Ref. Ares(2018)5558282 - 30/10/2018

Power Take-Off System for a Subsea Tidal Kite

D6.1
LCA Report

Deliverable number	Lead Beneficiary	Type	Dissemination level	Delivery date
D6.1	Chalmers	R	Public	M31

Editor	Johan Tivander
Authors	Mohamad Kaddoura
	Sverker Molander

Document history

Version	Author	Beneficiary	Date	Comment
iD6.1a	**Johan Tivander;Mohamad Kaddoura**	Chalmers	2017-12-21	Intermediary result
iD6.1_180427	**Johan Tivander** **Mohamad Kaddoura**	Chalmers Chalmers	2018-04-27	LCA report draft
iD6.1_180518	**Johan Tivander** **Mohamad Kaddoura**	Chalmers Chalmers	2018-05-18	LCA report first full draft
iD6.1_180522	**Johan Tivander** **Mohamad Kaddoura**	Chalmers Chalmers	2018-05-22	LCA report full draft
iD6.1_180525	**Patrik Pettersson**	Minesto	2018-05-25	Review comments
iD6.1_180611	**Johan Tivander** **Mohamad Kaddoura** **Sverker Molander**	Chalmers Chalmers Chalmers	2018-06-11	LCA report final draft (of public version)
D6.1	**Johan Tivander** **Mohamad Kaddoura** **Sverker Molander**	Chalmers Chalmers Chalmers	2018-06-29	LCA report (of public version). Adj. to reviewers' comments.
D6.1	**Johan Tivander** **Mohamad Kaddoura** **Sverker Molander**	Chalmers Chalmers Chalmers	2018-07-02	LCA report final for publication

Content

Internal Approval

Coordinator signature

Per Salomonsson	Midroc	3 July 2018

Reviewer signatures

Patrik Pettersson	Minesto AB	2 July 2018

Louise Kregting	Queen's University Belfast	3 July 2018

Abbreviations/Acronyms

1,4DB eq	1,4-dichlorobenzene equivalents; emissions contributing to freshwater ecotoxicity expressed as they were all emitted as 1,4DB
ADP	Abiotic resources Depletion Potential
CED	Cumulative Energy Demand
CF	Characterisation factor
DGU	Deep Green Utility
EOL	End of Life; life cycle phase involving dismantling and waste management
EPD	Environmental Product Declaration
EROI	Energy Return On Investment
C_2H_4 eq	ethylene equivalents; emissions contributing to POCP expressed as if they were all emitted as C_2H_4
CO_2 eq	carbon dioxide equivalents; emissions contributing to GWP expressed as if they were all emitted as CO_2
COD	Chemical Oxygen Demand; used to quantify amount of (bio)degradable organics in water expressed in units of oxygen consumed
H14	shorthand reference to (Hertwich et al., 2014)
GBF	Gravity Base Foundation; structure to anchor the kite to the seafloor
GHG	greenhouse gases (e.g. CO_2, methane, N_2O)
GWP	Global Warming Potential
kWhe	kilowatt hour of electrical energy
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compounds
P eq	phosphorus equivalents; emissions contributing to freshwater eutrophication expressed as if they were all emitted as P
PCR	Product Category Rules; also used as shorthand specifically for the PCR for electricity, steam, and hot/cold water generation and distribution (EPD, 2015)
PM_{10} eq	Particulate matter equivalents; particle emissions expressed as if all was emitted as particles with a diameter ≤ 10μm
PO_4^{3-} eq	phosphate equivalents; emissions contributing to eutrophication expressed as if they were emitted as phosphate, PO_4^{3-}
POCP	Photochemical (ground-level) Ozone-Creation Potential

PTO	Power Take-Off
PV	Photovoltaic electricity generation (solar panels)
SO_2 eq	sulphur dioxide equivalents; acidifying emissions expressed as if they were all emitted as SO_2
TMS	Tidal Marine Substation

1. Executive summary

The marine renewable energy technology company Minesto has developed and patented the Deep Green ocean energy power plant, where power is generated by a turbine that is attached to a wing moved like a kite by the water current. It can operate at ocean currents less than 2.5 m/s, which adds a new ocean energy potential to the market (Minesto, 2018a). The PowerKite project received funding from the European Union's Horizon 2020 research and innovation programme and was launched to enhance the structural and power performance of the power take-off (PTO) of Deep Green.

The environmental impacts of the technology are also assessed by the PowerKite project (WP 6). This Life Cycle Assessment (LCA), was carried out at the Environmental System Analysis division at Chalmers University of Technology, Gothenburg, Sweden, with Minesto as the main data provider. LCA is a well-established tool to assess a range of environmental impacts of a technical system (Baumann & Tillman, 2004). This initial LCA is intended to provide first indications of the environmental performance of the Deep Green Utility (DGU) tidal current power plant. This study is designed so results may guide and influence the design of hardware and operational procedures of the power plant as well as provide a benchmark compared to other electricity power generation technologies. Deliverables of the PowerKite project use a prototype design as starting-point and some of the conclusions will therefore not fully represent the potential of the Deep Green technology.

At the time of writing, the first DGU power plant is being installed in Holyhead Deep in the waters west of Holyhead, Wales. A prospective model has been assessed based on the initial plans for the Holyhead site with an array of 24 kites, four tidal marine substation (TMS), PTO to grid cables, and an onshore workshop and grid substation. The generator rated capacity of the kites assessed is 500 kW, with assumed power productions ranging from 1 to 2 GWh/year per kite, corresponding to a total installed capacity of 12 MW and a capacity factor between 23% and 46%. Since the output might increase depending on the location (installing in a site with higher flows), an additional scenario reflecting a more favourable tidal site has been assessed with 18 kites with a rated capacity of 750 kW and a 3 GWh/yr average power output, corresponding to a total installed capacity of 13.5 MW and a 46% capacity factor. In a continuous ocean current, Deep Green can operate at a capacity factor in the range of 70-95%. Downtime is then only due to maintenance, not tidal cycles.

This cradle to grave LCA of the DGU power plant includes material resource extraction, processing, component manufacturing, power plant construction, operation, electricity distribution, maintenance, dismantling, waste management with recycling, and transports. The function assessed is one (1) kilowatt hour electric energy (kWhe) delivered to the end consumer. All environmental impacts are calculated based on this functional unit.

The resulting impacts of the DGU power plant is in range with other renewable technologies in the impact categories land occupation, non-renewable energy demand, global warming potential (GWP), freshwater eutrophication, freshwater ecotoxicity, and particulate matter formation. Our results indicate that there are no major concerns in terms of impacts from the DGU in relation to the aforementioned categories. It is well known that fossil fuel combustion technologies in general have a substantially worse environmental performance than renewable energy technologies in these categories. (Nuclear power has not been compared). An exception is the impact on terrestrial land occupation where in some cases PV, hydropower, and land based wind power, are performing less well. Sea area occupation might be a more relevant issue to assess for the DGU power plant but it is not included in this study as it is still debated how to account for this.

The total GWP impact of the Holyhead site, including grid distribution losses and emissions, ranges between 22 to 50 g CO_2 eq/kWhe, depending on different scenarios and uncertainties in the system. Assuming the same array in a continuous ocean current would result in 14 to 18 g CO_2 eq/kWhe. For the favourable site scenario, the GWP impact is 20 g CO_2 eq/kWhe. These results indicate that DGU power plant emissions are in the same range as other ocean energy technologies, with reported ranges for off-shore wind power from 15 to 105 g CO_2 eq/kWh (Uihlein, 2016) or 11 to 20 g CO_2 eq/kWhe (Hertwich et al., 2014). Significant contributors to the GWP are the frequent replacements of the tether, emissions from offshore vessels used for construction and maintenance as well as the concrete and steel material production for the gravity base foundations.

Another important indicator that has been derived is the energy return on investment (EROI). It describes the relationship between energy generated and energy required throughout the life cycle of the plant. The energy required includes non-renewable and renewable sources as well as chemically bound energy in plastic materials made from fossil carbon resources. The power plant lifetime divided by the EROI yields the energy payback time. The estimate for EROI at the Holyhead site was found to be between 4.6 to 8.7, which can be compared with that of the wind power plants ranging between 6.1 to 33.5 (Kubiszewski, Cleveland, & Endres, 2010). This corresponds to an energy payback period of 3 to 6 years for the DGU power plant. The major contributor to this energy demand is the maintenance phase, especially the manufacturing of the tether replacement parts, and the diesel used in on-site ships during construction and maintenance.

When examining the contributions from individual processes it is evident that three main activities namely diesel combustion, steel production and utility electricity generation contribute significantly to a range of impact categories. The diesel combustion refers to fuel combustion mainly for construction and maintenance offshore vessel trips. Impact from steel production is directly connected to the amount of steel that is needed in components including replacement needs during maintenance. Emissions from utility electricity generation is mainly due to the use of fossil fuel technologies in the UK electricity mix, in this system mainly consumed by material production.

To improve the environmental performance of the DGU power plant system assessed in this LCA, the results points to that focus should be put foremost on a high capacity factor; less material-intensive kite foundation and mooring system; efficient offshore vessel utilisation during construction and maintenance, and possibilities of using alternatives to diesel fuel; lower material requirements, mainly steel, while not reducing component life-times; investigate possibilities to extend the lifetime of the tether and using recyclable materials; and strive for high recycling of steel and copper.

Since the Deep Green technology is still at a very early stage of development, improvements of its technical and environmental performance are expected. This LCA concludes that the environmental performance of the DGU power plant is in the same range as other renewable technologies. The environmental performance of DGU technology is likely to improve significantly with the development of the technology as, according to Arvesen and Hertwich (2012), there are strong economies of scale for wind turbines with power ratings up to 1 MW. Other possible gains from upscaling would be increasing the array (adding more kites), likely reducing common parts needed per kWhe, as well as more efficient component manufacturing from large scale implementation of the technology.

2. Background

The Deep Green Utility (DGU) is a novel technology consisting of underwater wings anchored to the ocean floor, moving like kites due to a current. Figure 1 shows an illustration of the DGU kite concept. The majority of global tidal currents move with a slow velocity of 2.5 m/s or less. Since the kite moves continuously in a pattern of a horizontal figure 8 perpendicular to the current, the flow velocity at the turbine is greater than the current velocity. Hence, it can operate efficiently at such slow-character currents. This unique ability compared to stationary designs enables electricity generation from a vast, yet untapped, predictable ocean energy potential (Minesto, 2018a).

Figure 1. Illustration of the Deep Green tidal current kite concept (Minesto).

The DGU technology is still in a relatively early phase of its development; a first DGU tidal current power plant is being installed at Holyhead Deep in the waters west of Holy Island, Wales, UK (Minesto, 2018b). A map of the location is shown in Figure 2 where the red polygon outlines the development area and the green circle indicates the placement of the first kite.

According to the Offshore Valuation Group (2010), a higher capacity of the tidal range and tidal stream power plants should be added in the UK offshore mix to be able to reach the target of 29% offshore renewables within the UK energy mix by 2050.

"PowerKite – Power Take-Off System for a Subsea Tidal Kite" is a project to develop and assess the DGU system. The project runs 2016 to 2018 within the EU's Horizon 2020 research and innovation programme (EC, 2016). Minesto is the company in charge of the design and development of the DGU power plant. Minesto is located in Sweden (Minesto AB) and UK (Minesto UK Ltd). To investigate the overall environmental performance of the DGU system, a cradle-to-grave life cycle assessment (LCA) was included in PowerKite. The LCA has been conducted by the Division of Environmental Systems Analysis at Chalmers University of Technology in collaboration with Minesto, serving as the main data provider. Additional environmental studies within the project include in-situ measurements of impacts on the local ecosystem. These are headed by Queen's University of Belfast and reported separately from this LCA in deliverable D6.2 Environmental Impact Report due Dec. 2018.

The PowerKite project was intended to build on design and operational experiences from the DG500 project, which was planned to precede PowerKite. DG500 comprises an initial demonstrator installation at Holyhead Deep with a single 500 kW prototype kite connected to a self-contained micro grid buoy acting as load dump and control station (Minesto, 2018b). However, these two projects have practically been executed in parallel. As a result, the PowerKite project has progressed into a situation where the prototype DG500 design and corresponding initial array configuration designs has been used for various analysis and benchmarking purposes. Consequently, deliverables from the PowerKite project are based on a prototype design, hence the full potential of the Deep Green technology may not be fully represented by the PowerKite deliverable reports.

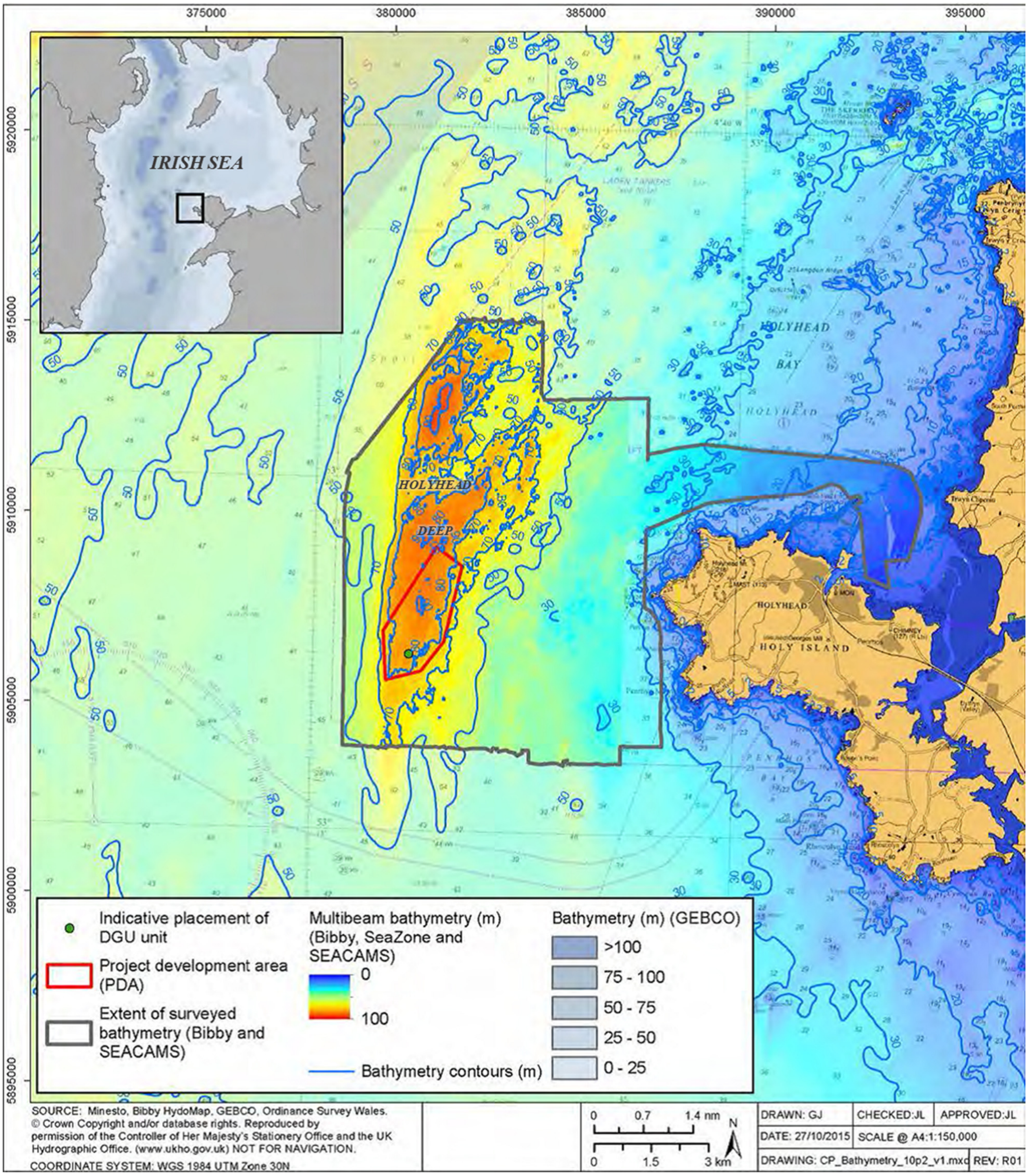

Figure 2. Map of the Holyhead Deep site for the DGU power plant. (The green circle indicates only the location of the first kite.) (Minesto, 2016).

The early development phase has advantages in terms of environmental research and development of the technology, because of the flexibility of the design and the lower costs associated with any design changes. Thus, a prospective LCA has now been carried out to provide a first benchmark to be able to compare the DGU with other electricity production technologies, and to be able to guide the ongoing development process towards improved environmental performance. Arvidsson et al. (2017) suggested a framework for performing a prospective LCA for emerging technologies, which was used in this study. This mainly implies modelling the foreground system with different scenarios, and methods to fill data gaps. Since no utility-scale DGU power plant is yet in operation, some quantities used in the study needed to be based on other LCA studies, estimates, and design concepts.

The life cycle technical scope of the assessed DGU array is based on the International Environmental Product Declaration (EPD) system, with defined Product Category Rules (PCR). The PCR applied here is that of electricity, steam, and hot/cold water generation and distribution (EPD, 2015). The EPD system is intended for products on the market where data are required to be obtained from measurements of actual products and production systems. The early development stage of the DGU and the prospective nature of this study makes it impossible to follow such data quality requirements. The intention of applying the PCR at this early stage is to follow a documented modelling structure to enhance transparency and comparability of our results with other LCA studies on electricity generation technologies. Furthermore, Hertwich et al. (2014) made an extensive comparison of environmental performance of a range of electricity production technologies. To enable a comparison with these technologies, our study aligns with the study by Hertwich et al. in terms of impact categories and impact assessment methods applied there. Additional impact categories and inventory results required by the PCR are also assessed apart from waste quantities due to substantial data gaps.

Our LCA is based on a future DGU array consisting of 24 kites as an initially planned stage of the full installation at Holyhead Deep with a total installed capacity of 80 MW (Minesto, 2018b). Each kite has a rated power of 500 kW, totalling 12 MW for the array. Based on prototype testing in Northern Ireland, Minesto estimates each kite to generate an average power output (including internal power plant transmission losses and stalls for maintenance, etc.) of ca 2 GWh/yr, corresponding to a 46% capacity factor, for the Holyhead Deep site. The actual output is still uncertain and hence a rather wide range from at least 1 GWh/yr per kite is assumed.

The Deep Green technology is also suitable for continuous ocean currents where a higher power production can be expected compared to tidal since downtime is then only due to maintenance, not tidal cycles. In such continuous currents the Deep Green can operate at a capacity factor in the range of 70-95% according to Minesto (2018c).

3. Goal and Scope

3.1 Goal of study

The goal of this LCA is to assess the environmental performance of a DGU tidal current power plant planned to be installed at Holyhead Deep, Wales, UK. It is intended to give a first indication of how this new technology compares with previous studies on other electricity production technologies. Further, it is intended to provide early guidance to the ongoing design and development process.

To produce results comparable with related studies on electricity production technologies this study is based on the technical scope defined in the PCR for electricity production technologies defined in International EPD System (EPD, 2015), (hereafter referred to as PCR). However, due to the prospective nature of this study, it is not possible to follow all requirements in the PCR including data quality requirements. Impacts and inventory results specified by the PCR are reported unless data is insufficient. Furthermore, the study aligns with impact categories and impact assessment methods applied by Hertwich et al. (2014) (hereafter referred to as H14) enabling a comparison with the environmental performance of related technologies reported there.

Since the power plant is still in the planning and development stage assumptions about the technical requirements and performance are needed. To meet these inherent uncertainties the study is based on a set of scenarios where dominating aspects assessed during the study are varied. A given scenario aspect is the power output which has been varied between a conservative assumption of 1 GWh/yr per kite to an estimated base case assumption of 2 GWh/yr per kite at Holyhead Deep.

3.2 Scope

3.2.1 Functional unit

One (1) kWhe of electricity delivered to the consumer, as defined for electricity production technologies in the PCR. The consumption is assumed to occur within the UK grid.

3.2.2 Type of LCA

This is a prospective study of a power plant that is, at the time of writing, in its first prototype stage for utility scale. Hence a prospective approach has been taken regarding the foreground system, i.e. projections and assumptions are by necessity made regarding the design and technical performance of this technology. However, to our knowledge, this is the first LCA of this type of technology and hence an accounting stand-alone approach was applied to get a first indication of the environmental performance of the technology itself. Furthermore, this novel technology still works on a very small scale. This means that the background energy system is assumed to be unaffected by the addition of this power plant on the electricity market and no further projections of potential future changes in the background during the lifetime of the power plant has been assumed.

3.2.3 Technical scope and boundary

According to the PCR, the system is divided into 3 parts: upstream, core, and downstream. The core consists of the material and component production, construction, operation (electricity generation), maintenance, and decommissioning of the power plant. The upstream processes include the production and infrastructure of the consumables including fuel used for on-site vessel trips. The downstream processes include the electricity distribution to the consumer together with its infrastructure. An overview flowchart is shown in figure 3.

The foreground modelling covers the core processes including power plant construction, power plant operation, power plant dismantling, reserve power (including test equipment), and maintenance. The component manufacturing modelling was based predominantly on data reported from Minesto, while some sub-level component models were based on published LCI data or reference background data. No reinvestments have been considered.

For inventory data of the background system the LCA reference database ecoinvent v3.3 was used. It includes upstream and downstream processes as well as material extraction, and waste management. All auxiliary energy used by the modelled system (i.e. not produced by the DGU tidal current power plant) including fuel and electricity production are hence based on reference data from ecoinvent.

Transport distances between foreground processes are based on data reported by Minesto. Reference data are used for applicable transportation vehicles. Other transports are fully based on reference data. It should be noted that offshore vessel trips for construction, operation, maintenance and dismantling on site are modelled separately from other transports.

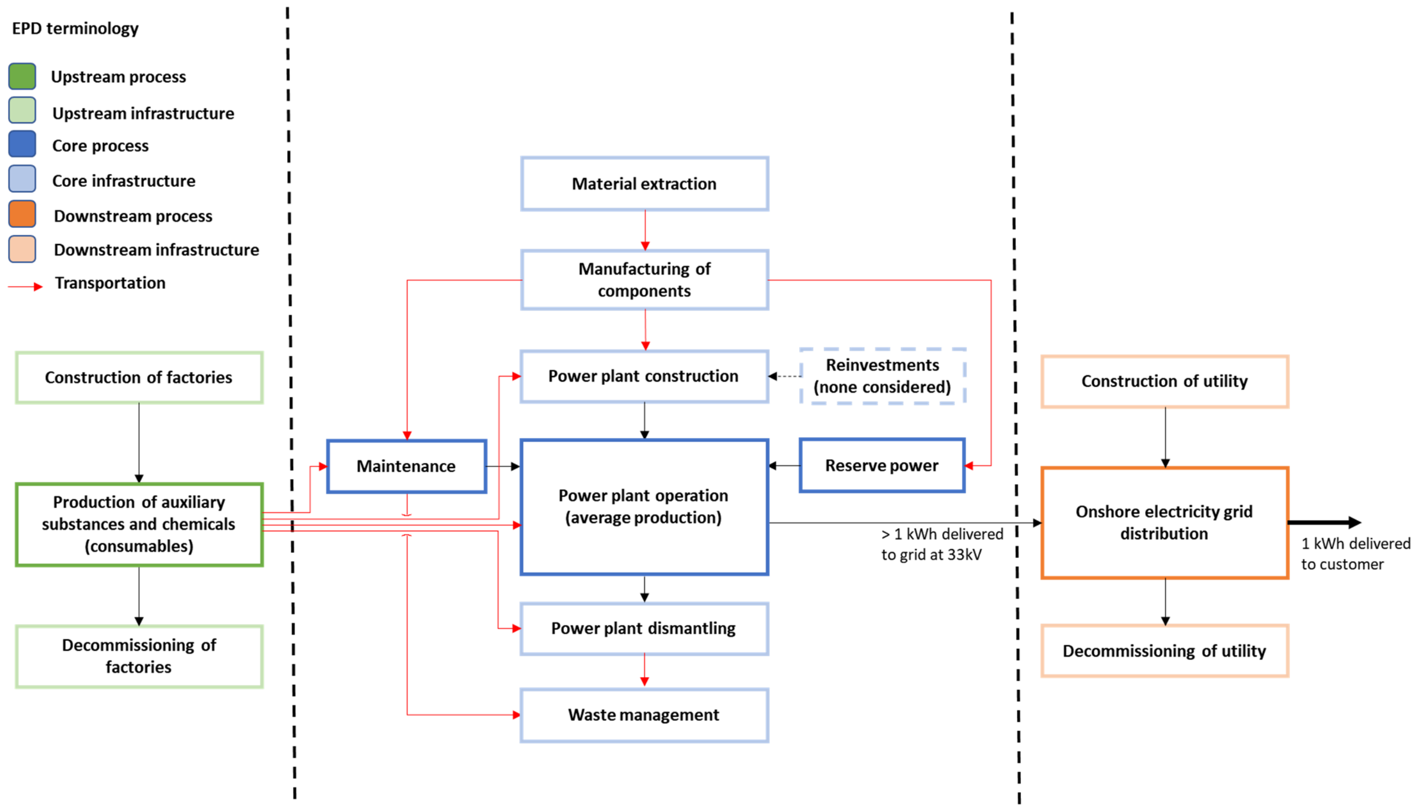

Figure 3. Overview flowchart of the inventory model for the DGU tidal current power plant based on the PCR.

3.2.4 Geographical system boundaries

This is a site-specific study of the planned power plant at Holyhead Deep, west of Holy island, Wales, UK. The natural conditions, including available tidal current speeds, distance to shore, etc. affect the performance of the power plant and will differ substantially from site to site. We have also in one scenario assumed another site with other hydrogeological conditions than at the Holyhead site favouring the power output of the DGU.

Data for the raw material extraction and refinement is based on models for European markets. The manufacturing was assumed to take place both in Sweden and UK, thus the electricity data used is according to the low voltage electricity market in these countries.

The distribution and consumption of the generated electricity was assumed to be on the UK grid.

3.2.5 Time boundaries

The LCA model in this study corresponds to a future DGU tidal current power plant with an expected lifetime of 25 years. However, the system (including the background system) was modelled based on the current state of technology, i.e. no further adjustments have been done to account for potential future changes. In this sense the model is valid for the state of technology in 2018. See also 3.2.2.

3.2.6 Impact categories assessed

The choice of impact categories assessed in this study is based on impact categories and impact assessment methods reported in H14 and, in addition, acidification potential and photochemical ozone-creation potential (POCP) according to the PCR. Most of the categories are calculated according to the ReCiPe impact assessment method (Huijbregts et al., 2016). Impacts on resource requirements are based directly on LCI results while non-renewable energy demand has been calculated based on the cumulative energy demand (CED) category as suggested by ecoinvent (Weidema et al., 2013) and in accordance with H14. Further reporting of inventory results including waste generated as required by the PCR have not been fully assessed mainly due to the uncertainty of available data. The categories assessed in this study are given in table 1.

Table 1. Impact categories assessed in this LCA (Huijbregts, et al., 2016; Weidema et al., 2013).

Impact category	Indicator unit	IA-Method applied
Material requirements:		
Aluminium	g	LCI result
Cement	g	LCI result
Copper	g	LCI result
Iron	g	LCI result
Non-renewable energy demand	MJ	CED 1.0.1
Land occupation	m^2yr	ReCiPe H v1.11
Global Warming Potential (GWP)	g CO_2 eq	ReCiPe H v1.11
Acidification potential	g SO_2 eq	ReCiPe H v1.11
Freshwater eutrophication potential	mg P eq	ReCiPe H v1.11
Freshwater ecotoxicity	g 1,4DB eq	ReCiPe H v1.11
Photochemical ozone-creation potential (POCP)	g C_2H_4 eq	ReCiPe H v1.05
Particulate matter formation	g PM_{10} eq	ReCiPe H v1.11

Hertwich et al (H14) reports aluminium, cement, copper and iron requirements for different electricity generating technologies. Resource demand is provided directly from the life cycle inventory (LCI) result. We report the required aluminium, copper, and iron contained in ore resources, and, for cement, we add the intermediary cement product flows of calcium carbonate, dolomite, and gypsum in accordance with H14. Recycling rates are assumed only for steel 90%, and copper 95%, based on previous studies, see also 3.2.8.

Non-renewable energy demand is the amount of energy (MJ) contained in fossil and nuclear fuel that is consumed by the system. We include chemically bound energy in materials, mainly plastics, made from fossil carbon resources. An additional key result determined by the study was the energy return on investment (EROI) which is the amount of energy delivered by the power plant divided by the total energy required to deliver that energy (including renewable electricity and chemically bound energy in materials, equation 1). The lifetime of the power plant divided by EROI yields the energy payback time, i.e. the time it takes to generate sufficient electric energy from this technology to cover the energy used in the life cycle of the system (equation 2).

Eq 1. $$EROI = \frac{Energy\ delivered}{Energy\ required\ to\ deliver}$$

Eq 2. $$Energy\ payback\ time = \frac{Powerplant\ lifetime}{EROI}$$

Land occupation is an impact category indicating potential habitat loss for natural terrestrial ecosystems expressed in m^2yr. It is the amount of surface area occupied by the system during a given time span of 1 year. We emphasize that the offshore area is not covered by the impact model but may be a more relevant indicator of habitat loss for this technology. There is currently no consensus on methodology on how to account for potential water body habitat losses.

Global Warming Potential (GWP) is the most common impact category used, and is expressed in units of CO_2 equivalents, i.e. as emissions of greenhouse gases expressed as if it was all emitted as carbon dioxide. The timeframe is impacts occurring within 100 years. This serves as the main benchmark reference with other technologies with the same functional unit.

Acidification potential is required by the PCR. It is a measure of how much the function contributes to lowering of pH in ecosystems with subsequent damage to species and water quality. It is expressed as if all acidifying emissions were emitted as sulphur dioxide, SO_2 eq.

Freshwater eutrophication potential is required by the PCR and reported in H14. It is a measure of added nutrition to freshwater bodies with subsequent increased primary production of aquatic plants (often microalgae) causing overgrowth and displacement of species, oxygen depletion and reduced water quality. To align with H14 we apply the ReCiPe method where it is expressed as if all emissions contributing to eutrophication were emitted as elemental phosphorous, P eq. The PCR requests this category to be reported in units of phosphate equivalents, PO_4^{3-} eq. Impact results can easily be converted on a mole mass basis (approximately divide P eq impacts by 3 to yield PO_4^{3-} eq impacts).

Freshwater ecotoxicity is expressed as if all emissions contributing to this category were emitted as dichlorobenzene, 1,4DB eq. This category considers exposure and effects of toxic substances that, through natural processes, ends up in freshwater bodies. Ecotoxicity impacts in other environmental compartments such as marine water or soil are not provided in H14. Quantifying total indirect toxic impacts is a very complex task due to large variations of natural processes operating on different substances. The PCR only requires that "LCI emissions of toxic substances" shall be reported.

Photochemical ozone creation potential (POCP) is a category required by the PCR that considers the added creation of ozone at ground level (lower atmosphere) expressed as if all contributing emissions were emitted as ethylene C_2H_4 eq. This is an indicator of smog creation and associated damages.

Particulate matter formation is related to respiratory health problems. It is expressed as if all particles were emitted as particles with less than a 10µm diameter, PM_{10} eq. The PCR also states that emissions of particle matter shall be reported.

For the localized (on-site) environmental impacts on the marine ecosystem we refer to other studies conducted on tidal energy devices. Schuchert et al (2018) found that natural variations in photosynthetic active radiation in the coastal and inshore environment had larger effects on phytoplankton dynamics than from changes in hydrodynamics as a result of an array of tidal devices. Kregting et al. (2016) also concluded that the generation of electricity using tidal arrays is unlikely to influence the benthic communities in high flow environments. See also PowerKite project deliverable D6.2 Environmental Impact Report due Dec 2018.

3.2.7 Data quality and collection

For the foreground model, whenever it was possible, specific data were directly acquired from Minesto, based on their DGU prototype, planned maintenance schedule, stated transport distances, etc. Minesto also provided a value on a scale from 0 to 5 corresponding to the accuracy of the component material weight data. Additional sources to fill data gaps where collected from other LCA studies, mainly LCAs of Wind power farms in Europe and EPDs of components.

The background data including upstream material and energy production was mainly collected LCI reference data from the ecoinvent database v3.3.

The LCA software openLCA was used for inventory and impact calculations based on data entry of the foreground process model with links to ecoinvent process data as specified in Appendix 2.

3.2.8 Assumptions and limitations

The major limitation in the study is that it is based on a prospective technology, where a significant proportion of the data cannot be measured, thus several assumptions have been necessary. The modelling was based on the current state of the DGU technology and no projections of potential future improvements or reinvestment have been considered. Scenarios have been modelled to assess how decisions on design and ocean current conditions would affect the environmental performance. A further limitation is that the background system is modelled as being unaffected by the DGU power plant and remains static during the lifetime of the system.

The main uncertainties are in data concerning the use phase and the end-of-life phase, whereas the production and installation stages have reasonably good data coverage. Where no data on foreground processes was available from Minesto assumptions have been based on other similar studies. A large uncertainty aspect is the capacity factor. To assess how this affects the results a set of scenarios has been defined where each kite generates between 1 and 3 GWh/year, depending on site and rated generator capacity. For the Holyhead site the likely output is assumed between 1 to 2 GWh/yr from a 500 kW rated kite. Another important uncertain parameter is the amount of maintenance vessel trips required, where Minesto has assumed a scenario for routine and non-routine trips. Recycling rates were assumed for copper and steel based on previous studies (Haapala & Prempreeda, 2014; Yang et al., 2018). The recycled steel and copper is assumed to reduce the need for production of virgin materials, which implies that the recycled material could be used in the construction of the system components. Assumptions in previous studies about recycling rates of other materials are generally not explicitly stated and vary. Hence, we make the conservative assumption that no other materials are recycled but go to landfills or incineration plants. Total waste quantities as required by the PCR have not been assessed due to substantial data gaps.

Electricity delivered to the grid from different technologies are assumed of equal quality and function. The added infrastructure and losses incurred from load balancing intermittent sources is in general not considered in LCA studies and in reference databases such as ecoinvent. While tidal power plants are intermittent they have a very predictable pattern of generated power and therefore could impose less load-balancing cost on the grid compared to wind and solar energy. The impact this has on the results and when comparing to other studies is not quantified.

4. Inventory Analysis

Inventory analysis comprises modelling and data collection of the life cycle inventory (LCI), including information of the technical processes and associated intermediate flows (products and waste) and elementary flows (natural re-sources and emissions) within the scope of this study. All flows are finally normalized per the functional unit of 1 kWhe delivered to consumer. The total LCI result is provided in Appendix 1.

During the study several iterations of inventory data collection and modelling, impact calculations, and interpretations have been conducted, to successively refine data on dominating aspects, as well as to define a set of relevant aspects for different scenarios. Impacts on GWP has mainly been used to benchmark intermediate results and define the dominating aspects.

4.1 Foreground model

The division between foreground and background is stated in 3.2.3 Technical scope and boundary. Here follows a more detailed description of data collection and modelling of the foreground processes.

4.1.1 Power plant overview

The inventory model was based on a power plant design consisting of an array of 24 kites in an optimised hexagonal pattern. It is the initial stage of the planned full implementation of the Holyhead DGU power plant derived from the prototype DG500 design.

Each kite is assumed to have a rated power of 500 kW, totalling 12MW for the complete array installation. Four Tidal Marine Substations (TMS) connect 6 kites each by a low voltage umbilical cable. Three of the TMSes are connected to a combined TMS and sub-hub with 33kV TMS-TMS cables. The TMS/sub-hub connects to the onshore sub-station with a 33kV export cable. The onshore substation connects the DGU power plant to the UK grid at 33kV, which distributes the electricity to the end consumer. The grid is modelled from background data. Figure 4 shows a schematic outline of the arrangement. In total the system is assumed to include 26 kites, since 2 spare kites, are used for swap-out during maintenance.

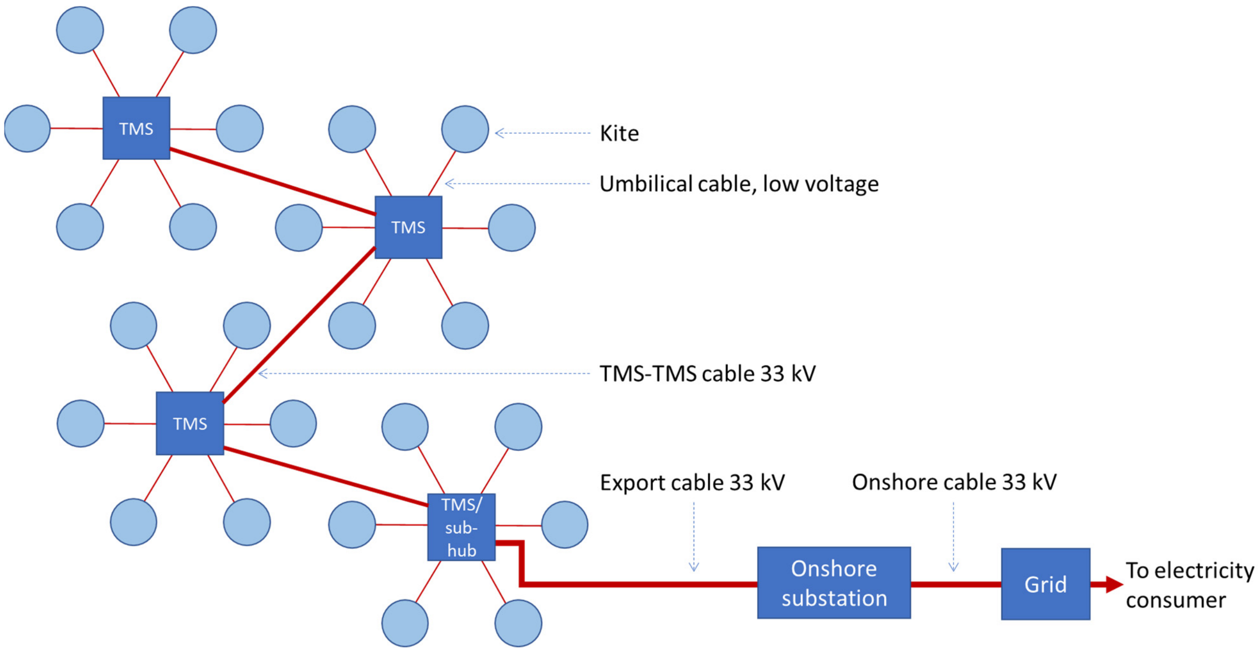

Figure 4. Schematic outline of the DGU tidal current power plant model assessed in this LCA.

At the time of writing other designs based on kites each with 750 kW rated power were being considered. According to Minesto, while a different design would substantially improve the power output, this would likely not change the material requirements significantly. Consequently, this redesigned system would likely have a better environmental performance than the system assessed here.

4.1.2 Scenario aspects

Since the functional unit is kWhe the environmental impact of the power plant is inversely proportional to the amount of electricity generated and sent to the grid. The direct emissions from the downstream grid infrastructure and distribution are however unaffected by the efficiency of the power plant. The rated power of each kite is 500 kW, which, with an ideal 100% output, corresponds to 4.38 GWh/yr per kite respectively. According to Minesto a realistic assumption for the average power output at the Holyhead site, including maintenance stops, was set as 2 GWh/yr per kite. A range from a pessimistic scenario of 1 GWh/yr to a Base case scenario of 2 GWh/yr was defined for the Holyhead site (see also Goal of study 3.1). This corresponds to a capacity factor range between 23% to 46%. As a hypothetical thought-experiment an optimistic scenario of 3 GWh/yr per kite was also defined with the same array configuration as at Holyhead Deep.

The assumption of a 3 GWh/yr power output from a 500 kW rated kite is unlikely to be met at the Holyhead site but could possibly be reached at other locations with more favourable current conditions such as continuous ocean currents. To assess the full potential of the DGU system location a scenario was defined that more realistically would yield such a high output in a tidal current. This favourable site scenario is characterized by stronger tidal currents close to shore and the electrical equipment of the TMSes are placed in the onshore substation. For this favourable site an array of 18 kites, each rated at 750 kW with 3 GWh/yr power output, has been assumed.

Further scenario aspects defined here are a result of the iterative approach. Early on it was evident that the foundations anchoring the kite to the seafloor (also referred to Gravity Base Foundations, GBF), contribute significantly to the impact on GWP. Three different GBF designs has therefore been assessed, Concrete, Steel, and Hybrid, see also 4.1.4.

The durability of the moving part components is still uncertain. An initial conservative assumption was set to 5 years for the tether lifetime. As the tether bulk material is assumed not to be recycled this yields a significant impact from the maintenance process. A scenario was therefore assessed where the tether lifetime parameter was doubled to 10 years to see how this would affect the overall results.

In addition to the scenario aspects assessed there are currently three options concerning how subsea and onshore cables are to be installed as shown in 4.1.6, figure 11. For this study, the shortest offshore cable path (middle path) was assumed. Further aspects that are likely relevant but have not been assessed would be material recycling rates mainly of steel, copper, and tether plastics as well as assumptions on maintenance trip schedule.

4.1.2.1 Scenario definitions

The Base case scenario was defined as assuming:

- Holyhead site and tidal conditions;
- 500 kW rated power per kite;
- 2 GWh/yr power output per kite;
- 24 kite array installed, 2 complete spare kites on shore (26 in total)
- Concrete foundation GBF design;
- no GBF re-use;
- tether lifetime of 5 years.

This represents a power plant with 12 MW installed capacity and average power output of 5.48 MW, corresponding to a 46% capacity factor.

Assumptions made for all scenarios are given in table 2. Scenarios 2 to 7 are variants of the Base case while the favourable site is assumed to be populated by 18 kites, each rated 750 kW (13,5 MW installed power); no TMS buoys; all transformers in a three times larger substation building; double length of umbilical cable; no TMS-TMS cables nor sub-sea export cable; and reduced number of required vessel trips due to reduced offshore equipment. All other assumptions remain as the Base case.

Table 2. Definition of scenarios assessed for GWP.

Scenario	Kite power rating, kW	Kite avg. power output, GWh/yr	Kite array, pcs[i]	GBF type	GBF re-use	Tether lifetime, yr	TMS, pcs
1 Base case	500	2	24	Concrete	no	5	4
2 BT	500	2	24	Concrete	no	10	4
3 BTR	500	2	24	Concrete	yes	10	4
4 Bsteel	500	2	24	Steel	no	5	4
5 Bhybrid	500	2	24	Hybrid	no	5	4
6 Optimistic	500[ii]	3[ii]	24	Concrete	no	5	4
7 Pessimistic	500	1	24	Concrete	no	5	4
8 Favourable site	750	3	18	Concrete	no	5	0

i) Two additional spare kites are included in each scenario.
ii) In the hypothetical optimistic scenario an identical configuration as the Base case is assumed. However, a 3 GWh/yr power output would require a greater generator power rating and/or a significantly more favourable location than Holyhead Deep.

Wherever data and calculated results are presented further on they represent the Base case, if nothing else is stated.

4.1.3 Kite and umbilical system

The core component of the DGU tidal current power plant is the Kite, i.e. the PTO unit. It consists of a wing, turbine, nacelle, rudder, struts, and top joint that connects to the tether. Figure 5 illustrates the main components of the kite. The wing is used to create lift and propulsive force for the power plant. It mainly consists of a composite structure and metal insert points for attachment to the nacelle and the struts. Guided by the rudders the kite rides the ocean current in a continuous lying figure 8 pattern.

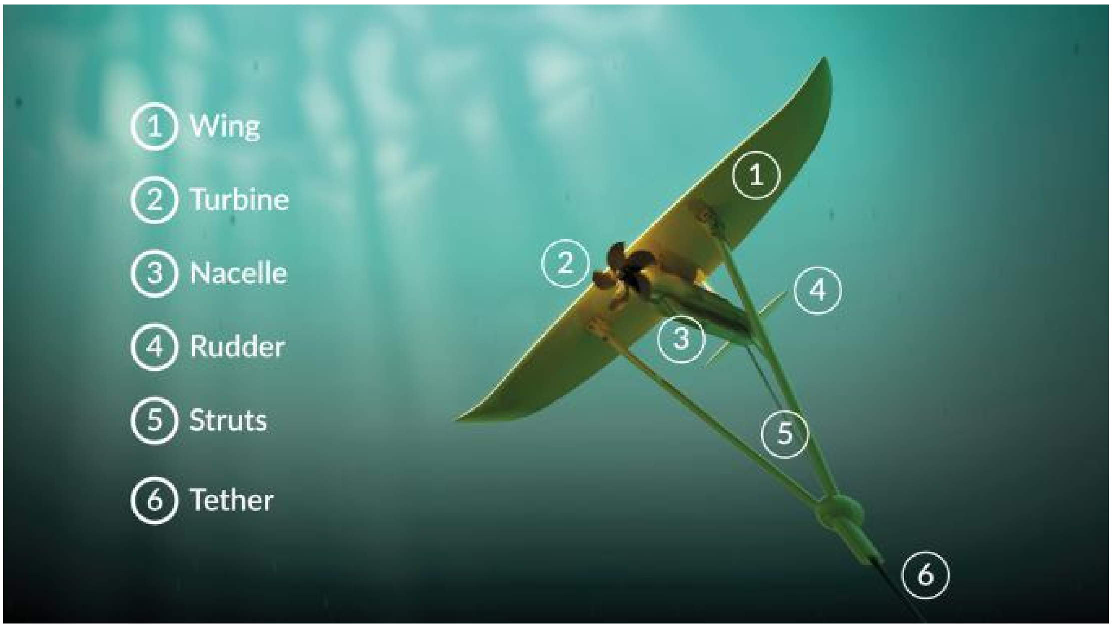

Figure 5. Illustration of the kite and its components (Minesto).

The nacelle is a steel housing that encapsulates the electronic equipment, including a generator, a gearbox, and two converters. This system transforms the kinetic energy of the turbine to electrical energy which is transferred through the umbilical cable in the tether. It also includes sensors and electronics for controlling the rudder and providing kite performance control data. The front struts connect the wing to the top joint and transfer most of the tether load. The top joint connects the kite to the tether system.

The tether system consists of the tether fairing, the tether rope, the umbilical cable including power and communication signal cables. The rope bears the bulk load in the tether system. It connects the tether to the kite at the top joint and to the GBF at the bottom joint. The tether fairing made of various plastic materials covers the rope cables while also providing low flow resistance. A cross-section of an early design of the fairing is shown in figure 6. Manufacturing of the tether involves significant energy demand during the polyurethane curing.

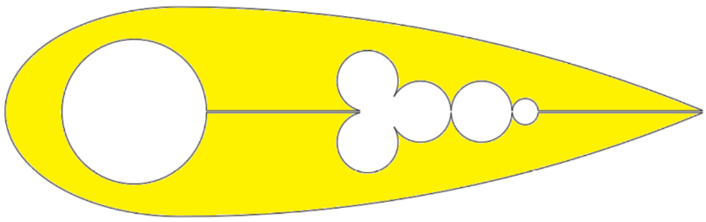

Figure 6. Cross-section view of a tether fairing, showing the spacing for the rope and cables (Minesto).

The bottom joint, illustrated in figure 7, connects the end of tether to the gravity base foundation.

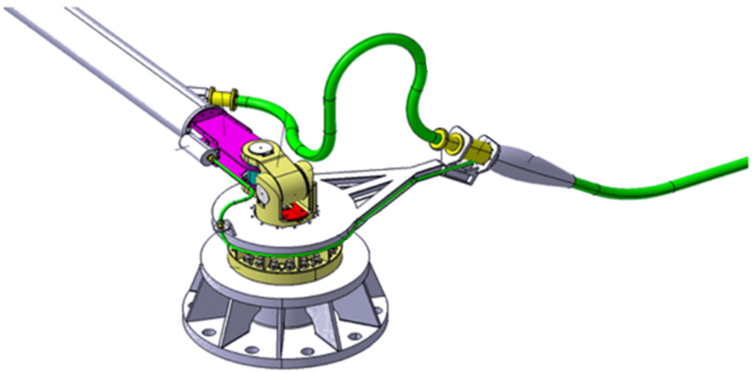

Figure 7. illustration of the Bottom joint (Minesto).

The data for the kite materials has mainly been provided by Minesto. Additional data for the converter and the generator has been taken from both ABB EPDs for ACS 600 frequency converter (2001) and DMI type DC machine (2000) respectively, scaled to match the onboard components. Data (mainly VOC emissions) for the paint was taken from Jotun data sheet (2017), and for the carbon fibre from Romaniv (2013). Table 3 gives material requirements per kite and umbilical system. Resin includes epoxy, PVC, and polyester resin.

Table 3. Material requirements for the kite and umbilical system.

Material	per 1 kite and umbilical (kg)
Steel, unalloyed	590
Steel, chromium	3 020
Steel, low-alloyed	8 500
Copper	3 470
Aluminium	150
Carbon fibre	790
Glass fibre	2 100
Polystyrene	1 520
Resin	710
Polyethylene	8 330
Polyurethane	3 900
Polypropylene	80

4.1.4 Gravity base foundation

The GBF anchors the kite to the seafloor. Three different GBF designs have been assessed, see also 4.1.2.1 Scenario definitions. The first GBF design (Base case) is a concrete block with steel reinforcement, illustrated in figure 8.

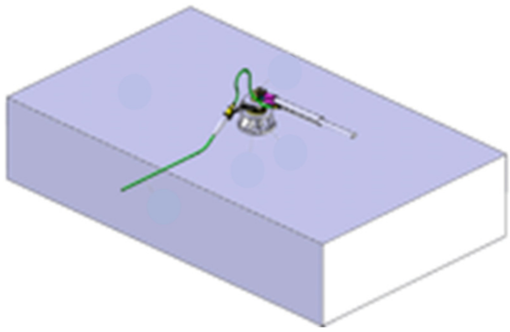

Figure 8. Illustration of the reinforced concrete foundation of the Base case with the bottom joint mounted on top (Minesto).

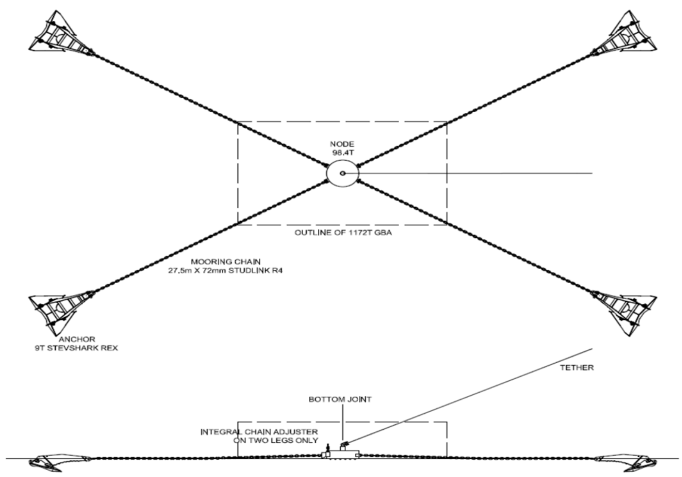

Figure 9. Illustration of two alternative designs – steel and hybrid - of the Gravity Base Foundation (Minesto).

The other two alternatives are based on the designs illustrated in figure 9. The steel foundation consists of a steel based centre node with 4 steel mooring chains and anchors. The hybrid foundation is similar to the steel foundation;

however, the centre node is based on a concrete block with steel reinforcement. The main material requirements for the three optional GBF designs are provided in table 4.

Table 4. Material requirements for the three alternative GBF designs.

Material	Gravity Base Foundation (tonne)		
	Concrete foundation (Base case)	Steel foundation	Hybrid foundation
Steel, low-alloyed	5.7	84	64
Steel, un-alloyed	-	100	-
Concrete	1 100	-	290
Reinforcing steel	120	-	30

4.1.5 Tidal Marine Substation and Sub-hub

The Tidal Marine Substation (TMS) shown in figure 10 is used to receive the energy from the kites (6 kites per TMS in this system) through the kites' umbilical cables, and step-up the voltage to 33 kV through a transformer. The TMS buoy is anchored to a clump weight (made of recycled steel) using polyester mooring lines. The output of this transformer is sent to the sub-hub, which in our case is one of the TMSes, through the TMS-TMS cable. The final output of the sub-hub is sent to the onshore station through subsea export cables. Table 5 shows the material requirements for each TMS. The transformers used were modelled according to the ABB EPD for large distribution transformer (2003), adjusted to the power levels of the DGU system.

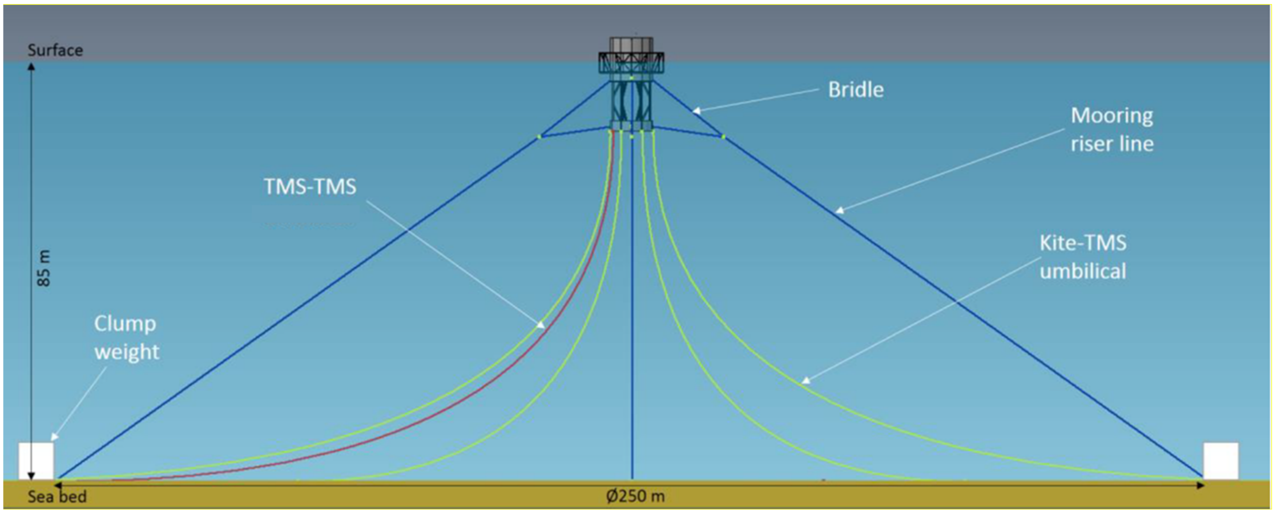

Figure 10. Illustration of Tidal Marine Substation buoy (Minesto).

Table 5. Material requirements for the TMS.

Material	per 1 TMS (kg)
Steel, low alloyed	107 000
Steel, unalloyed	72 000
Steel, recycled	430 000
Concrete	17 000
Copper	3 500
Polyester	6 700
Polyethylene	340
Hydraulic oil	6 800

4.1.6 Cables

There are four types of main cable to transfer the electricity from the kite to the grid: the Umbilical cable, the TMS-TMS cable, the Export cable and the Onshore cable (see also figure 4 for a schematic outline of the cables).

The 500 m, low voltage umbilical cable connects to the kite at the top joint through the tether, but continue beyond the bottom joint on the seafloor where it connects with the TMS. The 33 kV TMS-TMS cables connects three of the TMSes to the sub-hub. (The sub-hub is in itself a TMS and hence needs no additional TMS-TMS cable.)

There are currently three options concerning how the 33 kV subsea and onshore cables are going to be installed, as shown in figure 11. For this study, the shortest offshore path (middle path) was assumed with an 8 000 m subsea export cable and an 4 500 m onshore cable.

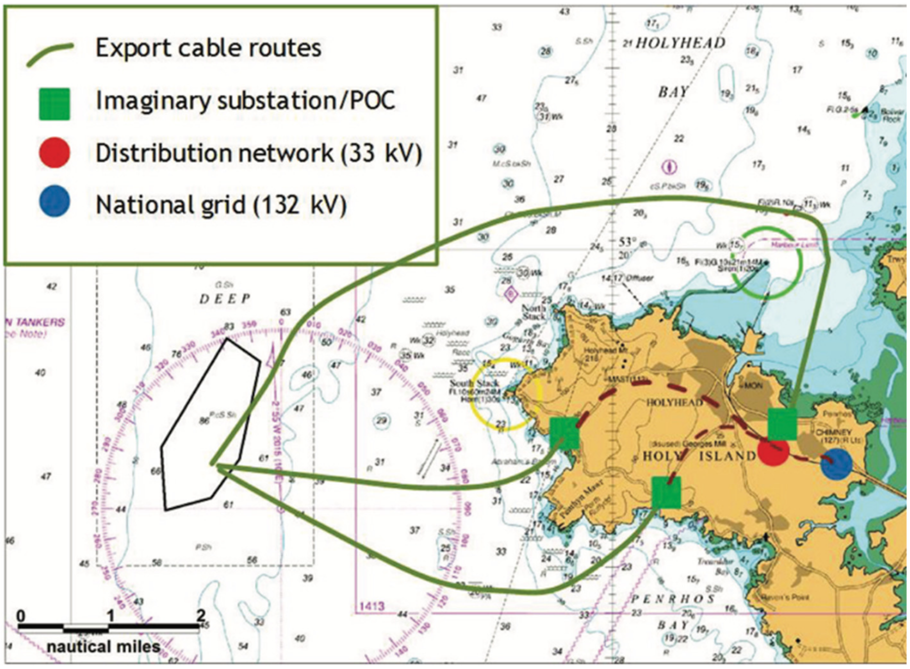

Figure 11. Options for offshore and onshore export cable routes (Minesto). The path with the shortest offshore export cable (middle) has been modelled in this study.

Data for the cables is based on technical data sheet from Nexans (2013). The main materials in the cables are shown in table 6. Material data for the umbilical cable is included in table 3.

Table 6. Cable material requirements in total. (Material for the umbilical cable is included in table 3).

	per 1 cable (kg)		
Material	TMS-TMS cable 1000 m (x3)	Export cable 8000 m (x1)	Onshore cable 4500 m (x1)
Copper	5 400	32 000	18 000
Steel	1 200	35 000	20 000
Polyethylene	16 000	110 000	59 000
Polyester	160	-	-
Polypropylene	-	6 200	3 500

4.1.7 Onshore substation

The main purpose of the onshore station (figure 12) is to connect the power plant with the grid. Various monitoring activities also take place there. Since the voltage is already at grid level after the TMS, no further transformation is needed. Next to the substation, there is a building for the maintenance of the kites, consisting of 2 bays for the current 12MW array. The houses were modelled with the provided dimensions using a building dataset from ecoinvent. For the electrical components, the reactor and earthing transformers were modelled according to the ABB EPD for large distribution transformer (2003). Table 7 shows the main components and materials for modelling of the onshore substation.

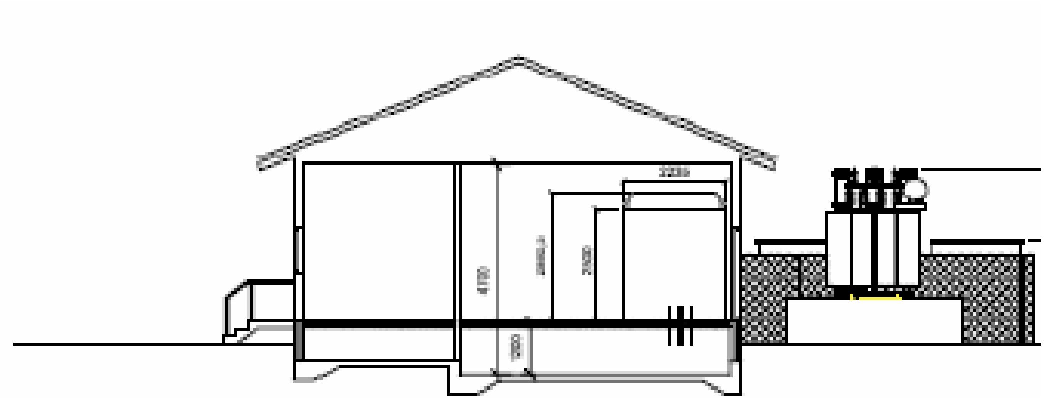

Figure 12. Illustration of the onshore substation (Minesto).

Table 7. Onshore substation component requirements in total

Material	Unit	Quantity
Substation buildings	m3	1 150
Road	m*yr	2 600
Aluminium	kg	16
Steel, low-alloyed	kg	4 000
Copper	kg	880
Polyethylene	kg	84
Hydraulic oil	kg	1 700

4.1.8 Power plant construction

The construction phase starts with the transportation of different parts of the DGU from the manufacturing site to Holyhead. Table 8 shows the source, distance, and mode of transportation for different parts.

Table 8. Data on transportation from component manufacturing to the shore on site at Holyhead.

Part	Source	Distance (km)	Mode of Transportation
Wing	Southampton, UK	480	trailer
Nacelle	Gothenburg, SE	1 200	lorry
Top Joint	UK	500	lorry
Struts	Gasport, UK	530	trailer
Umbilical	Norway	2 000	lorry
Tether	North Yorkshire, UK	300	lorry
Bottom Joint	Liverpool, UK	160	vessel
Offshore Foundation (Concrete)	Liverpool, UK	160	tugboat
Offshore Foundation (Steel)	Netherlands	1 800	vessel
Offshore Foundation (Hybrid)	Netherlands	1 800	vessel
TMS	UK	500	lorry

In the on-site construction phase different vessels are used to install different parts. This includes towing and installing kite foundations, deploying the tether with bottom joint and umbilical, deploying the TMS, and deploying the export cable. Assumptions on standby times for the vessels, where diesel consumption was less, were also included. Vessels include different tugboats, multicats, and ships. This phase was modelled by the diesel combustion used by the vessels according to Jivén et al. (2004). The total diesel needed for all the kites was approximately 820 tonnes.

4.1.9 Maintenance

The maintenance phase was also modelled as diesel used in vessels to perform routine and non-routine inspection and maintenance for the kite, buoy, and cables. This is done mainly by multicat vessels. The diesel needed for all the maintenance trips across the lifetime of the system is around 1160 tonnes. In the maintenance are also included the production of replacement parts and transportation of those parts to the site. The assumptions of replacement rates and lifetime for different parts was modelled according to table 9.

Table 9. Lifetime and replacement rate of components.

Part	Lifetime (years)	Replacement Rate (per year)
Wing	25	0%
Nacelle	10/25*	0/10%*
Top Joint	25	0%
Struts	25	0%
Umbilical cable	20	5%
Tether	5	20%
Bottom Joint	25	0%
Offshore Foundation	25	0%
TMS	25	0%

*) Lifetime of nacelle innards 10 years; other parts 25 years.

A scenario has been assessed where the life-time of the tether is doubled to 10 years to assess how this would improve the environmental performance (see 4.1.2.1).

The onshore maintenance building is modelled as part of the onshore substation.

4.1.10 Power plant dismantling

The decommissioning of the power plants was modelled as diesel used for vessels to remove different parts. The total diesel needed for that is around 420 tonnes. This phase also includes the transportation of different parts to different disposal facilities, which is assumed to be done using lorries for an average distance of 100 km.

4.1.11 Waste management model

Modelling the waste management of novel offshore energy technologies is problematic. Assumptions are necessary since almost none of the already deployed power plants (offshore wind farms for example) have yet reached their end-of-life stage (Andersen, Eriksson, Hillman & Wallhagen, 2016). But as an estimation, all the iron (including steel) is assumed to be recycled at a rate of 95% and copper at a rate of 90% (Haapala & Prempreeda, 2014; Yang et al., 2018). The only exceptions are the steel used for the clump weights and ballast anchor shackles for the TMS as well as ballast steel in the Steel GBF scenario which is not assumed to be recycled due to high uncertainty of recyclability of the lower quality steel made from scrap. The recycling was modelled as crediting the system by avoiding production of virgin material. Other waste materials are assumed to either be sent to landfills or incinerators, but no credits (or burdens) have been modelled due to the uncertainties.

Since the GBF contributes significantly to GWP a scenario was defined where the concrete GBF is re-used once (i.e. the GBF life-time is extended to 50 years) in another system, based on suggestions by Andersen et al. (2016) (referred to as scenario BTR in 5.4).

4.2 Background model

The background system comprises of an expansion of the product system to include e.g. resource extraction and electricity grid infrastructure, for the default product flow providers and recipients as defined in ecoinvent v3.3. The resulting system consists of around 11 200 processes and associated data sets. The background processes include:

- production of materials used in the core components;
- production of sub-components used in the core where material weight data was not provided by Minesto (see A.2.3);
- upstream production of consumables (fuels and chemicals);
- downstream grid distribution;
- auxiliary electricity generation;
- transports – truck, train, ship.

All background LCI datasets linked from the foreground are listed in Appendix 2. This includes datasets from ecoinvent as well as datasets modelled from other sources that in turn are linked to ecoinvent.

Downstream grid distribution losses add up to 7.2% according to the ecoinvent data on the UK grid.

4.3 LCI result

The LCI result consist of all elementary flows i.e. resources from and emissions to nature per kWhe from the total inventory model. It has been calculated from the completed inventory model in openLCA. A truncated list of the resulting flows contributing more than 1% to any of the impact categories assessed in this study is provided in Appendix 1.

5. Life Cycle Impact Assessment

Results on calculated impacts on the assessed impact categories (see 3.2.6) are reported here. For most of the impact results we have assumed a Base case of 2 GWh/yr average power output per kite which corresponds to a capacity factor of 46% with kites of 500kW rated power. Should it be the case that the actual outcome only meets the pessimistic scenario of 1 GWh/yr per kite (23% capacity factor with a kite rated 500 kW) all Base case impact results should be multiplied by 2. Similarly, if the output is 3 GWh/yr as in the optimistic scenario the Base case impacts should be multiplied by 2/3. The only small but not insignificant exception to this linear rule is the contribution to Global warming potential (GWP) impacts caused by direct emissions from the grid. These emissions are the same for each kWhe delivered to consumer regardless of the power output of the power plant. The grid losses, however, imply increased resource needs and emissions from the power plant; with losses calculated to 7.2% according to the ecoinvent background data the power plant must produce 1.072 kWhe per 1 kWhe to consumer. These added impacts due to grid losses are directly dependent on the power plant efficiency.

5.1 Impact overview

Table 10 shows the overall impact on all impact categories assessed from four scenarios (see 4.1.2.1)

Table 10. Total environmental impacts

Impact Category		**Impact, $kWhe^{-1}$**			
	Unit	Base	Bsteel	Bhybrid	Pessimistic
Aluminium req.	g	0.042	0.042	0.041	0.083
Cement req.	g	3.4	1.2	1.6	6.7
Copper req.	g	0.041	0.044	0.042	0.082
Iron req.	g	0.85	1.0	0.91	1.7
Non-renewable energy demand	MJ	0.41	0.40	0.39	0.82
Land occupation	m^2yr	0.0020	0.0018	0.0018	0.0040
Global warming potential	g CO2 eq	26.3	24.3	24.3	50.0
Acidification potential	g SO2 eq	0.20	0.20	0.20	0.40
Freshwater eutrophication potential	mg P eq	7.1	7.8	7.0	14
Freshwater ecotoxicity	g 1,4DB eq	0.42	0.49	0.42	0.84
Photochemical ozone-creation potential	g C2H4 eq	0.20	0.19	0.19	0.39
Particulate matter formation	g PM10 eq	0.075	0.070	0.070	0.15

To provide an overview of how the processes contribute to impact on mainstream LCA impact categories GWP, acidification potential, freshwater eutrophication potential, photochemical ozone-creation potential (POCP), and freshwater ecotoxicity, a normalized contribution diagram is presented in figure 13, and data is given in table 11. Each bar represents the impact on one category and colours represent different processes. As can be seen the material extraction and manufacturing of components as well as operation and maintenance are dominant in all categories. The "negative" impact refers to the avoided production of virgin material when steel and copper is recycled compared to not recycling at all.

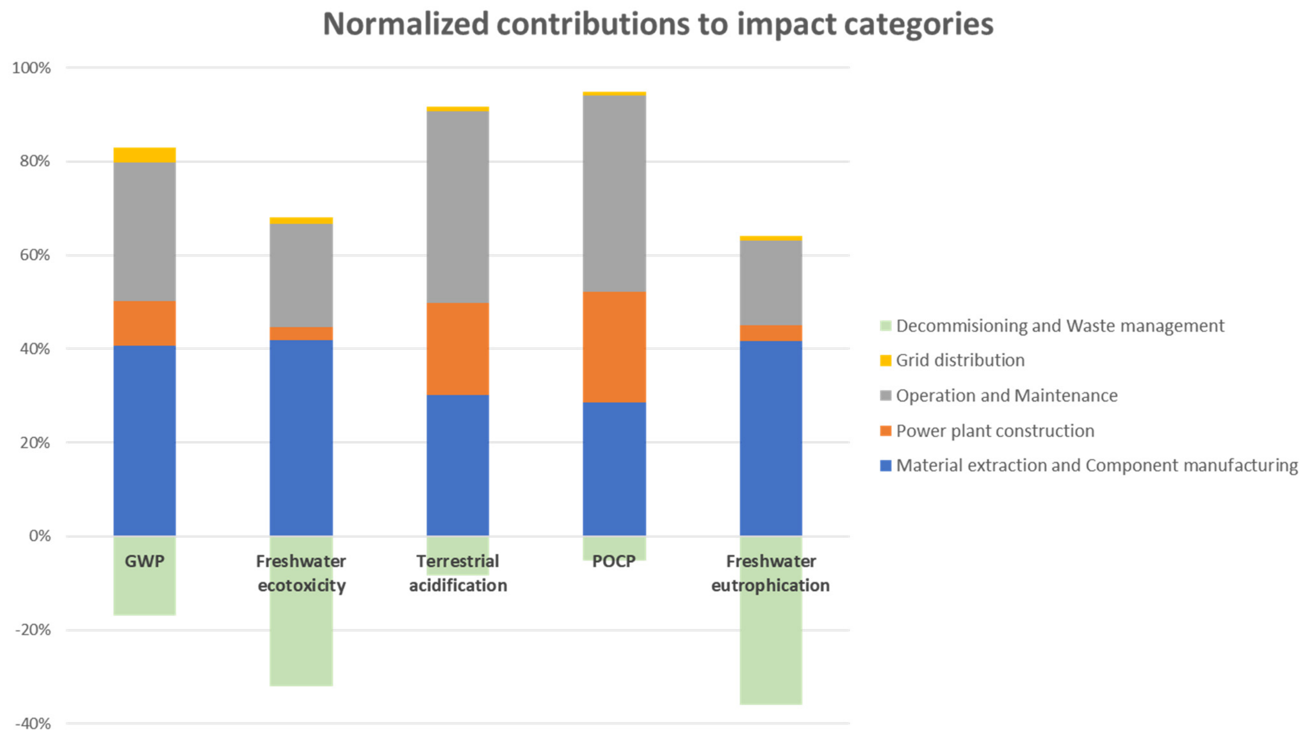

Figure 13. Overview of some assessed impact categories normalized to 100%, for the Base case scenario. The bar segments represent the different life-cycle stages. Processes contributing less than 1% are excluded.

Table 11. Overview of impacts distributed over life-cycle stages, impact categories normalized to 100%, Base case scenario. Processes contributing less than 1% are excluded.

Impact Category	**Life-cycle stage contribution (%)**				
	Material extraction and Component manufacturing	Power plant construction	Operation and Maintenance	Grid distribution	Decommissioning and Waste management
GWP	41	10	30	3	-17
Freshwater ecotoxicity	42	3	22	1	-32
Terrestrial acidification	30	20	41	1	-8
Photochemical ozone-creation potential	29	24	42	1	-5
Freshwater eutrophication	42	3	18	1	-36

5.2 Material requirement

The material requirements for copper, iron, aluminium and cement for the three kite foundation designs are in total given in table 10. As expected the concrete GBF requires more cement while steel requirement is higher for the steel GBF. If no recycling of steel and copper is assumed the impacts would be 10 times higher for steel and 20 times higher for copper.

5.3 Energy demand and energy payback time

The energy total and non-renewable demand per kWhe produced by the DGU power plant is shown in table 12. Based on these resources and the total energy output from the power plant, the energy return on investment (EROI) and the energy payback time is calculated and compared later with other tidal energy technologies in table 20. It is to be noted that the data used for non-renewable energy demand is sometimes inconsistent between different studies.

For example, crude oil is a raw material to produce polyurethane (as seen in figure 14); however, it might not be considered as an energy resource in other studies since the energy in the material is not utilized. The CED method applied here does include the chemically bound energy. Hence, the results are may be conservative compared to other studies.

Table 12. Energy demand and energy pay-back time (grid included) for different scenarios.

	Non-renewable energy demand		Total energy demand		EROI	Energy payback time
	MJ/kWhe	kWh/kWhe	MJ/kWhe	kWh/kWhe	kWhe/kWh	yr
Base case	0.41	0.11	0.43	0.12	8.3	3.0
Bsteel	0.40	0.111	0.42	0.12	8.5	2.9
Bhybrid	0.39	0.11	0.41	0.12	8.7	2.9
Optimistic	0.27	0.076	0.29	0.080	12.5	2.0
Pessimistic	0.82	0.23	0.87	0.24	4.6	6.0

Impact contributions from processes to demand of non-renewable energy resources are illustrated in figure 14 and data is given in table 13. The total impact from fossil resources (excluding uranium) is 0.36 MJ eq/kWhe (Base case), which is the majority of the non-renewable energy demand. Crude oil for the diesel production (mainly used for the vessel trips) contributes the most to this category (see also figure 15). Since the UK depends on fossil energy sources, mainly hard coal and natural gas, in its electricity generation mix, this also contributes significantly to the non-renewable energy demand. Another heavily coal dependent process is the production of reinforcing steel, where coke (heated coal in an oven) is a vital process in iron making. Polyurethane production stands out from other plastics as is mainly used in the tethers which also needs frequent replacements. For the nuclear non-renewable resources, the total demand is 0.05 MJ, and it is mainly due to the uranium used in the utility electricity generation mix.

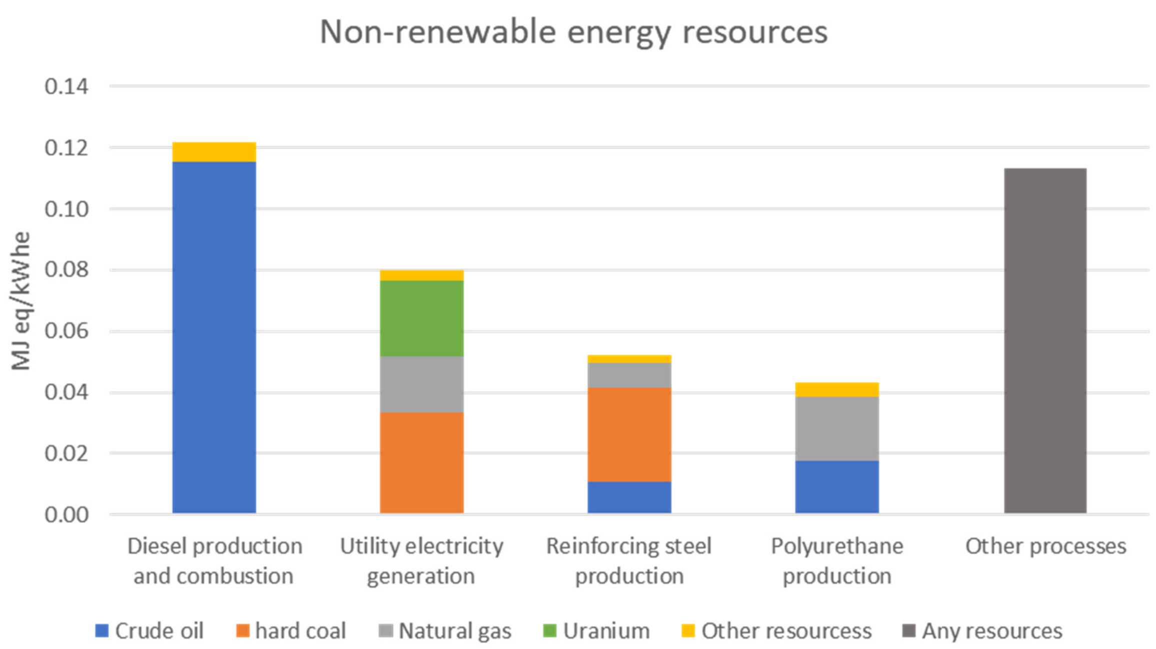

Figure 14. Non-renewable energy resources - fossil in MJ eq/kWhe, contributions from processes and resources (Base case). Processes contributing less than 1 % are aggregated into “Other processes”.

Table 13. Non-renewable energy resources - fossil in MJ eq/kWhe, contributions from processes and resources.

Processes \ Emission	Non-renewable energy resources, MJ eq/kWhe					
	Crude oil	Hard coal	Natural gas	Uranium	Other resources	Any resources
Diesel production and combustion	0.12				0.01	
Utility electricity generation		0.03	0.02	0.02	0.004	
Reinforcing steel production	0.01	0.03	0.01		0.002	
Polyurethane production	0.02		0.02		0.005	
Other processes						0.11

Another way of representing the contribution to non-renewable energy demand is according to different stages in the life cycle as shown in figure 15. It is obvious that the fossil consumption is dominated by production of replaced parts and the production of the gravity base foundation material, while the nuclear dominates the replaced parts production.

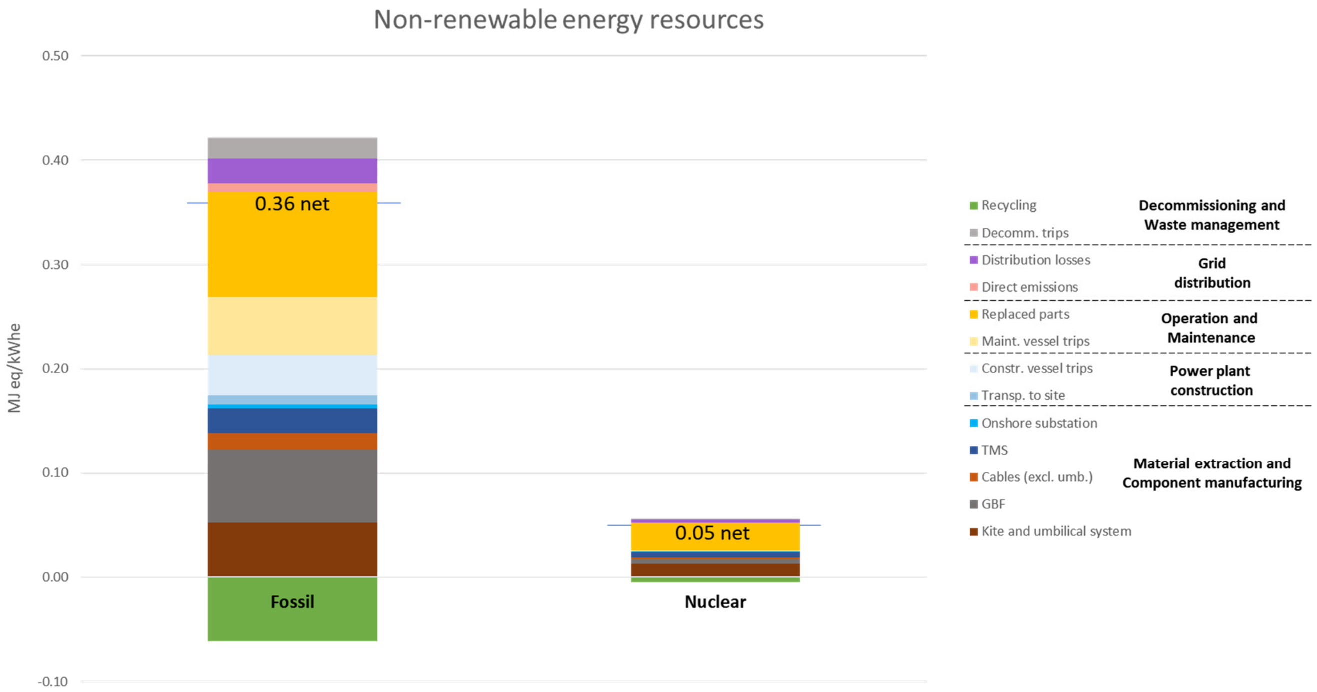

Figure 15. Non-renewable energy resources demand by different life cycle stages. The net demand is shown in numbers.

Since crude oil is a large contributor to the energy demand, figure 16 shows the contribution of different processes to the crude oil demand specifically. The total (including chemically bound) crude oil energy used is 0.20 MJ per kWhe generated, where the maintenance phase accounts for 40%, and diesel used in vessels for maintenance accounts for 25% alone.

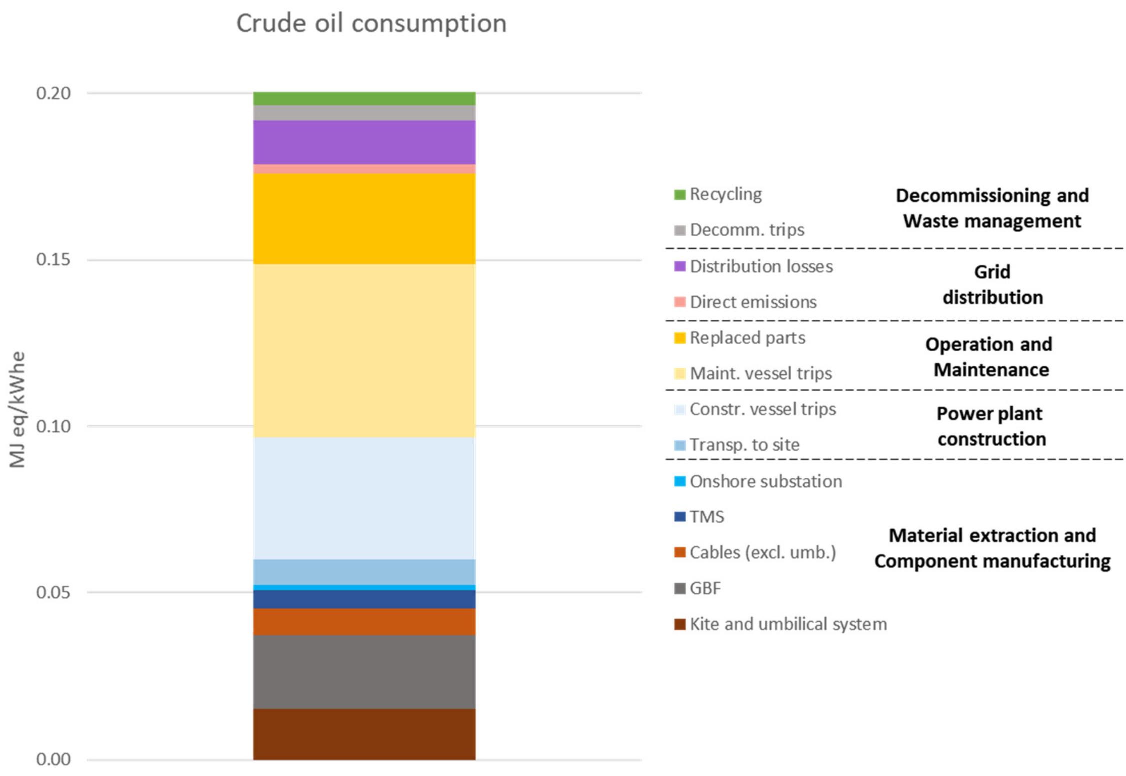

Figure 16. Contribution to crude oil demand by life cycle stages.

5.4 Impact on global warming potential and scenario comparisons

Impact on GWP from 7 scenarios as defined in 4.1.2.1 are shown in figure 17. The pessimistic scenario is not shown as it is almost identical to doubling impacts from the Base case. Data is given in table 14 including the pessimistic scenario of 1 GWh/yr power output per kite.

The leftmost bar represents the Base case. BT shows the improvement when extending the tether lifetime from 5 to 10 years. BTR shows the additional improvement of re-using the GBF, i.e. extending its lifetime to 50 years. BSteel and BHybrid show the change in impact when using different kite foundation designs compared to the Base case. The Optimistic scenario shows the improvement when the power output is increased from 2 to 3 GWh/yr. The rightmost bar shows the impacts from the Favourable site scenario. The negative sign of the impact from recycling reflects the avoided impact from production of virgin materials.

A dominating aspect contributing to GWP in the Base case is the manufacturing of the concrete GBF. This impact is halved in the BTR scenario where the GBF is re-used once. Using steel or hybrid foundations also results in a slightly lowered impact on GWP mainly due to avoided concrete production which in contrast to steel is assumed not to be recycled. Of the avoided GWP impacts from recycling, 96% is credited from recycling of steel and 4% from copper for the Base case. In fact, the rebars in the concrete GBF adds up to more steel weight in total than the other kite mooring alternatives but it has little net impact due to the high steel recycling rate.

Replacement of components is a significant contributor to GWP. 5.4 g CO_2 eq/kWhe (84%) of this is due to replacements of the tether in the Base case. In the scenario BT and BTR where replacement rate of the tether is halved the impact from component replacement is significantly reduced.

On-site vessel trips are also contributing substantially to GWP impacts. In the Base case the maintenance, construction, and decommissioning trips cause 3.45, 2.42, and 1.24 respectively and in total 7.5 g CO_2 eq/kWhe. In the favourable site scenario, the impact from vessel trips are lower based on the lesser number of kites and absence of TMSes.

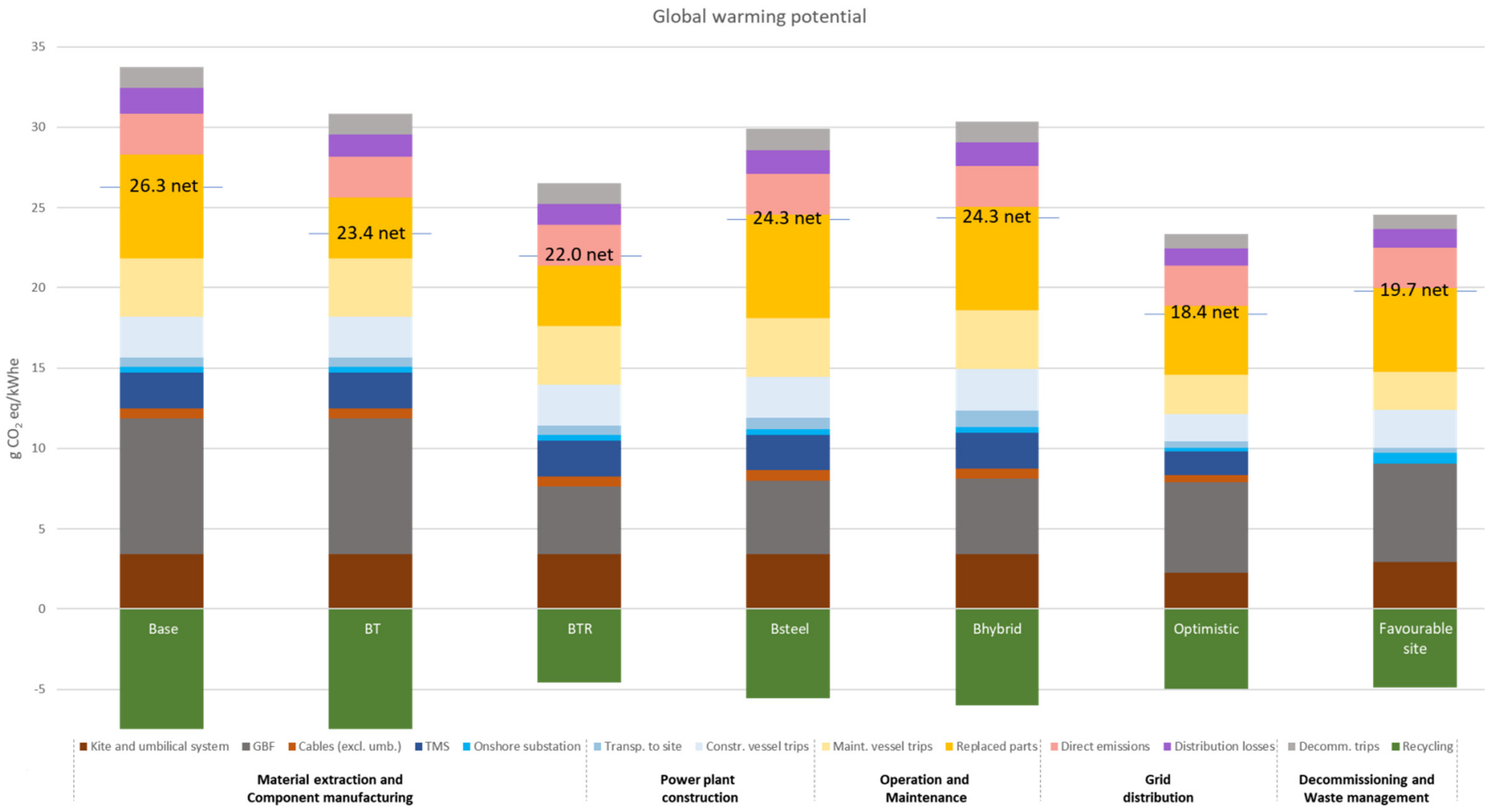

Figure 17. Impact on global warming potential g CO_2 eq/kWhe for 7 of the scenarios defined in 4.1.2.1. The material yields from recycling copper and steel are credited as avoided impacts from producing virgin materials. The net impact is shown in numbers.

Table 14. Impact on Global warming potential, process contributions from different scenarios.

Processes	Scenario	Base	BT	BTR	Bsteel	Bhybrid	Optimistic	Pessimistic	Favourable site
		Global warming potential, g CO_2 eq/kWhe							
Decommissioning and Waste management	Recycling	-7.45	-7.45	-4.57	-5.57	-6.02	-4.96	-14.9	-4.87
	Decomm. trips	1.31	1.31	1.31	1.31	1.31	0.87	2.61	0.90
Grid distribution	Distribution losses	1.60	1.40	1.30	1.46	1.46	1.06	3.19	1.15
	Direct emissions	2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Operation and maintenance	Replaced parts	6.47	3.76	3.76	6.47	6.47	4.31	12.94	5.24
	Maint. trips	3.65	3.65	3.65	3.65	3.65	2.43	7.29	2.36
Power plant construction	Constr. trips	2.56	2.56	2.56	2.56	2.56	1.71	5.12	2.34
	Trp. to site	0.58	0.58	0.58	0.71	1.06	0.39	1.17	0.32
Raw material and Component manufacturing	Onshore substation	0.33	0.33	0.33	0.33	0.33	0.22	0.66	0.65
	TMS	2.22	2.22	2.22	2.22	2.22	1.48	4.44	0.00
	Cables (excl. umb.)	0.66	0.66	0.66	0.66	0.66	0.44	1.32	0.00
	GBF	8.45	8.45	4.23	4.59	4.72	5.64	16.91	6.15
	Kite and umbilical system	3.39	3.39	3.39	3.39	3.39	2.26	6.78	2.93
Total		**26.3**	**23.4**	**22.0**	**24.3**	**24.3**	**18.4**	**50.1**	**19.7**

5.5 Impact on acidification potential

Contributions to impact on acidification potential from processes and emissions are illustrated in figure 18, data is given in table 15 (Base case). The total impact is 0.20 g SO_2 eq (Base case). Emissions of sulphur and nitrogen oxides from diesel combustion and reinforcing steel production contributes most to the impact.

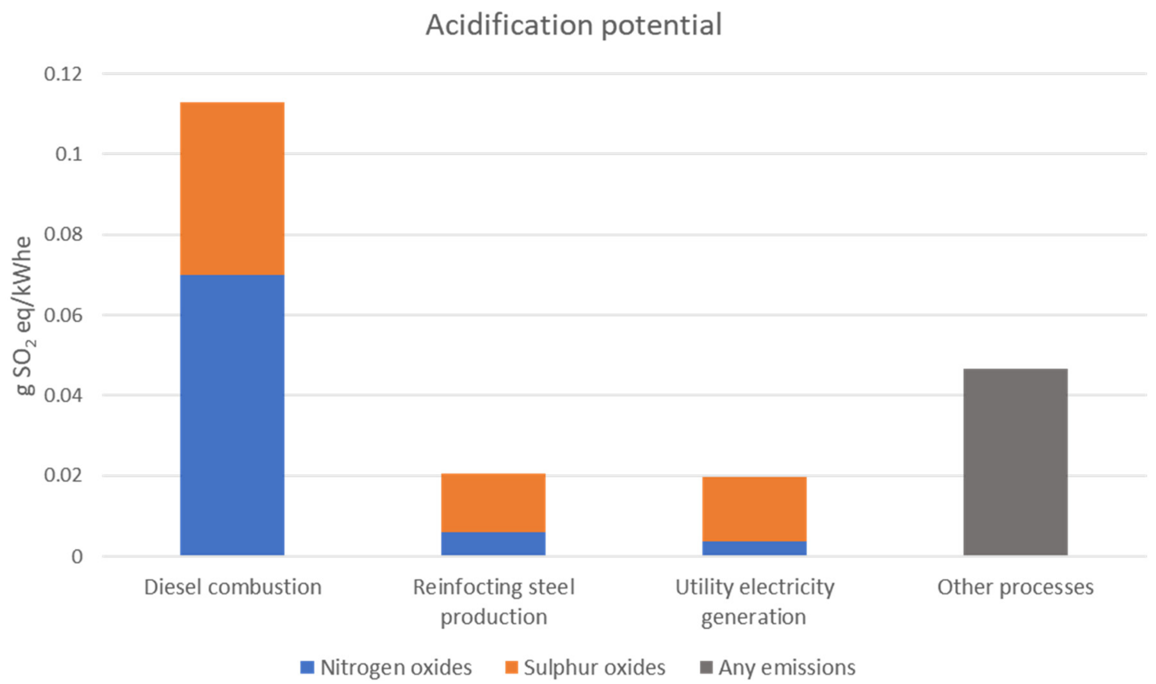

Figure 18. Impact on acidification potential in g SO_2 eq/kWhe, contributions from processes and emissions (Base case). Processes contributing less than 1 % are aggregated into "Other processes".

Table 15. Impact on acidification potential, contribution from processes and emissions for the Base case.

	Acidification potential, g SO_2 eq/kWhe		
Processes \ Emission	Nitrogen oxides	Sulphur oxides	Any emissions
Diesel combustion	0.070	0.043	
Reinforcing steel production	0.0061	0.015	
Utility electricity generation	0.0036	0.016	
Other processes			0.047

5.6 Impact on freshwater eutrophication potential

Process contributions to impact on freshwater eutrophication potential are illustrated in figure 19 and data is given in table 16. The total impact is 7.1 mg P eq (Base case). More than 99% is caused by phosphate emissions mostly from steel production and utility electricity generation.

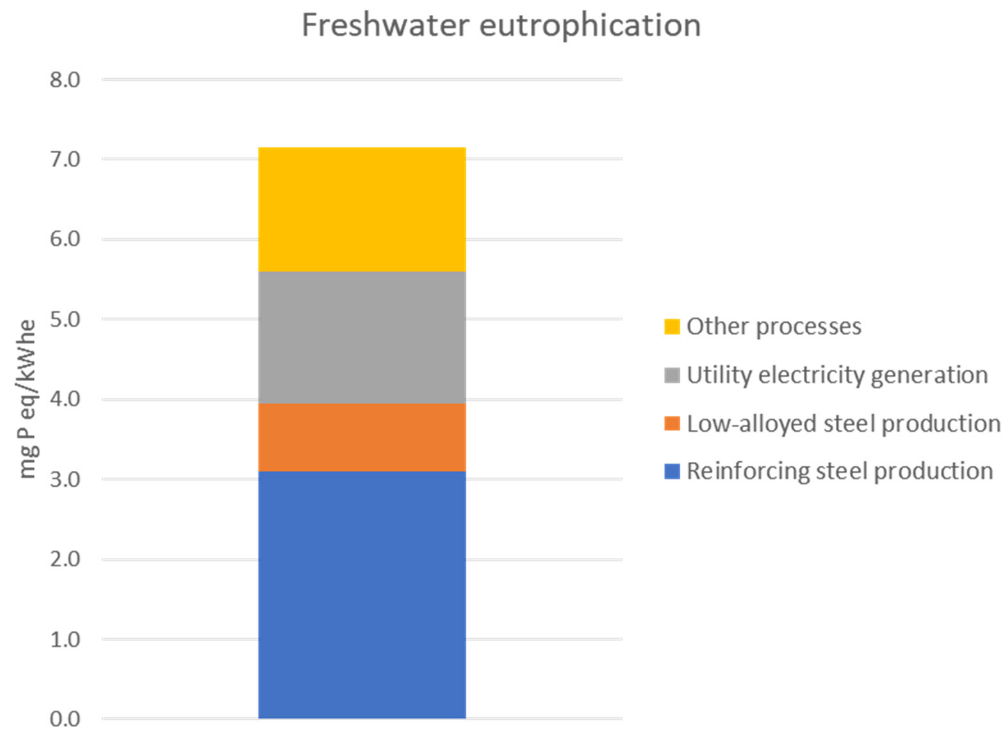

Figure 19. Impact on freshwater eutrophication potential in mg P eq/kWhe (Base case). Processes contributing less than 1 % are aggregated into "Other processes".

Table 16. Impact on freshwater eutrophication potential, contribution from processes.

Process	**Freshwater eutrophication, mg P eq/kWhe**
Reinforcing steel production	3.1
Low-alloyed steel production	0.86
Utility electricity generation	1.6
Other processes	1.6

5.7 Impact on freshwater ecotoxicity

Impact contributions from processes and emissions to freshwater ecotoxicity are illustrated in figure 20 and data is given in table 17. The total impact is 0.42 g 1,4DB eq (Base case). Emissions of metal elements from utility electricity production and steel production contribute most to this impact category. Potentially toxic direct emissions from the operation and maintenance of the DGU power plant remains uncertain; it has not been assessed since no data was available.

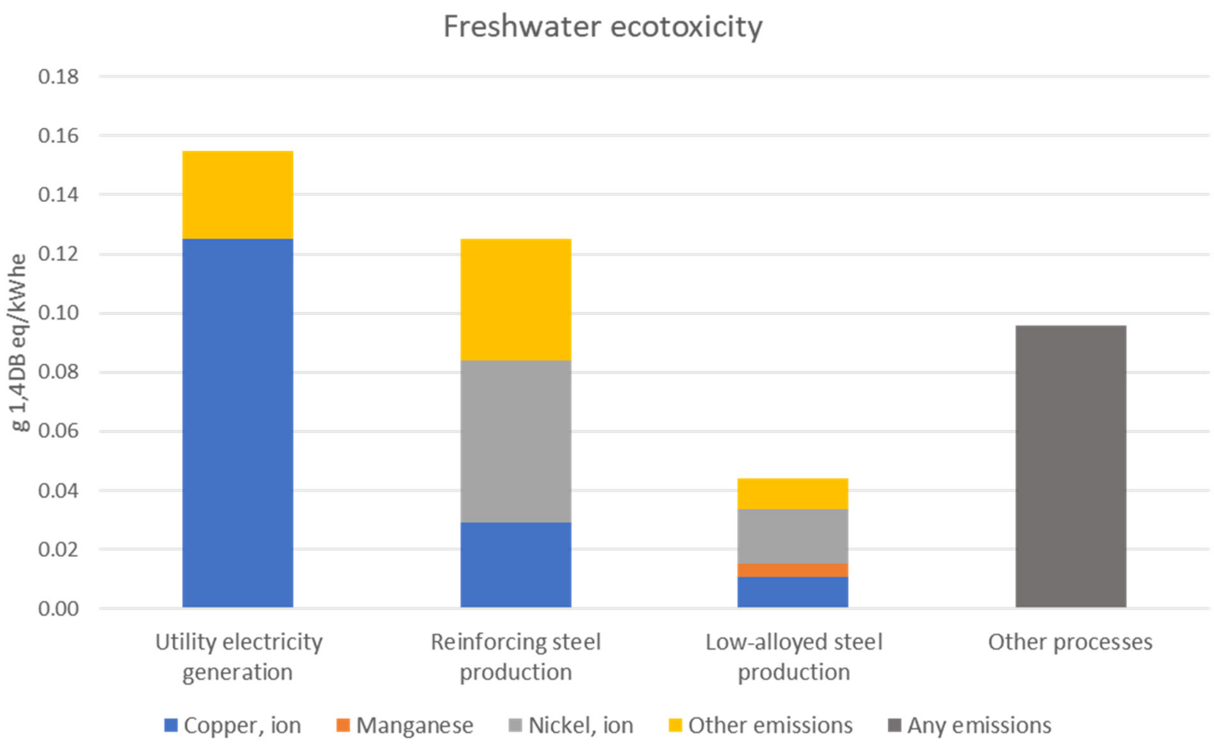

Figure 20. Impact on freshwater ecotoxicity in g 1,4DB eq/kWhe, contributions from processes and emissions (Base case). Processes contributing less than 1 % are aggregated into “Other processes”.

Table 17. Impact on freshwater ecotoxicity in g 1,4DB eq/kWhe, contributions from processes and emissions.

	Freshwater ecotoxicity potential, g 1,4DB eq/kWhe				
Emission / **Processes**	Copper, ion	Manganese	Nickel, ion	Other emissions	Any emissions
Utility electricity generation	0.13			0.030	
Reinforcing steel production	0.029		0.055	0.041	
Low-alloyed steel production	0.011	0.0045	0.018	0.010	
Other processes					0.0960

5.8 Impact on photochemical ozone-creation potential

Impact contributions from processes and emissions to photochemical ozone-creation potential (POCP) are illustrated in figure 21 and data is given in table 18. The total impact is 0.20 g C_2H_4 eq (Base case). Nitrogen oxides are dominating and are mainly emitted from diesel combustion from offshore vessel trips.

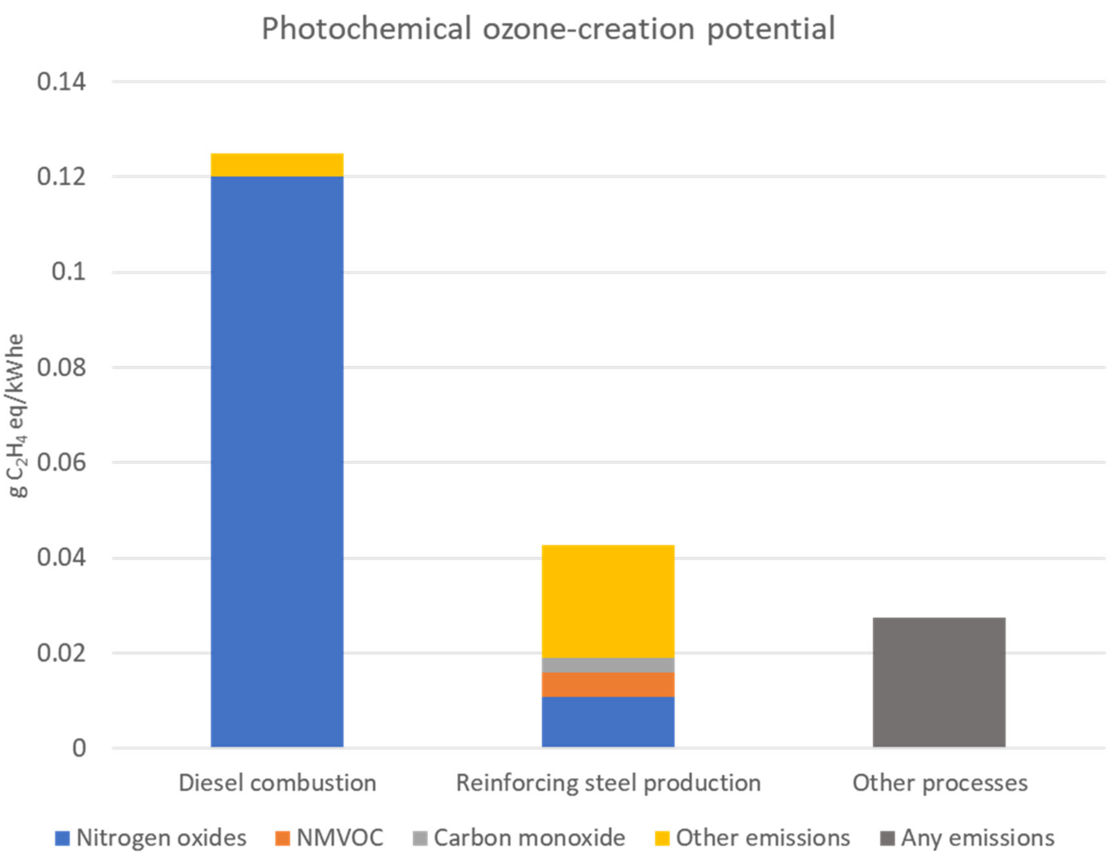

Figure 21. Impact on POCP in g C_2H_4 eq/kWhe, contributions from processes and emissions (Base case). Processes contributing less than 1 % are aggregated into "Other processes".

Table 18. Impact on POCP, contributions from processes and emissions

	Photochemical ozone-creation potential, g C_2H_4 eq/kWhe				
Emission / **Processes**	Nitrogen oxides	NMVOC	Carbon monoxide	Other emissions	Any emissions
Diesel combustion	0.12			0.005	
Reinforcing steel production	0.011	0.0051	0.0030	0.024	
Other processes					0.027

5.9 Impact on particulate matter formation

Contributions to particulate matter formation are shown in figure 22, data is given in table 19. The total impact is 0.075 g PM_{10} eq (Base case). Sulphur and nitrogen oxides from diesel combustion together with $PM_{2.5}$ and PM_{10} from production of reinforcing steel are dominating.

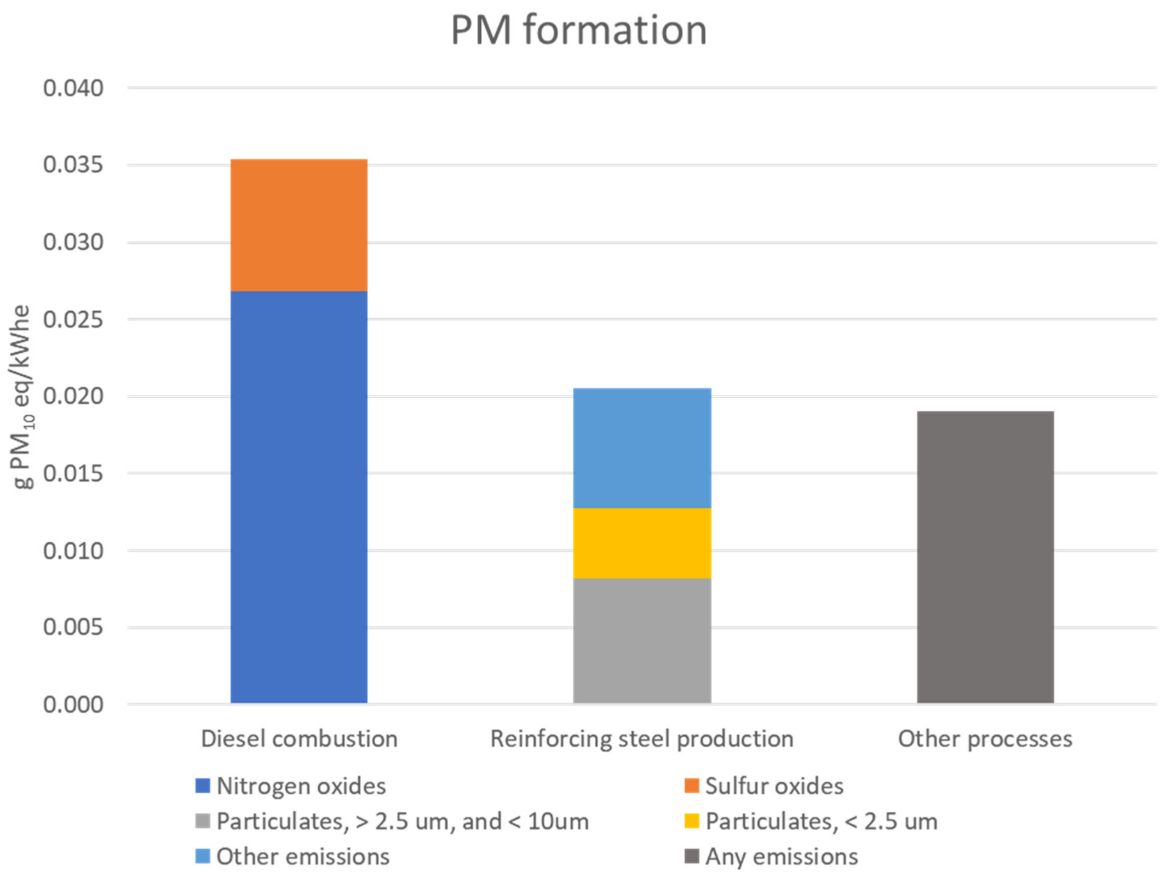

Figure 22. Impact on PM formation in g PM_{10} eq/kWhe, contributions from processes and emissions (Base case). Processes contributing less than 1 % are aggregated into “Other processes”.

Table 19. Impact on PM formation, contributions from processes and emissions.

	Particulate matter formation, g PM10 eq/kWhe				
Emission / **Processes**	Nitrogen oxides	Sulphur oxides	Particulates, > 2,5 um, and < 10um	Particulates, < 2,5 um	Any emissions
Diesel combustion	0.027	0.0086			
Reinforcing steel production			0.0082	0.0046	
Other processes					0.019

5.10 Comparison with other electricity generation technologies

To benchmark the environmental performance of the DGU power plant assessed here, we compare the impact with three previous studies: The H14 (Hertwich et al., 2014) assessed a wide range of technologies renewable and fossil-based, Uihlein (2016) made a review focussing on ocean technologies, and Walker et al. (2015) focused on tidal technologies in a 10MW array.

The comparisons of the results in this study for the DGU with impacts reported in H14 are shown in figures 23 and 24.

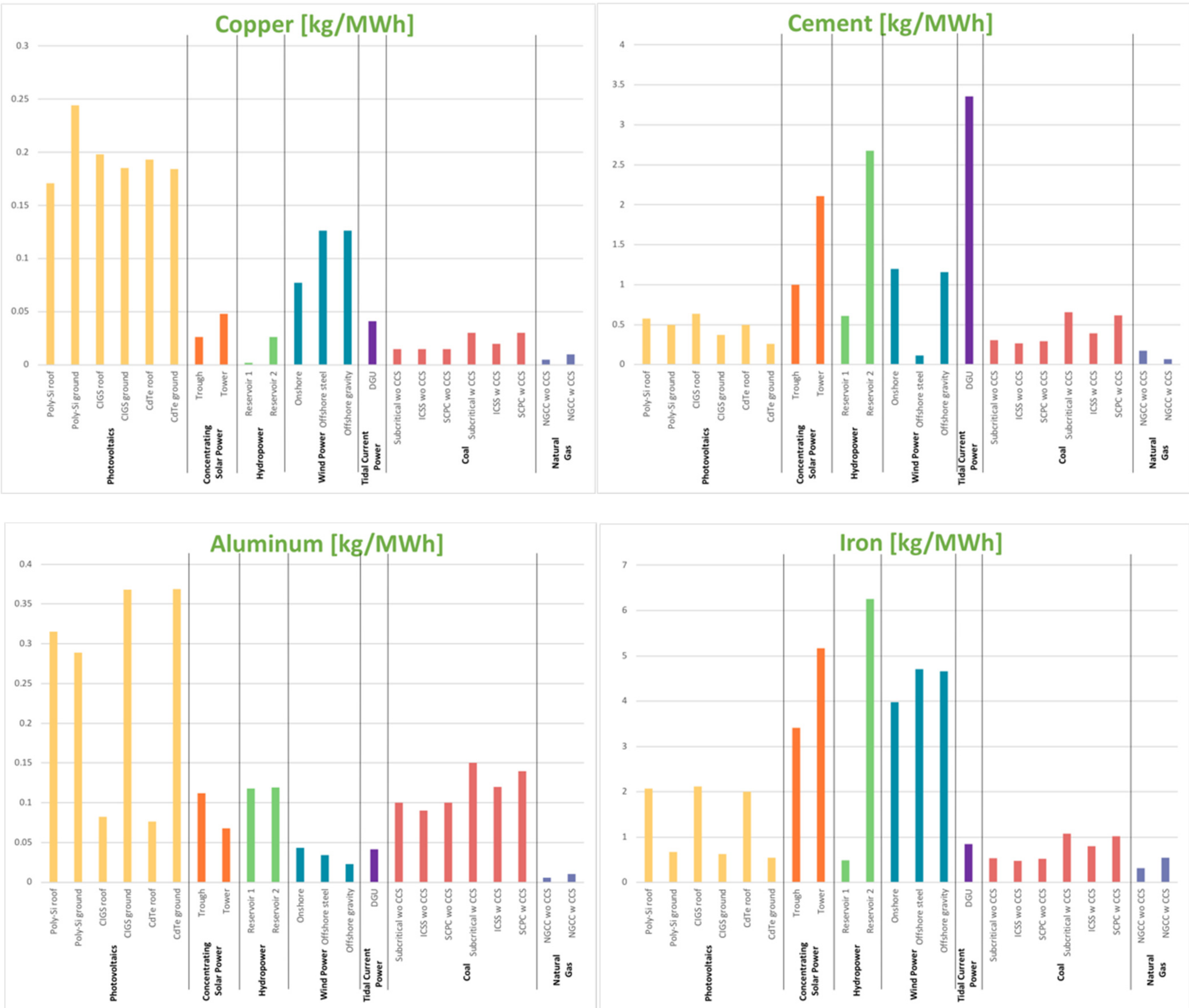

Figure 23. Material requirements in kg/MWh (or g/kWh). Comparison of the DGU tidal power plant (purple – Base case) with the mean value of wide range of electricity generation technologies reported in H14.

A critical aspect influencing material requirement is the waste management model applied. H14 builds on several previous studies where it is not always transparently reported how recycling has been modelled. In the H14 study it is specified that they accounted for recycling as a percentage of the raw materials, but without further details. The recycling assumption applied here for the DGU power plant is 90% iron and 95% copper recycling. The cement consumption seems to be higher than for other technologies, but according to table 10, if steel or hybrid GBF is used instead, the cement consumption will drop in expense of iron, which would still be less than other technologies.

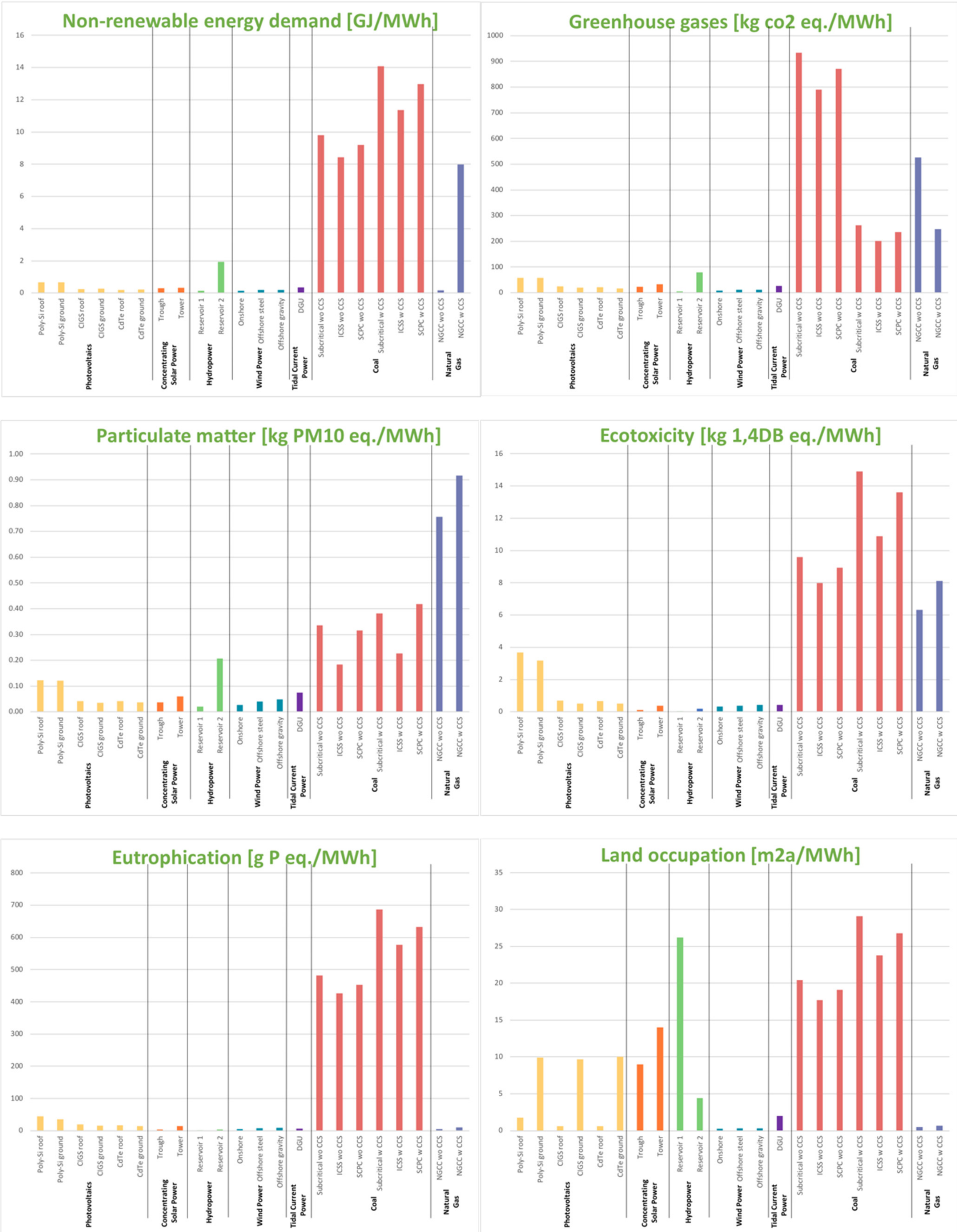

Figure 24. Impact on Land occupation, Non-renewable energy demand, Greenhouse gases (GWP), Freshwater eutrophication, Freshwater ecotoxicity, and Particulate matter formation. Comparisons of the DGU tidal power plant (purple – Base case) with the mean value of wide range of electricity generation technologies reported in H14.

Figure 24 shows impact on the categories land occupation, non-renewable energy demand, GWP, freshwater eutrophication, freshwater ecotoxicity, and particulate matter formation. The DGU is in range with other renewables while fossil fuel combustion technologies are in general performing worse than renewables in these categories. An exception is terrestrial land occupation where PV and hydropower in some cases have a substantial impact. H14 only included the direct land occupied by installations; hence the area required between land based wind power turbines is not included. Sea area occupation might be a more relevant issue to assess for the DGU power plant but it is not included as it is still debated how to account for this.

A comparison of the GWP impact of the DGU power plant (Base case) and other ocean based technologies reported by Uihlein (2016) is shown in figure 25. Among these is a technology named "Tidal kite" which may refer to an assessment of an earlier version of Minesto's tidal kite concept, but it remains unclear since no description can be found in the given source. The component-wise model in Uihlein, without an identifiable use and maintenance phase, differs from our model. Uihlein concludes that the installation, maintenance, and operation contribution is negligible, unlike our findings, where these activities contribute a substantial share of the emissions. This may partly be only an apparent discrepancy as we suspect that Uihlein does includes both the initial production and the replacements throughout the lifetime of the power plant with the components, i.e. they are not considered as part of the maintenance process. However, the validity of neglecting the impact of installation and maintenance vessel trips remains questionable as they account for 26% of the GWP impact in this study.

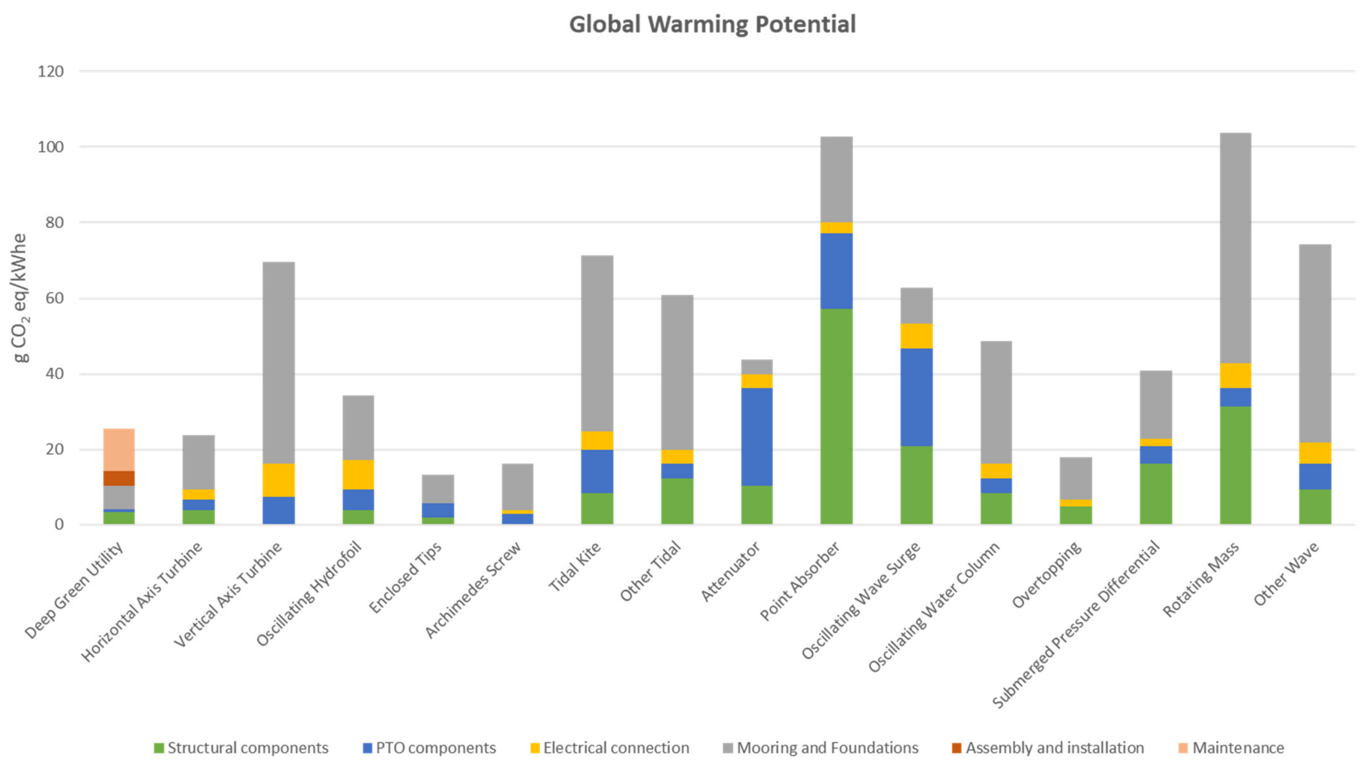

Figure 25. Impact on GWP. Comparison of the DGU tidal power plant (Base case) with other ocean-based electricity generation technologies reported by Uihlein (2016).

Another interesting finding regards the differences between this and other studies. For example, the horizontal axis turbine inventory data was taken from Douglas et al. (2008) which was an early study on the SeaGen technology. The Douglas et al study showed that the GWP for the technology was 15 g CO_2 eq/kWhe, whereas in Uihlein's study, 8 years later, the reported value was 23.1 g CO_2 eq/kWhe using the same data. Thus, it is important to be critical when comparing with other technologies because results are directly related to assumptions and system boundaries selected.

Walker et al. (2015) studied tidal power plants; 3 horizontal axis turbine technologies, and one Archimedes screw. In their study, they assumed that the devices were placed in an array of 10MW, which is of comparable size to the 12MW DGU array assessed in this study. Table 20 shows the specifications and impacts (GWP and energy payback time) from the different technologies. The energy payback time and the lifetime is given for each device.

Table 20. Specifications and impacts from different tidal energy technologies.

Device	**Technology**	**Rated Power,** kW	**Lifetime,** years	**GWP,** g CO_2 eq/kWhe	**Energy payback time,** years
DeepGen	Horizontal axis turbine	1000	25	34.2	2.8
OpenHydro	Horizontal axis turbine	2000	20	19.6	1.5
SR2000	Horizontal axis turbine	2000	20	23.8	1.7
Flumill	Archimedes screw	2000	20	18.5	1.4
Deep Green Utility	Tidal kite	500	25	25.6	3

6. Discussion and conclusions

This study is a prospective LCA to assess the environmental performance of a future DGU power plant currently under development by Minesto. Since the system is not yet in operation several assumptions have been made by necessity. For example, a large uncertainty aspect is the capacity factor. How much of the rated 500 kW will be produced? Will it be 23%, 46%, or perhaps more?

Since the DGU developer Minesto is the main provider of the foreground data, we deem the results from this study as coming close to the actual outcome of the environmental performance of the foreground model, given the present design of the kite technology, which if scaled up will change. Data on manufacturing of hardware, i.e. material requirements and components are more robust while data on operation, maintenance and waste management are less certain.

It should be stressed that the foreground model in this study is based on a configuration using the DG500 prototype power plant, which is a low voltage export system with a generator capacity of 500 kW. The next generation Deep Green power plant, which is currently being designed, will have a higher generator rating, higher export voltage, higher efficiency, simplified launch and recovery characteristics, enhanced drag performance and be designed for certain maintenance activities to take place offshore to name a few improvement areas. These technology upgrades will fit within the wing span and flow rate constraints as used in the PowerKite project, and it is also anticipated that the total material consumption for the power plant will be similar if not lower than of the DG500 design. The improvements will also lead to other and more simplified array configurations and will likely be more efficient with the utilization of vessels for operation and maintenance. Consequently, the foreground model and the calculated impacts do not reflect the full potential of the Deep Green technology.

The use of reference LCI databases, in this case ecoinvent v 3.3 to cover the background data, is a mainstream LCA approach and is therefore attached with the same uncertainties as numerous other LCA studies. This together with the assumption that the background is unaffected by the DGU (no consequential approach applied in this LCA) and that the background remains unchanged over the 25-year lifetime of the power plant is a rather large uncertainty aspect.

A tidal power plant is an intermittent energy technology; however, it has a very predictable pattern of generated power. This would imply potentially less load-balancing cost incurred on the grid compared to wind and solar energy. The environmental effects of the required back-up capacity and other interdependencies between different technologies at grid-level grid is not well understood and in general not considered in LCA studies (H14). Since the quality of the electricity and the functionality provided to grid stability is assumed equal regardless of electricity generating technology, the significance of these issues has not be assessed.

The results are highly dependent on the assumed power output. Most of the impact results presented are assuming 2 GWh/yr average power output per kite. To roughly recalculate the impacts to another scenario with an assumed output of X GWh/yr per kite is a simple matter of multiplying the results from a 2 GWh/yr scenario by 2/X. The only exception to this linear rule is the impacts caused directly by the downstream grid. These impacts are the same for each kWhe delivered to consumers regardless of the power output of the power plant. They are however small in relation to the core and upstream impacts and only significant in the case of GWP (10% of Base case GWP impacts). The grid distribution losses, however, imply increased resource needs and emissions from the power plant; with losses calculated to 7.2% according to the ecoinvent background data the power plant must produce 1.072 kWhe per 1 kWhe to consumer. These added impacts are indirectly dependent on the power plant's environmental performance.

Recycling rates and recycling model applied have a substantial impact on the results. The assumption of recycling rates applied here of 90% for steel and 95% for copper is based on similar studies. We have fully credited the yield from steel and copper recycling as avoided production of virgin material based on the approach in previous studies on offshore wind (e.g. Haapala & Prempreeda, 2014; Yang et al., 2018). With these assumptions the results indicate that material requirements are not a primary concern of the DGU technology.

The results of the DGU power plant is in range with other renewable technologies in the impact categories GWP, land occupation, non-renewable energy demand, freshwater eutrophication, freshwater ecotoxicity, and particulate matter formation. Our results indicate no major concerns in terms of environmental performance of the DGU in these categories. It is well known and evident from H14 (figure 24) that fossil fuel combustion technologies in general have a substantially worse environmental performance than renewable energy technologies in these categories. (Nuclear power is not reported in H14). An exception is terrestrial land occupation where PV and hydropower in some cases have a substantial impact. H14 only include the direct land occupied by installations; hence the area required between land-based wind power turbines is not included. Sea area occupation might be a more relevant issue to assess for the DGU power plant but it is not included as it is still debated how to account for this.

Regarding GWP, the impact category most frequently occurring in environmental discourse, the DGU power plant (Base case) impact at 26 g CO_2 eq/kWhe. Significant contributors to the GWP are frequent replacement of the tether, trips with offshore vessels used for construction and maintenance as well as the concrete and steel material production for the gravity base foundations. Regardless of scenario the direct emissions from the grid is calculated to a fixed 2.5 g CO_2eq/kWhe due to small but potent emissions of SF_6 from electrical equipment and generation of N_2O from high voltage aerial powerlines. Improvements from the Base case with a halved tether replacement rate and re-use of the concrete GBF yields 21 g CO_2 eq/kWhe. Assuming the Base case array with the hypothetical 3 GWh/yr per kite would result in 18 g CO_2 eq/kWhe. The scenario reflecting a more favourable site and different array configuration than Holyhead with 3 GWh/yr power from 18 kites (46% capacity factor) yields 20 g CO_2 eq/kWhe.

The results on GWP impact indicate that the environmental performance of the DGU power plant is in range with other ocean energy technologies, with reported ranges from offshore wind from 8 to 35 g CO_2 eq/kWh (IPCC, 2013), 15 to 105 g CO_2 eq/kWh (Uihlein, 2016), 11 to 20 g CO_2 eq/kWhe (Hertwich et al., 2014) to 28 to 44 g CO_2 eq/kWhe (Arvesen, Birkeland, & Hertwich, 2013). In the worst-case scenario with an assumption of only 1 GWh/yr per kite, the GWP impact is 50 g CO_2 eq/kWhe, which is still substantially lower than fossil fuel combustion technologies (~500-900 CO_2 eq/kWhe) and already competitive with many reported results on PV, biofuel and some hydro installations (e.g. IPCC, 2014; H14; Vattenfall, 2012).

Another important indicator derived is the energy return on investment (EROI). It describes how much more energy is generated with respect to the energy required throughout the life cycle of the plant. This indicator also helps in calculating the energy payback time, simply by taking its reciprocal and multiplying it by the life time. The estimate for EROI at the Holyhead site was found to be between 4.6 (pessimistic) to 8.3 (Base case), which can be compared with that of the wind power plants ranging between 6.1 to 33.5 (Kubiszewski Cleveland, & Endres, 2010). This corresponds to an energy payback time of 36 (Base case) to 72 months (pessimistic) for the DGU array. The major contributor to this energy is that needed in the maintenance phase, especially for the manufacturing of the tether spare parts, and for the diesel used in ships during the maintenance. It should be noted that, in this study, we have included all sources of fuel and electricity, non-renewable and renewable, as well as chemical bound energy in fossil carbon resources used in plastic materials. This extended approach is not always applied when calculating the total energy demand for the EROI and energy payback time.

When examining the contributions from individual processes it is evident that three main activities namely diesel combustion, steel production and utility electricity generation contributes significantly to several categories. The diesel combustion refers to fuel combustion mainly for maintenance and construction trips with offshore vessels. Impact from steel production is directly connected to the amount of steel needed in components including replacement needs in maintenance. Emissions from utility electricity generation is mainly due to the use of fossil fuel technologies in the average UK electricity mix; in this system mainly consumed by material production.

To improve the environmental performance of the DGU power plant system assessed in this LCA, the results points to that the work should be focused on reaching a high capacity factor; having a less material-intensive kite foundation and mooring system; employing efficient offshore vessels and investigate possibilities of using alternatives to diesel fuel; lowering steel requirements (while not reducing component durability and thereby increasing replacement needs); investigating possibilities to extend the lifetime of the tether and using recyclable materials; and strive for high recycling of steel and copper.

Considering that this is a world-first and rather small (12 MW rated power) commercial installation of this type of power plant based on prototype data, efficiency benefits from upscaling of the technology as well as gradual improvements are expected. The environmental performance of DGU technology is likely to improve significantly with the development of the technology as, according to Arvesen and Hertwich (2012), there are strong economies of scale for wind turbines with power ratings up to 1 MW. Other possible gains from the economies of scale would be increasing the array (adding more kites), likely reducing common parts needed per kWhe, as well as more efficient component production from large scale implementation of the technology.

7. Information on EU funding / Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654438.

The content of this report reflects only the author's view and the Agency is not responsible for any use that may be made of the information it contains.

8. References

ABB. (2003). *Environmental Product Declaration for Large Distribution Transformer 10 MVA*. Retrieved from https://library.e.abb.com/public/57c1d5721712c65fc1256de9003d9401/10%20MVA.pdf?x-sign=6lm9n20/x6U8CFRRScbospcDaLlja81Ojv7/HOHBz/v5vzJXGGbHPmzEbj+cXcQI

ABB. (2011). *Environmental Product Declaration for ACS 600 frequency converter, 250 kW power*. Retrieved from https://library.e.abb.com/public/3aad93ad845f4988c1256d630040684a/9780_EPD%20for%20ACS600lowres.pdf?x-sign=UkUOYpjAgDj1j4McKdNLn4ajOR32M/A6oBiFhGVL4t/fNOdfOGX6mWxfP17ASat6

ABB. (2010). *Environmental Product Declaration for DMI type DC machine—180-471 kW power range*. Retrieved from https://library.e.abb.com/public/afa15104424 15fc6c1256d640022e99f/Product%20Declaration%20S-P%2000009%20rev%20P.pdf?x-sign=OyM9xKoFDAa4dPThofiDKCm97rt8S8RMi44z0+gUbTGWTmR2A2x7XNfNvKngSm6G

Andersen N, Eriksson O, Hillman K, & Wallhagen M. (2016). Wind turbines' end-of-life: Quantification and characterisation of future waste materials on a national level. *Energies*, *9*(12).

Arvesen A & Hertwich E G. (2012). Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. *Renewable and Sustainable Energy Reviews*, *16*(8), 5994–6006.

Arvesen A, Birkeland C, & Hertwich E G. (2013). The importance of ships and spare parts in LCAs of offshore wind power. *Environmental Science and Technology*, *47*(6), 2948–2956.

Arvidsson R, Tillman A.-M, Sandén B. A, Janssen M, Nordelöf A, Kushnir D, & Molander S. (2017). Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *Journal of Industrial Ecology*, *0*(0), 1–9.

Baumann, H & Tillman A-M. (2004). *The Hitch Hiker´s Guide to LCA An orientation in life cycle assessment methodology and application*. Studentlitteratur, Lund.

Douglas, C. A., Harrison, G. P., & Chick, J. P. (2008). Life cycle assessment of the Seagen marine current turbine. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 222(1), 1–12. https://doi.org/10.1243/14750902JEME94

EC. (2016). *PowerKite - Power Take-Off System for a Subsea Tidal Kite*. European Commission, Community Research and Development Information Service (CORDIS). Retrieved from https://cordis.europa.eu/project/rcn/199439_en.html

EPD. (2015). *Product Category Rules according to ISO 14025. Product group classification: UN CPC 171 and 173 Electricity, Steam and Hot/Cold Water Generation and Distribution*. The International EPD System.

Haapala K R & Prempreeda P. (2014). Comparative life cycle assessment of 2.0 MW wind turbines. *Int. J. Sustainable Manufacturing*, *3*(2), 170–185.

Hertwich E G, et al. (2014). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *PNAS* 112 (20) pp 6277-6282.

Huijbregts M, et al. (2016). *ReCiPe 2016 v1.1 A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization*. RIVM Report 2016-0104a, National Institute for Public Health and the Environment, The Netherlands.

IPCC. (2014). *Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p 1335.

Jivén K, Sjöbris A, Nilsson M, Ellis J, Trägårdh P, & Nordström M. (2004). *LCA-ship, Design tool for energy efficient ships - A Life Cycle Analysis Program for Ships, 61*. Retrieved from http://www.mariterm.se/wp-content/uploads/2016/08/Final-report-LCA-ship.pdf

Jotun. (2017). *Jotamastic 87 Aluminium Technical Data Sheet*. Retrieved from https://www.jotun.com/Datasheets/Download?url=%2FTDS%2FTDS__523__Jotamastic%2087%20Aluminium__Euk__GB.pdf

Kregting L, Elsäßer B, Kennedy R, Smyth D, O'Carroll J, & Savidge G. (2016). Do changes in current flow as a result of arrays of tidal turbines have an effect on benthic communities? *PLoS ONE*, *11*(8), 1–14.

Kubiszewski I, Cleveland C J, & Endres P K. (2010). Meta-analysis of net energy return for wind power systems. *Renewable Energy*, *35*(1), 218–225.

Minesto. (2018a). *The future of renewable energy*. Minesto AB. Retrieved from https://minesto.com/our-technology

Minesto. (2018b). *Holyhead Deep*. Minesto AB. Retrieved from https://minesto.com/projects/holyhead-deep

Minesto. (2018c). *Ocean Energy*. Minesto AB. Retrieved from https://minesto.com/ocean-energy

Minesto. (2016). *Deep Green Holyhead Deep Project - Phase I (0.5 MW) - Environmental Statement*. Minesto, document nr L-100194-S14-EIAS-001

Nexans. (2013). *Submarine Power Cables.* Retrieved from http://www.nexans.com/Germany/2013/SubmPowCables_FINAL_10jun13_engl.pdf

Romaniw Y A, (2013). *Relationship between light-weighting with crabon fiber reinforced polymers and the life cycle environmental impacts of orbital launch rockets*, PhD Dissertation, Georgia Institute of Technology

Roos S, Sandin G, Zamani B, & Peters G. (2015). *Environmental assessment of Swedish fashion consumption. Five garments-sustainable future*. Mistra Future Fashion project deliverable D2.6.

Schuchert P, Kregting L, Pritchard D, Savidge G, & Elsäßer B. (2018). Using coupled hydrodynamic biogeochemical models to predict the effects of tidal turbine arrays on phytoplankton dynamics. *Journal of Marine Science and Engineering,* 6(2), 58.

The Offshore Valuation Group. (2010). *The Offshore Valuation*, 1–108. Retrieved from http://publicinterest.org.uk/offshore/downloads/offshore_valuation_exec.pdf

Uihlein A. (2016). Life cycle assessment of ocean energy technologies. *International Journal of Life Cycle Assessment*, *21*(10), 1425–1437.

Vattenfall. (2012) *Livscykelanalys. Vattenfalls elproduktion i Norden*. Vattenfall AB.

Walker S, Howell R, Hodgson P, & Griffin A. (2015). Tidal energy machines: A comparative life cycle assessment study. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, *229*(2), 124–140. https://doi.org/10.1177/1475090213506184

Weidema B P, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo C O, Wernet G. (2013). *Overview and methodology. Data quality guideline for the ecoinvent database version 3*. ecoinvent Report 1(v3). St. Gallen: The ecoinvent Centre

Yang J, Chang Y, Zhang L, Hao Y, Yan Q, Wang C. (2018). The life-cycle energy and environmental emissions of a typical offshore wind farm in China. *Journal of Cleaner Production* Volume 180, pp 316-324

Appendices

Appendix A.1 LCI result

This section presents selected inventory data for both resources and emissions, per 1 kWhe generated for the Base case scenario.

A.1.1 Natural resources

A.1.1.1 Non-renewable material resources[1]

Resource	Weight (g/kWhe)
Gravel	2.81E+01
Calcite (calcium carbonate)	3.35E+00
Clay	1.16E+00
Sodium chloride	6.10E-01
Iron	9.70E-01
Aluminium	5.59E-02
Copper	4.09E-02
Chromium	1.20E-02
Nickel	8.80E-03
Manganese	4.64E-03
Zinc	3.31E-03
Fluorspar	1.02E-03
Titanium dioxide	5.27E-04
Fluorine	1.08E-04

A.1.1.2 Renewable material resources

Resource	Volume (m^3/kWhe)
Wood	8.72E-07

A.1.1.3 Water use

Resource	Volume (m^3/kWhe)
Water, unspecified	5.59E-02
Freshwater	1.26E-05
Saltwater	5.08E-06

A.1.1.4 Non-renewable energy resources[2]

Resource	Energy (MJ)
Crude oil	2.02E-01
Natural gas	8.22E-02
Hard coal	6.80E-02
Nuclear	2.33E-02
Lignite	5.94E-03

A.1.1.5 Renewable energy resources

Resource	Energy (MJ)
Biomass	1.23E-02
Hydropower	7.62E-03
Wind power	2.48E-03
Solar power	1.67E-04

[1] Accounts for recycling of steel 90% and copper 95%. No other material recycling has been considered.
[2] Includes chemically bound energy in materials from fossil carbon resources.

A.1.2 Emissions

A.1.2.1 Emissions to air contributing most to environmental impact categories

Emission	Mass (g/kWhe)
Carbon dioxide, fossil	2.32E+01
Methane, fossil	6.44E-02
Nitrogen oxides	1.59E-01
Sulphur oxides	4.28E-02
Sulphur dioxide	6.22E-02
Carbon monoxide, fossil	6.85E-02
NMVOC	1.30E-02
Dinitrogen monoxide	5.95E-06

A.1.2.2 Emissions to water contributing most to environmental impact categories

Emission	Mass (g/kWhe)
Phosphate	2.14E-02
COD	5.91E-02
Nitrate	3.74E-02
Copper, ion	1.99E-03
Nickel, ion	6.88E-04
Manganese	7.67E-03
Cobalt	2.37E-04

A.1.2.3 Emissions of radioactive isotopes

Emission	Radioactivity (KBq)
C-14	2.01E-04
Rn-222	1.41E+00
Kr-85	2.70E-02
Noble gases, radioactive	0.25941
H-3, tritium	1.96E-02
Xe-133	1.06E-03

A.1.2.4 Emissions of biogenic carbon dioxide

Emission	Weight (g/kWhe)
Carbon dioxide, biogenic	9.64E-01

A.1.2.5 Emissions of toxic substances to air

Emission	Weight (g/kWhe)
Particulates, <2.5 um	9.49E-03
Particulates, >10 um	1.52E-02
Particulates, >2.5 um and <10 um	7.30E-03

A.1.2.6 Emissions of oil to water and ground

Emission	Weight (g/kWhe)
Oils, unspecified to water	2.18E-02
Oils, unspecified to soil	1.10E-02

Appendix A.2 Linked background processes.

This appendix lists the background processes directly linked via intermediate flows to foreground model. Most of the processes are taken from the ecoinvent database v3.3, but others are modelled according to EPDs, reports, and other LCA studies. These in turn are linked to ecoinvent data. The level of detail of materials is higher here than that in the inventory level (for example, more steel types are shown here).

A.2.1 Core material production

Material	Process name	Source
Aluminium 6082	aluminium alloy production, AlMg3 | aluminium alloy, AlMg3 | APOS, U - RER	ecoinvent 3.3
Carbon Fibre	Carbon Fibre production	Romaniw, 2013
Cast Copper	copper production, solvent-extraction electro-winning | copper, from solvent-extraction electro-winning | APOS, U - GLO	ecoinvent 3.3
Concrete	concrete block production | concrete block | APOS, S - DE	ecoinvent 3.3
Copper	copper production, primary | copper | APOS, S – RER	ecoinvent 3.3
Epoxy	epoxy resin production, liquid | epoxy resin, liquid | APOS, S – RER	ecoinvent 3.3
Foam	polystyrene foam slab production | polystyrene foam slab | APOS, S - RER	ecoinvent 3.3
Glass Fibre	glass fibre production | glass fibre | APOS, S – RER	ecoinvent 3.3
Polyethylene, high density	polyethylene production, high density, granulate | polyethylene, high density, granulate | APOS, U - RER	ecoinvent 3.3
Polyethylene, low density	polyethylene production, low density, granulate | polyethylene, low density, granulate | APOS, S - RER	ecoinvent 3.3
Polyurethane	polyurethane production, flexible foam | polyurethane, flexible foam | APOS, S - RER	ecoinvent 3.3
Polyurethane, in tether	polyurethane production, rigid foam | polyurethane, rigid foam | APOS, U – RER	ecoinvent 3.3
PVC	Polyvinylchloride resin (E-PVC), production mix, at plant, emulsion polymerisation – RER	ecoinvent 3.3
Reinforcing steel	reinforcing steel production | reinforcing steel | APOS, S - RER	ecoinvent 3.3
Stainless steel 1.4404	steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | APOS, S – RER	ecoinvent 3.3
Steel 355	steel production, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | APOS, S - RER	ecoinvent 3.3
Steel, ballast	steel production, electric, low-alloyed | steel, low-alloyed | APOS, U - RER	ecoinvent 3.3
Steel, waste	steel production, electric, low-alloyed | steel, low-alloyed | APOS, U - RER	ecoinvent 3.3
Steel grade R4	steel production, electric, low-alloyed | steel, low-alloyed | APOS, S - RER	ecoinvent 3.3
Superduplex steel 1.4410	steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | APOS, S – RER	ecoinvent 3.3
Thermoplastic polyester	polyester resin production, unsaturated | polyester resin, unsaturated | APOS, S – RER	ecoinvent 3.3
Polyester fibre	Polyester fibre production	Roos et al., 2015

A.2.2 Consumable materials (fuels and chemicals) production and infrastructure

Material	Process name	Source
Coolant	chemical production, inorganic | chemical, inorganic | APOS, U - GLO	ecoinvent 3.3
Hydraulic oil	rape oil mill operation | rape oil, crude | APOS, U - Europe without Switzerland	ecoinvent 3.3
Diesel	diesel production, low-sulfur | diesel, low-sulfur | APOS, S - Europe without Switzerland	ecoinvent 3.3
Lubricating oil	lubricating oil production | lubricating oil | APOS, S - RER	ecoinvent 3.3
Paint	Minesto paint production and application	Jotun (2017)

A.2.3 Sub-components

Sub-component	Process name	Source
Anodes	anode production, for metal electrolysis | anode, for metal electrolysis | APOS, U – RER	ecoinvent 3.3
Unspecified electrical components in nacelle	capacitor production, electrolyte type, > 2cm height | capacitor, electrolyte type, > 2cm height | APOS, U - GLO	ecoinvent 3.3
Generator, 500kW	ABB Generator production, 180-471 kW	ABB (2010)
Onshore substation and maintenance building	building construction, multi-storey | building, multi-storey | APOS, S - RER	ecoinvent 3.3
HV transformer, 12MW	ABB Transformer production, 10MVA	ABB (2003)
MV transformer, 3MW	ABB Transformer production, 10MVA	ABB (2003)
Power converter, 250kW	ABB Converter production, 250kW	ABB (2011)
Reactor	ABB Transformer production, 10MVA	ABB (2003)
Road	road construction | road | APOS, S - CH	ecoinvent 3.3

A.2.4 Transport modes

Mode	Process name	Source
Ship	Diesel combustion, medium speed diesel engine	Jivén et al. (2004)
Lorry	transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | APOS, S – RER	ecoinvent 3.3

A.2.5 Auxiliary electricity production

Location	Process name	Source
British Electricity mix	market for electricity, low voltage | electricity, low voltage | APOS, S - GB	ecoinvent 3.3
Swedish Electricity mix	market for electricity, low voltage | electricity, low voltage | APOS, S - SE	ecoinvent 3.3

A.2.6 Downstream grid distribution and infrastructure

Type	Process name	Source
High voltage transmission	electricity transmission, high voltage | electricity transmission, high voltage | APOS, U - GB	ecoinvent 3.3
Voltage transformation, high to medium	electricity voltage transformation from high to medium voltage | electricity, medium voltage | APOS, U - GB	ecoinvent 3.3
Voltage transformation, medium to low	electricity voltage transformation from medium to low voltage | electricity, low voltage | APOS, U – GB	ecoinvent 3.3

A.2.7 Waste management

Recycling was modelled as avoided burden from production of virgin materials.