eutrophication, fossil resource scarcity, and water consumption impact, respectively. According to recent research, the

Table 8
Results of LCIA.

Impact category	Unit	Total
Global warming in 100 years horizon (GW)	kg CO_2 eq	1004491
Stratospheric ozone depletion (SOD)	kg CFC11 eq	0.517
Ionising radiation (IR)	kBq Co-60 eq	49616
Ozone formation, Human health (OF, HH)	kg NOx eq	2325
Fine particulate matter formation (FPMF)	kg $PM_{2.5}$ eq	2166
Ozone formation, Terrestrial ecosystems (OF, TE)	kg NOx eq	2393
Terrestrial acidification (TA)	kg SO_2 eq	4490
Freshwater eutrophication (F Eutro)	kg P eq	812
Marine eutrophication (M Eutro)	kg N eq	99
Terrestrial ecotoxicity (T Etox)	kg 1,4-DCB	15545663
Freshwater ecotoxicity (F Etox)	kg 1,4-DCB	128250
Marine ecotoxicity (M Etox)	kg 1,4-DCB	184264
Human carcinogenic toxicity (HCT)	kg 1,4-DCB	267841
Human non-carcinogenic toxicity (HNCT)	kg 1,4-DCB	4306194
Land use	m2a crop eq	20385
Mineral resource scarcity (MRS)	kg Cu eq	28133
Fossil resource scarcity (FRS)	kg oil eq	228362
Water consumption (WC)	m3	10721

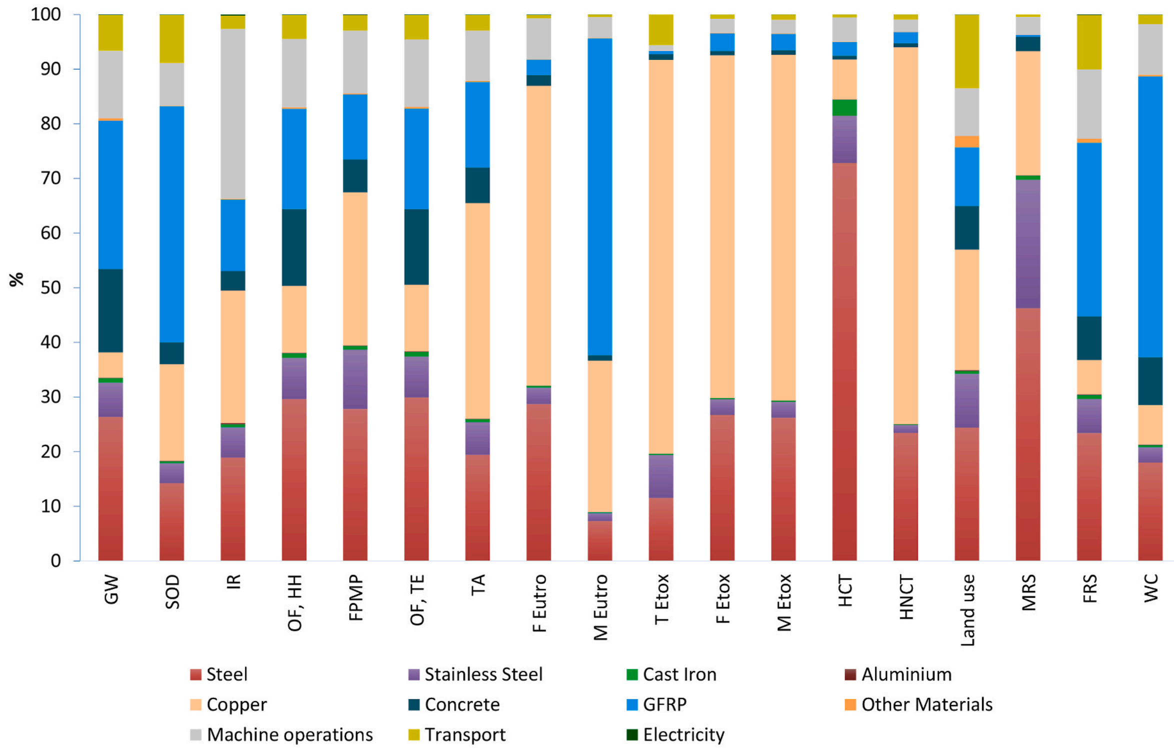

Fig. 4. Breakdown of impacts by materials and processes (acronyms are defined in Table 8).

production of GFRP entails high level of fossil fuel depletion, smog, acidification, and air pollution, and this is similarly depicted in Fig. 4 (Lee and Jain, 2009). The EoL impacts are also important, as it was determined that half of the GFRP waste would be disposed of in landfills and the other half would be incinerated.

Despite possessing the smallest mass of all metals (as shown in Fig. 3), copper was responsible for approximately 70% of all emissions for freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, aquatic ecotoxicity, and human non-carcinogenic toxicity. Copper manufacturing issues variety of waste materials, including sulfidic tailings, which, if not properly managed, delivers major toxicity effect to the environment (Park et al., 2022; Akinyemi and Alaba, 2022). In addition, machine operations have quite high impacts across the board, particularly in the areas of global warming, ionising radiation, and fossil resource scarcity, with 12 percent, 31 percent, and 13 percent, respectively. Next, comparing to other materials and processes, transportation processes appear to deliver minimal consequences. Fig. 4 shows that transportation mostly contributes to stratospheric ozone depletion, land usage, and fossil resource scarcity, accounting for 9 percent, 13 percent, and 10 percent impact, respectively, with road transport making up the majority of all transport. In addition, the electricity used in assembly and maintenance phases had little to no impact on all 18 impact categories, with ionising radiation getting the largest contribution of 0.2 percent.

Six of the 18 impacts have been chosen for further analysis in subsequent sections which will demonstrate a list of life cycle processes contributing to these impacts.

3.2. Selected impacts

3.2.1. Global warming in 100 years horizon

The contribution of various materials to global warming is depicted in Fig. 5. The gross global warming emission of the turbine stands at approximately 1 kt CO_2 eq. Taking into account the previously listed recycling credits, the products that contribute the most are steel and GFRP, which contribute 26 and 27 percent of global warming emission, respectively. Steel, which accounts for 80% of the device's mass, is predicted to be one of the largest. GFRP, on the other hand, releases more carbon dioxide than steel while accounting for just 7% of total mass. This implies that the emissions from composite production and processing are substantially higher than steel production for each unit mass. The decommissioning of composites also contributes to the total emissions. In addition, concrete has a total mass of 876 tonnes but contributes only up to 15% of total emissions, implying that the turbine-base does not contribute substantially to global warming. The findings show that drilling holes for piles releases the most of all machine operations, accounting for around a tenth of all greenhouse gas (GHG) emissions. In addition, all modes of transportation appear to emit very little GHGs.

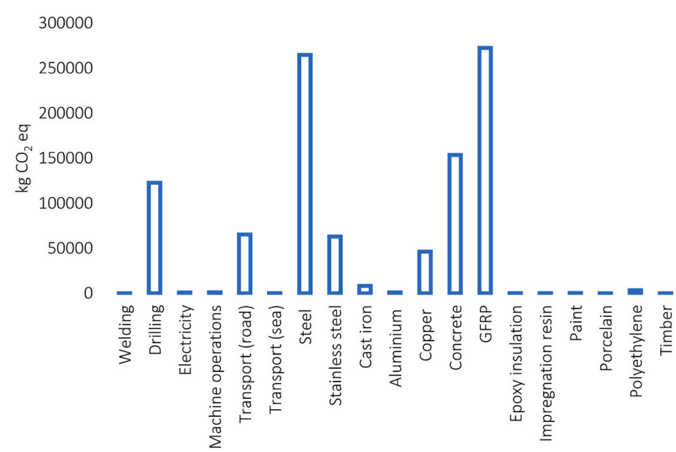

Fig. 5. Material contribution to global warming.

Fig. 6 presents the top sub-process contributions to the global warming. This figure excludes any process that contributes less than one percent of total GHG emissions. As compared to electricity, pig iron, hard coal, and iron sintering, the clinker method for making cement

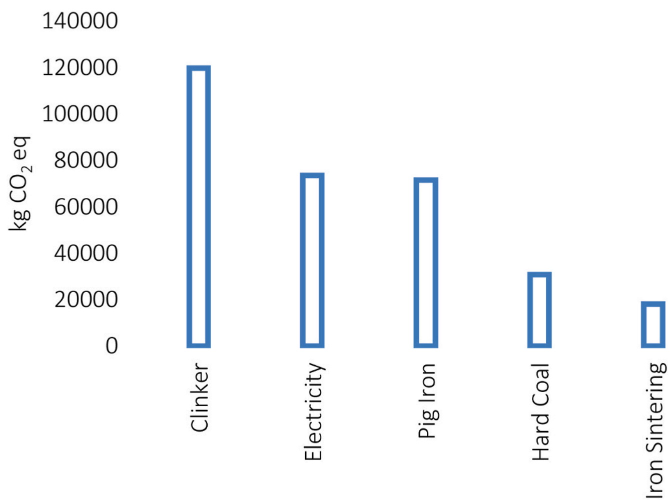

Fig. 6. Top process contributors to global warming.

produces the most emissions. The large amount of concrete required for the base necessitates a similarly high amount of cement, which requires a large amount of clinker to produce it. Electricity and pig iron emissions contribute approximately equally, which is noteworthy given that pig iron is a commodity used in the steel manufacturing process. The contribution of electricity in global warming along different life cycle processes is depicted in Fig. 7. This is significant since most processes that manufacture material require electricity, therefore it is critical to evaluate whether less carbon-intensive energy systems can be utilized to manufacture the materials and products. Steel production and deep-sea drilling are two of the most significant contributions. This is expected, as large amount of electricity is needed to manufacture raw steel and operate deep sea drilling. Emissions from hard coal and iron sintering processes do not issue large GHG contribution.

The top substances that are directly or indirectly associated to each of the materials and processes in the inventory are also examined. Carbon dioxide, sulfur hexafluoride, methane, and dinitrogen monoxide are the most significant compounds that produce the largest GHG emissions with a 0.25 percent cut off criteria. With a total of 903816 kg CO_2 eq, carbon dioxide accounts for the most emissions, followed by methane with 85056 kg CO_2 eq. Steel and GFRP manufacture are the most significant contributors to carbon dioxide emissions, meaning that changing these materials with better ones may result in considerable reductions in carbon emissions. Drilling pile holes accounts for a tenth of all emissions, which is to be expected as three 10 m depth holes is required through subsea drilling apparatus. Emissions from trucks and transoceanic ships are negligible when compared to material output, accounting for only around five percent of total GHG emissions.

3.2.2. Ionising radiation

The cumulative emission for ionising radiation potential is shown in Fig. 8. The gross ionising radiation stands at 49616 kBq Co-60 eq where Co represents cobalt. Steel and copper production are two of the most significant contributors to this impact, accounting for 18% and 24% of the total radiation, respectively. However, subsea drilling is the source of the most radiation, accounting for roughly 31% of the total. Fig. 9 depicts the top sub-processes that are directly or indirectly linked to each of the materials and processes included in the inventory in order to determine the highest emitting processes for creating these products. The figure excludes all processes that contribute less than 1% of total emissions. Clearly, tailings produced as a by-product of raw material extraction process are the most significant contributor. Mine tailings can be radioactive, and sulfidic tailings in particular are especially hazardous to the environment, which explains why copper contributes so much despite its limited total mass relative to other metals (Rashedi and Khanam, 2020; Akinyemi and Alaba, 2022). Because of the slurry of fine particles that will likely be released during subsea drilling and trenching process, emission of radioactive material in water is clearly high as well. Since it is submerged, naturally occurring radioactive material may be released into the ocean, posing a threat to marine life.

The top substances directly or indirectly linked to each of the materials and processes in the inventory are also investigated. Any substance generating less than 0.25 percent of total radiations is excluded, and radon-222 and carbon-14 appear as the most significant contributors, with 45973 kBq Co-60 eq and 3269 kBq Co-60 eq, respectively. The drilling process and copper carry the highest level of radon-222 while the same drilling process alongside steel contribute the highest carbon-14 based radiation.

3.2.3. Stratospheric ozone depletion

The cumulative emissions for stratospheric ozone depletion account to 0.51673 kg CFC11 eq and the material contributions are shown in Fig. 10 (here, CFC represents for chlorofluorocarbon). GFRP is responsible for 43% of total emissions, while copper and steel are responsible for 18% and 14% of total emissions, respectively. The primary cause of this contribution appears to be the processing and recycling of GFRP. The rise in ultraviolet radiation, as it can cause health hazards and kill some marine life, is particularly unfavourable for both crop produces and living beings. The highest contributing sub-processes are shown in Fig. 11, while processes that contribute less than 1% of total emissions are excluded from the graph. Nitric acid, petroleum, and electricity emit virtually little trichlorofluoromethane, according to the findings. The electricity contribution in ozone depletion linked to the LCI of the Deepgen is shown in Fig. 12. The emissions from electricity used to

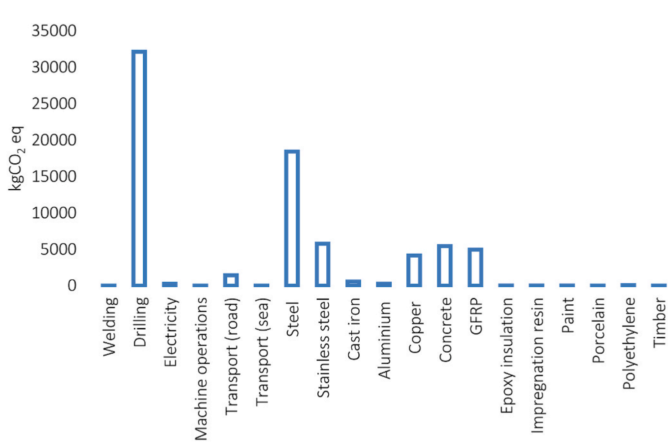

Fig. 7. Electricity contribution to global warming.

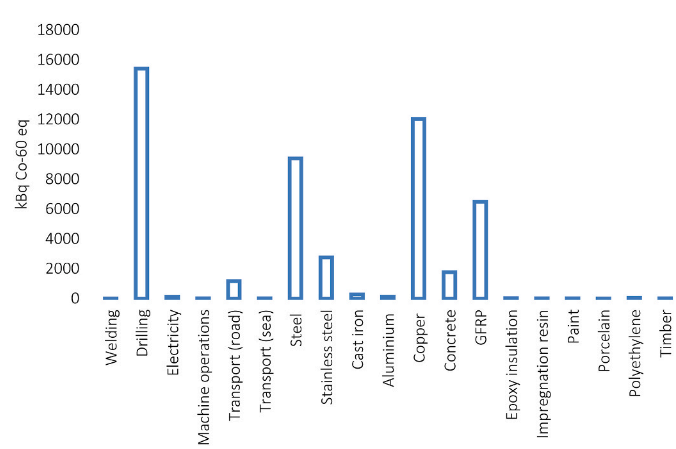

Fig. 8. Total material contribution to ionising radiation.

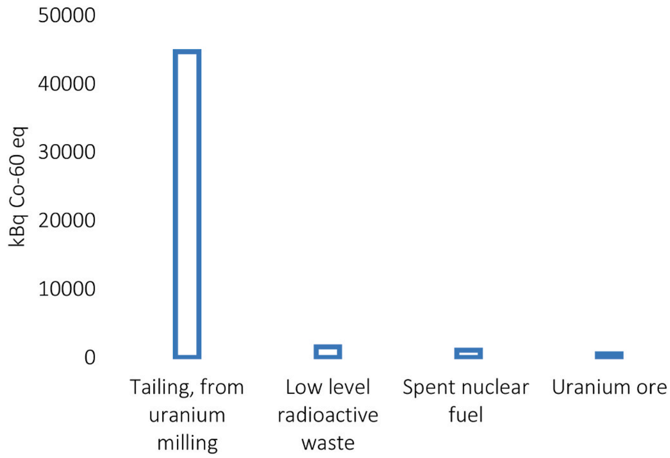

Fig. 9. Top processes impacting ionising radiation.

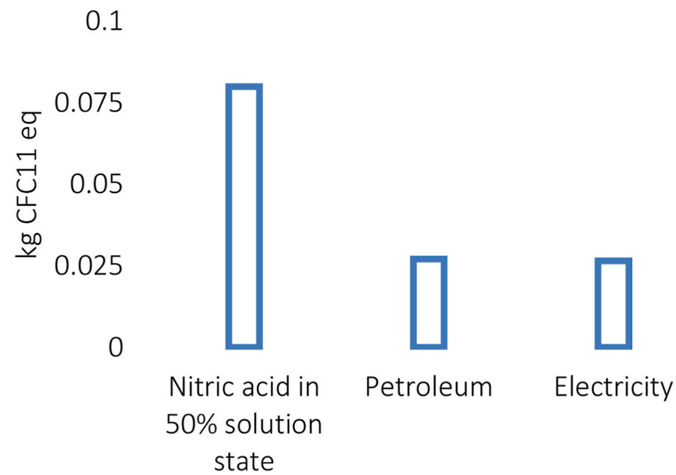

Fig. 11. Top processes impacting stratospheric ozone depletion.

manufacture the materials are relatively high as indicated by Fig. 12, however, it should be noted that the electricity used to produce steel and the drilling process account for the majority of the ozone depletion impact.

The substances associated to each of the materials and processes are also reviewed. Any substance that contributed less than 0.25 percent of total emissions has been excluded, and it was discovered that the top three substances, which are dinitrogen monoxide, ethane and methane, contributed 0.44669 kg CFC11 eq, 0.0014 kg CFC11 eq, and 0.04932 kg CFC11 eq, respectively. Among this, dinitrogen monoxide contributed the most of all substances with 86% of total impact.

3.2.4. *Fine particulate matter formation*

The overall contribution of all processes to fine particulate matter formation is 2166 kg $PM_{2.5}$ eq and the material contribution is shown in Fig. 13. With 27 percent and 28 percent, respectively, steel and copper contribute the most to this impact. GRFP and offshore drilling also highly contribute with 12 percent and 11 percent, respectively. The highest emitting processes directly and indirectly linked to the materials and processes in the inventory are shown in Fig. 14. On the graph, only processes that contribute more than 1% of particulate matter emissions are shown. $PM_{2.5}$ is clearly released throughout many processes during

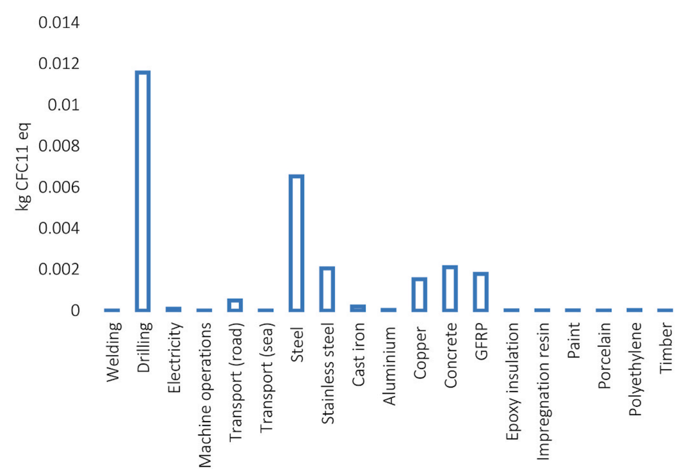

Fig. 12. Electricity contribution impacting stratospheric ozone depletion.

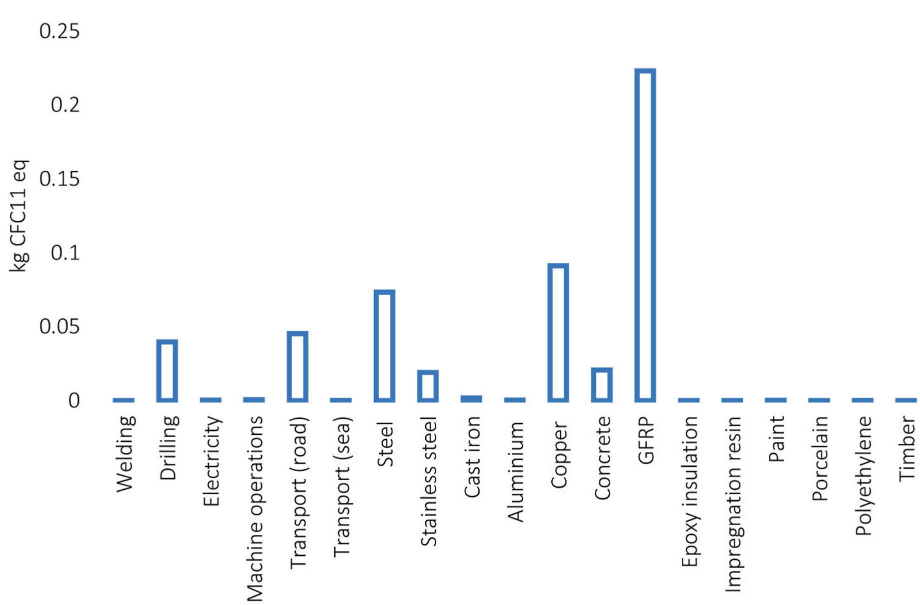

Fig. 10. Total material contribution to stratospheric ozone depletion.

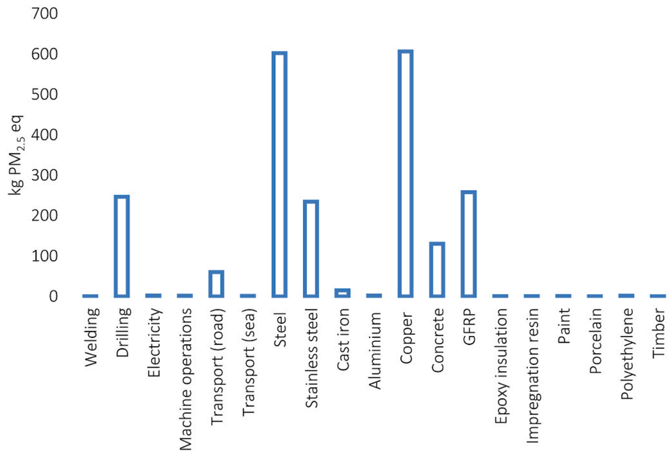

Fig. 13. Total material contribution to fine particulate matter formation.

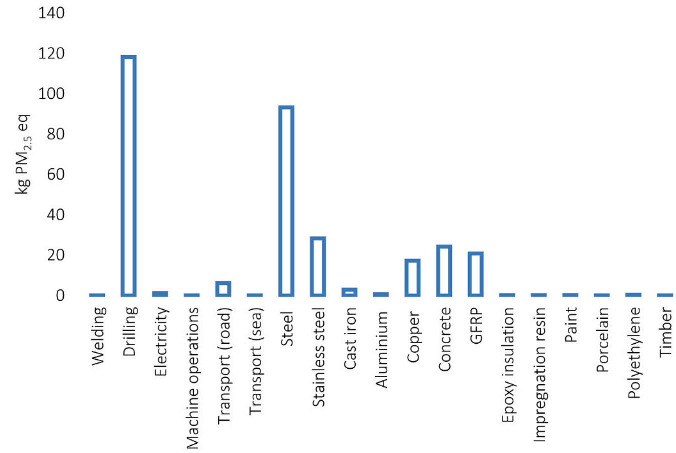

Fig. 15. Electricity contribution to fine particulate matter formation.

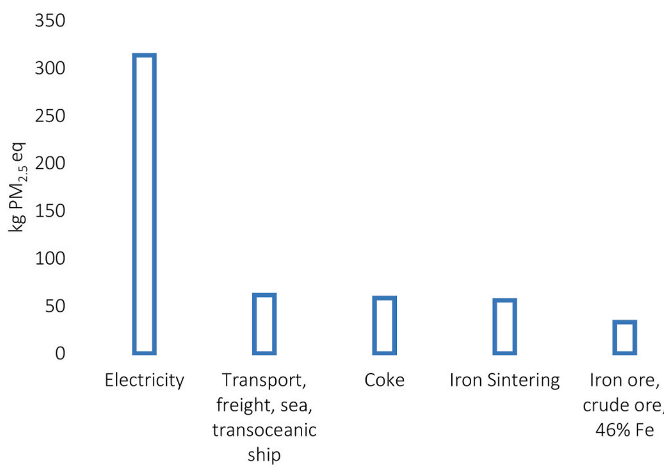

Fig. 14. Top processes impacting fine particulate matter formation.

the manufacturing of materials and each process contributes very little, with the processes that use electricity emitting the most. Particulate matter is released into the environment mostly as a result of incomplete fossil fuel combustion and any LCI process that suspends material in the atmosphere (such as, construction or drilling). The findings support this, as the manufacture of raw materials such as steel, copper, and GFRP requires processes that can result in particulate suspension in the air. Electricity generation, for example, would require the burning of fossil fuels and incomplete combustion of these fuels can lead to a release of fine particulate matter. The electricity contribution that are directly and indirectly contributing to these materials are shown in Fig. 15. The drilling and steel processes produce the most emissions, but other products like copper, concrete, and GFRP carry noticeable impacts as well. Clearly, electricity-powered manufacturing, construction, and drilling processes pollute the air significantly as these processes produce fine matter that are released to the atmosphere. Electricity generation is also associated with the possibility of incomplete fossil fuel combustion, which can result in smog being released into the atmosphere.

The leading substances directly or indirectly linked to each of the materials and processes in the inventory have been examined as well. For this impact, substances that generated less than 0.25 percent of total emissions are excluded. Sulfur dioxide, 2.5 μm particles, nitrogen oxides, and ammonia are discovered to be the highest linked substances. Sulfur dioxide and particulates, with 1026 kg $PM_{2.5}$ eq and 877 kg $PM_{2.5}$ eq, respectively, are the only substances that significantly contributed to the top contributions. These substances are found in abundance in steel and copper, implying that using secondary metals would result in fewer particles being emitted.

3.2.5. *Mineral resource scarcity*

Fig. 16 shows the overall loss of minerals throughout the Deepgen's life cycle with a total loss of 28134 kg Cu eq. Steel, stainless steel, and copper are the materials that contribute the most, with 46, 23, and 22 percent, respectively. Fig. 17 depicts the Deepgen turbine's total highest process contributions that are directly and indirectly linked to the LCI with a cut-off criteria of 1%. According to the findings, the ferronickel production process contributes the most to the mineral resource scarcity impact. Other process contributions are all minor, indicating that the mineral resource scarcity is mostly linked with the production of various component materials. The top substances impacting mineral resource scarcity are also investigated and presented in Fig. 17. Any substance that accounted for less than 0.5 percent of total impact has been excluded. The findings reveal a large number of contributions, but the ones that emit the most are iron and ferronickel, which emit 7659 kg Cu eq and 10494 kg Cu eq, respectively. This implies that a reduction in steel in turbine design could result in a reduction of mineral loss.

3.2.6. *Fossil resource scarcity*

Fig. 18 depicts the material contributions to the fossil resource scarcity category with a total loss of 228362 kg oil eq. The largest contributors to fossil fuel depletion are GRFP and steel, which account for 32 percent and 23 percent, respectively. However, most of the materials have an influence in this impact, as can be seen from the figure. This means that the production of such primary materials plays a significant role in this impact. Despite the fact that steel carries

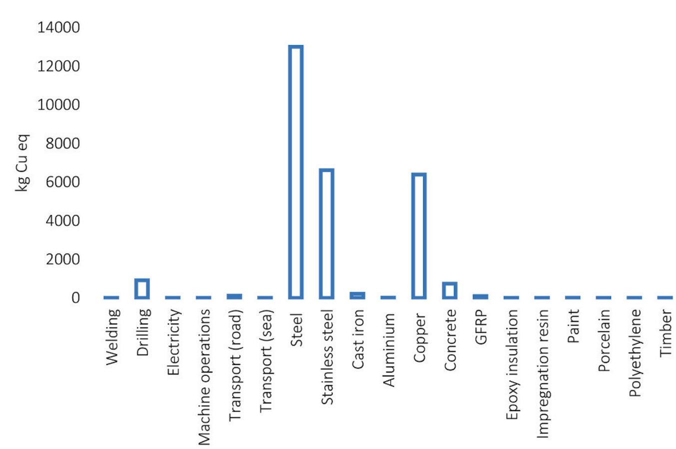

Fig. 16. Total material contribution to mineral resource scarcity.

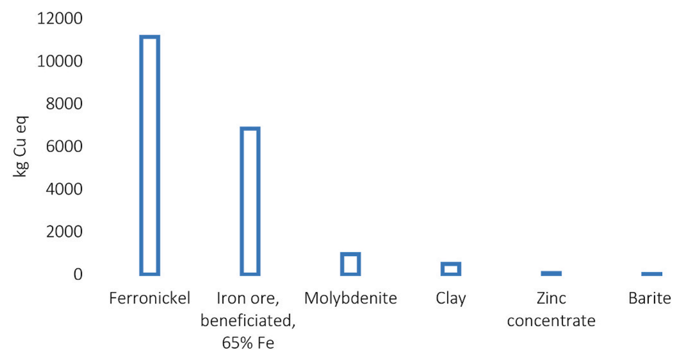

Fig. 17. Top processes impacting mineral resource scarcity.

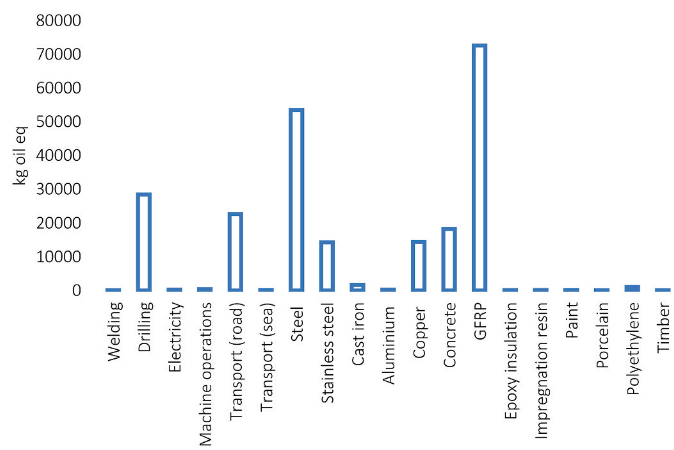

Fig. 18. Total material contribution to fossil resource scarcity.

approximately 11 times the mass of GFRP, GFRP uses more oil. The manufacturing and decommissioning processes seem to have the greatest effect on GFRP, as the existing decommissioning process includes incineration, which requires significant amount of fuel. Road transport also contributes highly with a total impact of 22758 kg oil eq. The large road travel distances required to transport the materials and the device itself is likely why the contribution is so high in this section. Fig. 19 shows the overall process contribution towards fossil resource scarcity with a 1% cut-off criteria. Of all process contributions, hard coal and petroleum are the most significant. These fossil fuels are expected to be used the most to generate energy to produce materials in both construction and decommissioning phase, whether through recycling or

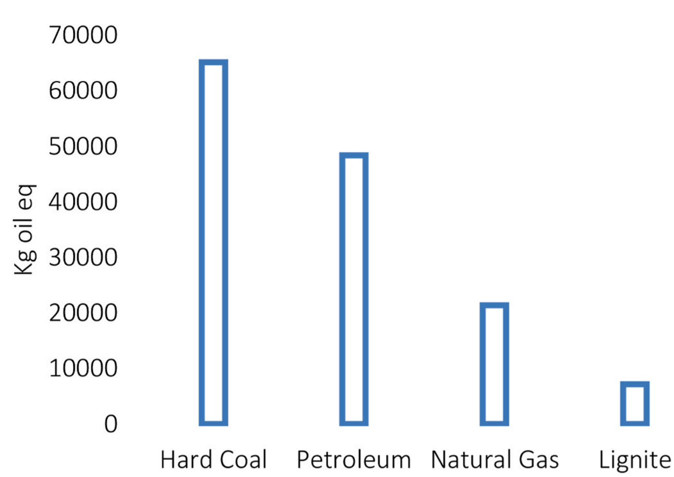

Fig. 19. Top processes impacting mineral resource scarcity.

incineration.

3.2.7. *Other impacts*

The other impacts demonstrate similar patterns to the six previously analysed with respect to material contribution. Steel and GFRP are the most significant contributors to ozone formation, accounting for 29% and 12%, respectively, for both human health and terrestrial ecosystem ozone formation. The results are validated by the fact that steel has the biggest mass in turbine, which causes the highest emissions for photochemical ozone production.

In contrast, copper is the most emitting material in terrestrial acidification, accounting for 39 percent of the total, with steel coming in second with 19 percent. The by-products of copper production, as previously indicated, generate significant acidification, eutrophication, and toxicity, which explains its major contribution. Freshwater eutrophication may be particularly harmful to the ecosystem since the nutrient discharged is usually phosphate, which can generate algal blooms that can harm marine life (Goedkoop et al., 2013; Khalid et al., 2021). Copper alone contributes up to 54 percent, 72 percent, 62 percent, 63 percent, and 69 percent of the total freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity, respectively. The negative impact of sulfidic tailings is also responsible for these large emissions.

GFRP is the most influential factor in marine eutrophication and water consumption, with 58 percent and 51 percent, respectively. The emissions from GFRP manufacturing and decommissioning is the cause for high marine enrichment (Goedkoop et al., 2013; Muhammadi et al., 2022). Next, human carcinogenic and non-carcinogenic toxicities are issued by different materials. Steel is the most carcinogenic to humans (73 percent), with stainless steel contributing the second highest (9 percent). Copper, on the other hand, contributes the most to human non-carcinogenic toxicity, accounting for 69 percent and steel contributing the second highest with 23 percent. While this category does not consider the possibility of cancer, the mining and processing of copper and steel release tailings. The proper disposal of these tailings is critical as they can pose serious health risks to human being.

The contribution of land use is evenly distributed among most significant materials, implying that the production and use of these materials and processes require roughly equal amounts of land. With 24 percent and 22 percent, respectively, steel and copper production contribute the most to this impact category. The similar trend is seen in the LCA of the Buoy-rope-drum wave energy converter, where the device's structure, constructed primarily of raw materials, contributes the most to land use (Zhai et al., 2018). Using recycled materials for the device will, however, result in the Deepgen occupying less land over its lifetime.

3.3. *Improvements*

Many LCIA for various ocean energy technologies conclude that material extraction and manufacturing appear as the most environmentally impactful phases in a device's life cycle (Douziech et al., 2016; Sridhar and Tseng, 2012a; Verma et al., 2022a; Douglas et al., 2008). All the studies conclude that production of turbine blades, exterior structure, mooring foundation, and other structural elements significantly contribute to the emissions (Sridhar and Tseng, 2013; Sridhar et al., 2015). Steel, copper, GFRP, concrete, and the piled foundation drilling process are among the most significant contributions for the Deepgen, according to the LCIA findings. However, the decommissioning stage also involves significant impact to the environment (Raza et al., 2021). The study considered recycling rates based on current world average recycling situation which will be increased gradually in future (Norgate, 2013). However, at the moment, low recycling rates, landfill, and incineration scenarios all contribute an effect to the overall impact. Disposal of sulfidic tailings from copper mining, for example, increases overall ionising radiation impacts. In addition, the incineration of GFRP as a decommissioning process led to the depletion of fossil fuels.

A few material alternatives will also be useful in lowering Deepgen emissions. Since GFRP appears to be a major contributor to many impacts, a change in turbine blade material could reduce emissions across the board (Sridhar and Tseng, 2012b, 2013; Verma et al., 2022b; Joshi et al., 2004). Natural fibre composites (NFC) could be a viable alternative in this context. NFC is lighter than GFRP and carries a lower environmental impact although its structural performance may not be as superior as GFRP in offshore loading condition (Joshi et al., 2004; Marzouki et al., 2021). Natural fibre is also sourced from various plants or trees which need fertilizers to grow – these fertilizers ultimately contribute to large nitrate and phosphate emissions, causing marine eutrophication. If an effective recycling approach is implemented, composite emission rates can be reduced significantly (Sridhar and Tseng, 2016; Roik et al., 2022).

Next, copper processing, as previously mentioned, has high emission rates in the impact categories of toxicity and eutrophication. Raw copper production produces sulfidic tailings, which are toxic to the environment if not properly disposed of. Dong et al. (Dong et al., 2020/11) finds that secondary copper processing, which involves using recycled copper scraps, is the most environment-friendly alternative for copper production. This will reduce the amount of sulfidic tailings generated, which will have a major effect in reducing many impacts. Other than these, the emissions of metals were proportionally higher as the recycling rates were low; however, while recycled materials does not result in recycling credits, it does reduce the emissions generated by primary material production (Kaddoura et al., 2020; Norgate, 2013).

The Deepgen's piled foundation requires a large amount of concrete. The amount of concrete needed did not carry a big contribution on most of the impact categories, but there is a noticeable contribution in global warming potential, with a 15% contribution. Although it is not essential, changing the type of foundation will help to minimise the overall effect of concrete as well as the steel required to construct piles. A gravity-based foundation could be a viable alternative. However, depending on the ocean condition, a gravity base may bring complexities in installation (Walker).

4. Conclusion

This study evaluated the environmental sustainability matrix of the Deepgen tidal turbine through a detailed, cradle-to-grave LCA study. The findings revealed the effects of major materials across 18 different impact categories. The core findings of the study have been summarized below:

- Steel, GFRP, and copper are found to contribute the most significant impact among all materials. Steel, which accounts for 80% of the device's mass, contributes up to 30% across all impact categories on average. Specially, global warming, ozone formation, freshwater eutrophication, human carcinogenic toxicity, mineral resource scarcity, and fossil fuel scarcity impacts are mostly contributed by steel.
- GFRP carried large contribution in six of the 18 impact groups. Specially, with 43 percent, 58 percent, 32 percent, and 51 percent contribution, GFRP contributed the most to stratospheric ozone depletion, marine eutrophication, fossil resource scarcity, and water consumption impact, respectively, while accounting for only 7% of the device's overall mass. The EoL scenario of GFRP also entails additional impacts as half of the GFRP waste went to landfill while the other half was incinerated.
- Additionally, despite having the smallest mass of all metals, copper was responsible for approximately 70% of all emissions in freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, aquatic ecotoxicity, and human non-carcinogenic toxicity impact categories.
- In turn, concrete with a huge mass of 876 tonne just contributed 15% of total GHG emissions which confirms the base of the turbine as a relatively impact-savvy sub-assembly.
- Besides, machining operations carried considerably larger global warming, ionising radiation, and fossil resource scarcity impacts, with 12 percent, 31 percent, and 13 percent, of total impact respectively. In turn, drilling process contributed significant impact on global warming potential and particulate matter formation.
- Comparatively, transportation and energy need in installation and maintenance phases contributed very little impact across all impact categories.
- It has also been revealed that the production of the raw materials contributes the most impact in life cycle phases.
- Next, within 207 GHGs understudy, carbon dioxide, sulfur hexafluoride, methane, and dinitrogen monoxide contributed the largest global warming emissions, sequentially from higher to lower values.
- Amongst other findings, ionising radiation to sea water is noteworthy as slurry of fine particles get released in sub-sea drilling and trenching process. Herein, radon-222 appears as the most significant ionising radiation carrier.

Improvements are proposed in order to reduce the current high-level emissions. A modification in the turbine blade material would drastically reduce emissions. The use of recycled materials would have the added benefit of reducing primary material production emissions. Copper, in particular, would experience lower emission rates as a result of the reduction in sulfidic tailings.

CRediT authorship contribution statement

Ahmad Rashedi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Roles, Writing – original draft, Writing – review & editing. **Taslima Khanam:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing. **Byongug Jeong:** Writing – review & editing. **Majid Hussain:** Writing – review & editing.

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.

Acknowledgement

The authors greatly acknowledge the contribution of Mr Alwin Joseph Lal in supporting in writing.

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