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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Life cycle assessment of ocean energy technologies

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Abstract

Purpose Oceans offer a vast amount of renewable energy. Tidal and wave energy devices are currently the most advanced conduits of ocean energy. To date, only a few life cycle assessments for ocean energy have been carried out for ocean energy. This study analyses ocean energy devices, including all technologies currently being proposed, in order to gain a better understanding of their environmental impacts and explore how they can contribute to a more sustainable energy supply.

Methods The study followed the methodology of life cycle assessment including all life cycle steps from cradle to grave. The various types of device were assessed, on the basis of a functional unit of 1 kWh of electricity delivered to the grid. The impact categories investigated were based on the ILCD recommendations. The life cycle models were set up using detailed technical information on the components and structure of around 180 ocean energy devices from an in-house database.

Results and discussion The design of ocean energy devices still varies considerably, and their weight ranges from 190 to 1270 t, depending on device type. Environmental impacts are closely linked to material inputs and are caused mainly by mooring and foundations and structural components, while impacts from assembly, installation and use are insignificant for all device types. Total greenhouse gas emissions of ocean energy devices range from about 15 to 105 g CO_2-eq. kWh^{-1}. Average global warming potential for all device types is 53 ± 29 g CO_2-eq. kWh^{-1}. The results of this study are comparable with those of other studies and confirm that the environmental impacts of ocean energy devices are comparable with those of other renewable technologies and can contribute to a more sustainable energy supply.

Conclusions Ocean energy devices are still at an early stage of development compared with other renewable energy technologies. Their environmental impacts can be further reduced by technology improvements already being pursued by developers (e.g. increased efficiency and reliability). Future life cycle assessment studies should assess whole ocean energy arrays or ocean energy farms.

Keywords Device type · Horizontal axis turbine · Ocean energy · Point absorber · Tidal energy · Wave energy

1 Introduction

The world's oceans and seas are an abundant source of various forms of renewable energy. According to Falcão (2010) and Esteban and Leary (2012), six types of ocean energy can be distinguished: ocean wave, tidal range, tidal current, ocean current, ocean thermal energy and salinity gradient. In this paper, we focus on ocean wave and tidal current, which represent a potentially significant source of electricity in Europe (Magagna and Uihlein 2015). The corresponding energy industries have made considerable progress in recent years but are still at an early stage of development (Magagna and Uihlein 2015). A number of technologies are nearing the pre-commercial array

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demonstration stage, and others are being deployed in full-scale prototypes in real-sea environments (Magagna and Uihlein 2015).

As a form of renewable energy, ocean energy can contribute to a more sustainable energy supply, but it is not environmentally friendly per se. The activities involved in the manufacture, operation, maintenance and decommissioning of ocean energy devices will have various effects on the environment. However, only a few life cycle assessments (LCAs) of individual wave and tidal energy converters have been performed to date, with a main focus on devices at an advanced stage of development (Magagna and Uihlein 2015). Most studies (e.g. Parker et al. 2007; Douglas et al. 2008; Walker and Howell 2011) have looked only at energy and carbon as impact categories. According to Uihlein and Magagna (2015), good quality studies are lacking, especially for tidal current, ocean thermal energy and salinity gradient devices, and further LCA studies are needed to produce more estimates for all ocean energy technologies. For a number of wave energy device types, such as point absorbers and attenuators (the most common types), there are no LCA studies at all.

The European Commission's Joint Research Centre (JRC) has developed an ocean energy database which contains detailed technical information on 186 wave and tidal energy devices that have been tested or deployed in real-water conditions (Uihlein et al. 2015). In this paper, we assess the environmental impacts of eight types of wave energy and seven types of tidal energy devices on the basis of information in the JRC database. The remainder of the paper is structured as follows: In Section 2, we present our methodology, including goal and scope definition, functional unit and system boundaries. Section 3 gives an overview of the data, information and assumptions used to establish the LCA model. Section 4 sets out the results. Discussions and conclusions can be found in Section 5.

2 Methods

2.1 Goal and scope definition

The goal of the study is to assess the environmental impacts of various ocean energy devices producing electricity and delivering it to the European electricity network. The LCA is performed at aggregate level for tidal energy and wave energy device types, rather than on individual devices at a specific site. The study will help to identify variations between ocean energy device types with respect to environmental impacts, to identify the most important life cycle stages of ocean energy devices in terms of environmental impacts and to understand differences between wave and tidal devices.

2.2 Functional unit and system boundaries

The functional unit of the study is 1 kWh of electricity delivered to the European electricity network. The LCA encompasses all life cycle steps 'from cradle to grave', including device assembly, installation, use and end of life, as recommended in Raventos et al. (2010). Apart from the device itself (Section 3.1), it also covers mooring and foundations and the cable connection to the grid (Section 3.2). The study assumes deployment in Europe but takes account of worldwide upstream and downstream emissions and resource inputs (Section 2.3). Assumed device lifetime is 20 years. The life cycle of an ocean energy device is shown schematically in Fig. 1.

2.3 Life cycle impact assessment and interpretation

The life cycle impact assessment was performed at midpoint level and follows the recommendation in Hauschild et al. (2012). All impact categories rated levels II and III in Hauschild et al. (2012) have been included in this study (Table 1).

3 Life cycle inventory data

The GaBi v6.4 LCA software was used to model the system (Eyerer 1996; Thinkstep 2015a). Most of the primary data used stems from the JRC ocean energy database, while secondary data has mainly been retrieved from the GaBi professional database (Thinkstep 2015b). Below, we give a detailed description of the life cycle inventory and data sources used for modelling.

The JRC database includes information on tidal and wave energy devices that have been tested or deployed in real-water conditions. In addition, it contains information on tidal and wave energy projects in which such devices were used (Uihlein et al. 2015). In total, the database covers 83 tidal devices from 36 developers and 103 wave devices from 50 developers. These were all released after 1995, over 75 % after 2007 and over 50 % after 2010. They can be classified into seven tidal and eight wave energy device types (Magagna and Uihlein 2015). Figures 2 and 3 show a breakdown of the devices according to type. For some types (e.g. Archimedes screw, overtopping device), not many devices have been tested in real-water conditions, while others can be found more often: for example, the database contains 49 horizontal and 7 vertical axis turbines (tidal energy devices), 53 point absorbers and 16 oscillating wave surge converters (wave energy devices). For tidal energy converters, a design consensus seems to emerge in favour of horizontal axis turbines (Magagna and Uihlein 2015).

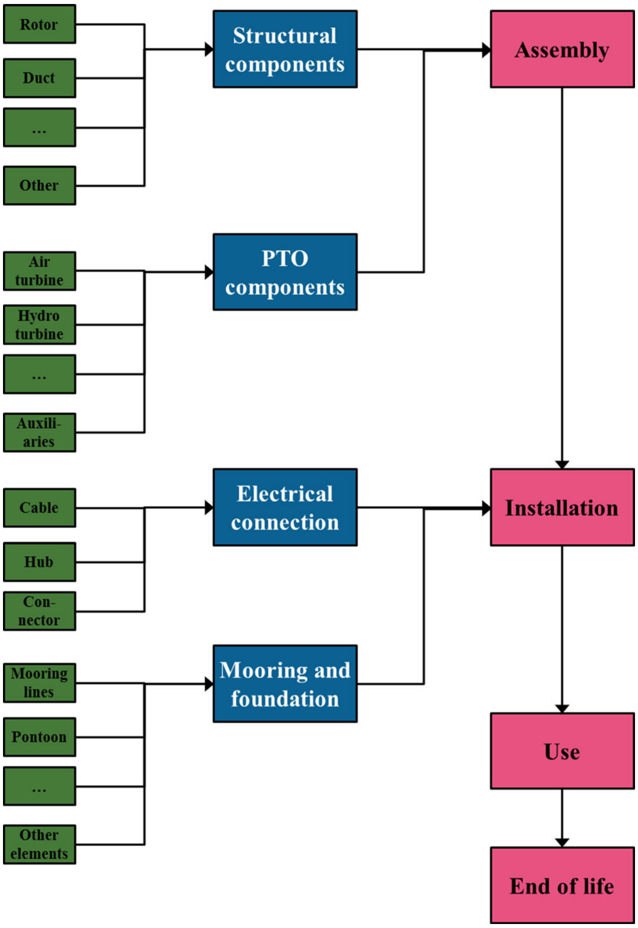

Fig. 1 Schematic life cycle of an ocean energy device. *Pink*: life cycle step, *blue*: component, *green*: sub-component

3.1 Device-specific data

At device level, the database hosts technical information on structural components and sub-components, such as numbers, weight, dimensions and materials. In addition, it contains information such as device type and developer, power rating, release year, technology readiness level and technical information (e.g. rotor speeds, blade tip speeds, pitch angles, freeboard). The type of technical information and the parameters for structural components are shown in Table A1 (Electronic supplementary material).

3.1.1 Structural components

Device types differ considerably in terms of design and structural components. Some components are found in certain device types only and are not applicable or not used for others. Figure 4 shows an example of the structural components of tidal devices in the database according to device type. The most common structural component is a rotor, as these are used in the most common device types (horizontal axis turbines, vertical axis turbines and enclosed-tip devices). Some components, such as pods or ballast, are used more rarely.

In many cases, data gaps exist in the database because information was unavailable or not disclosed by a developer for reasons of confidentiality. Various assumptions and estimates were made in order to fill the gaps (Table C1, Electronic supplementary material). In general, component mass was estimated on the basis of dimensions and average database values, and it was assumed that the most common material type was used in each case. For horizontal axis turbines and point absorbers, for example, about 90 % of the input parameters for calculating the mass of the structural components had to be based on average data. More importantly, however, we performed sensitivity analyses to assess the influence of these uncertainties and identified the most significant parameters determining the LCA results (Section 4.3).

3.1.2 Power take-off and related components

We also retrieved from the database information on power take-off (PTO) and related components, including data on turbine, shaft, gearbox, generator, control systems, frequency converter and auxiliary systems. The type of technical information and the PTO parameters are shown in Table A2 (Electronic supplementary material). Data gaps were filled in the same way as for structural components (Table C2, Electronic supplementary material).

3.2 Project-specific data

The type of mooring and foundation used for individual devices and the electrical connection, installation and maintenance depend on the individual project in which the device is deployed.

3.2.1 Mooring and foundations

Of the types of mooring and foundation used for the projects in the database (see Table B1, Electronic supplementary material), foundations were by far the most used, followed by moorings and anchors. Mooring and foundation information was used where available. If devices had been deployed in several projects, we used the mooring and foundation information from the most recent project (assuming that commercial deployment equates to more realistic conditions of use). For devices for which there was no information, we calculated and assumed the average of all mooring and foundations used in projects involving the device type in question (Table C3, Electronic supplementary material).

Table 1 Life cycle impact assessment methods used in this study

Impact category	Short name	LCIA method	Indicator	Unit
Climate change	Global warming	IPCC baseline model	Global warming potential	kg CO_2 eq.
Acidification	Acidification	Accumulated exceedance	Accumulated exceedance	Mole of H+ eq.
Ozone depletion	Ozone depletion	WMO model	Ozone depletion potential	kg CFC-11 eq.
Particulate matter/respiratory inorganics	Particulate matter	RiskPoll model	Fine particles	kg $PM_{2.5}$ eq.
Ionising radiation, human health	Ionising radiation	Human health effect model	Human exposure	kg U235 eq.
Human toxicity, cancer effects	Human tox. cancer	USEtox model	Comparative toxic units	CTUh
Human toxicity, non-cancer effects	Human tox. non-cancer	USEtox model	Comparative toxic units	CTUh
Photochemical ozone formation	Summer smog	LOTOS-EUROS model	Ozone concentration increase	kg NMVOC
Freshwater eutrophication	Freshwater eutroph.	EUTREND model	Nutrients reaching end compartment	kg P eq.
Marine eutrophication	Marine eutroph.	EUTREND model	Nutrients reaching end compartment	kg N eq.
Terrestrial eutrophication	Terrestrial eutroph.	Accumulated exceedance	Accumulated exceedance	kg N eq.
Freshwater ecotoxicity	Freshwater ecotox.	USEtox model	Comparative toxic units	CTUh
Resource depletion, fossil and mineral	Resource depletion	CML2002 reserve based	Scarcity	kg Sb eq.

3.2.2 Electrical connection

Not all the projects in the database were grid connected. The electrical connection was modelled using three parts: cable, connector and hub (Table B1, Electronic supplementary material). We assumed a 33-kV AC transmission cable (Lopez et al. 2010) with an assumed weight of 20 kg/m (Anonymous 2011). Electrical losses from the connection were not considered in this study. Cable length was retrieved from the database; if it was unavailable, we assumed the average value (2980 m). For connector and hub, we assumed a weight of 5000. No substations were included in this study.

In some cases, additional electricity networks have to be built and the existing grid has to be upgraded or reinforced when ocean arrays are deployed in remote areas with weaker grids (Magagna and Uihlein 2015). Such upgrades have not been included in this study.

3.2.3 Installation and maintenance

The database includes records of maintenance and installation operations carried out in the course of ocean energy projects. These include duration and vessel types used. If no information was available, we used average values (26 h for installation and 100 h maintenance per year).

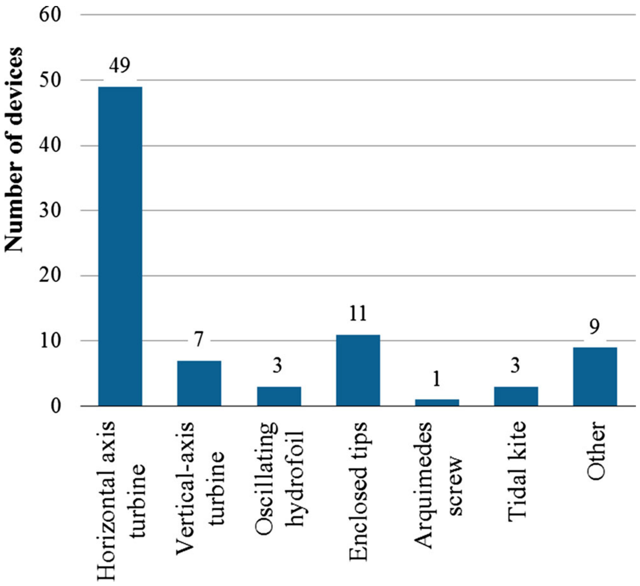

Fig. 2 Number of tidal energy devices in the database according to device type

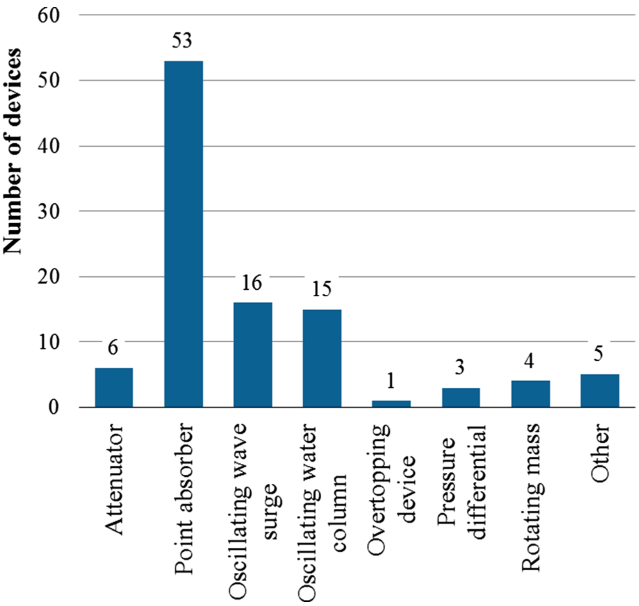

Fig. 3 Number of wave energy devices in the database according to device type

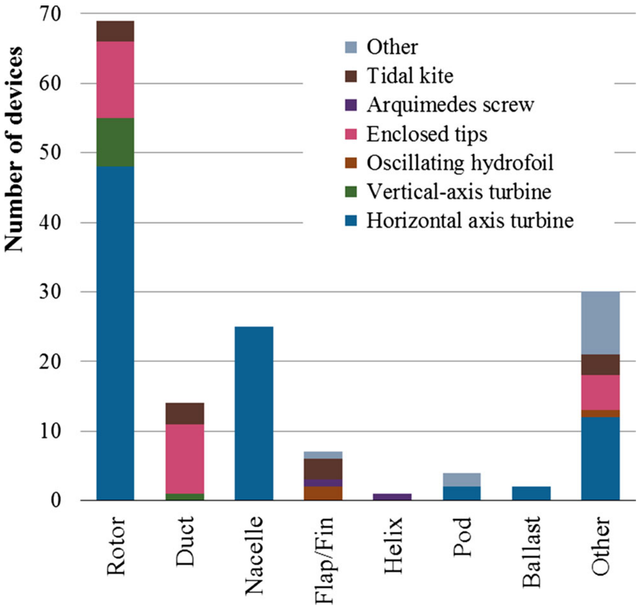

Fig. 4 Structural components of tidal devices in the database

We assumed that 70 % of the operations are executed using a vessel and 30 % using a barge.

As deployment of ocean energy devices has been limited to date, the database provides no information on replacement parts and replacement intervals. Following the example of previous studies (Parker et al. 2007; Thomson et al. 2011; Dalton et al. 2014), we assumed that no parts have to be replaced.

3.3 Power output

Electricity production was calculated using the nominal capacity of the devices. Reported capacities range from 0.07 to 3000 kW, with the majority of devices having a nominal capacity between 500 and 1000 kW (Fig. 5).

We assumed capacity factors of 34 % for tidal and 20 % for wave energy devices, which is in the range of values given by Esteban and Leary (2012).

3.4 LCI data and assumptions for upstream and downstream processes

3.4.1 Upstream datasets—materials and energy

For materials and energy carriers used to produce structural and PTO components, electrical connections and mooring and foundations, we used secondary data from databases, mainly from Thinkstep (2015b) (Table 2). We performed a sensitivity analysis as regards the type of steel assumed in the model (Section 4.3).

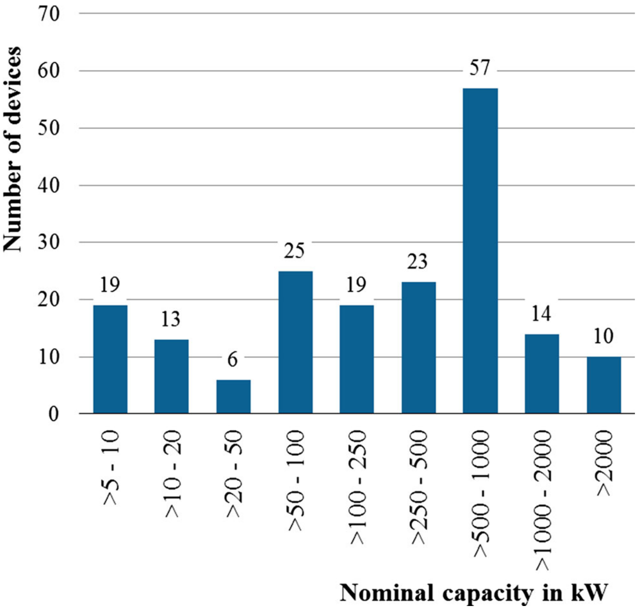

Fig. 5 Nominal capacity of ocean energy devices in the database

3.4.2 Assembly and manufacturing

We modelled device assembly assuming an electricity input of approximately 1.5 kWh/kg with an assumed electrical energy/heat ratio of 2:1 (Sullivan et al. 2013)[1] for the assembly of structural components, PTO components, mooring and foundations and the electrical connection.

Manufacturing processes for structural components (e.g. plastics injection moulding, steel sheet deep drawing, aluminium cast machining) were modelled using GaBi datasets (Thinkstep 2015b).

3.4.3 Transports

All transport was assumed to be by lorry (EU-27: articulated lorry transport). We assumed a distance of 500 km for the transport of structural and PTO components to the point of assembly and of the material for electrical connections and mooring and foundations to the harbour from which installation is carried out.

We assumed a distance of 1000 km for the transport of sub-components to the point where the components are assembled (e.g. rotor to the point of assembly of the structural components) and of upstream materials from the place of production to the place of sub-component manufacturing (e.g. transport of steel to the location where the rotor is built).

We did not include transport of the fully assembled device to the harbour since we assumed that it would be assembled at the harbour and transport distance would be negligible. We

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[1] Energy demand of machining, HVAC and lighting, heating and material handling according to Sullivan et al. (2013) have been included.

Table 2 Datasets used for materials and energy carriers

Material	Dataset used	Source
Steel	RER: stainless steel Quarto plate (316)	Thinkstep (2015b)
Plastic	DE: polycarbonate granulate (PC)	Thinkstep (2015b)
Composites	DE: sheet moulding compound resin mat (SMC)	Thinkstep (2015b)
Aluminium	EU-27: aluminium ingot mix	Thinkstep (2015b)
Water	EU-27: tap water	Thinkstep (2015b)
Copper	DE: copper mix (99.999 % from electrolysis)	Thinkstep (2015b)
Electronics	Modelled according to electronic component	Heck (2007)
Lead	EU-27: lead primary and secondary mix ILA	Thinkstep (2015b)
PVC	RER: polyvinylchloride injection moulding part	Thinkstep (2015b)
PE pipe	RER: polyethylene pipe (PE-HD)	Thinkstep (2015b)
Tin	RER: tin, at regional storage	Ecoinvent (2007)
Platinum	RER: platinum, at regional storage	Ecoinvent (2007)
Nickel	GLO: nickel, 99.5 %, at plant	Ecoinvent (2007)
Concrete	CN: prefabricated concrete part slab, 40 cm	Thinkstep (2015b)
Electricity	EU-27: electricity grid mix	Thinkstep (2015b)
Heat	EU-27: thermal energy from natural gas	Thinkstep (2015b)
Light fuel oil	EU-27: light fuel oil at refinery	Thinkstep (2015b)

included transport of 1000 km to the final disposal site (landfill, incineration) after use.

The results show that the environmental impacts of transport are negligible as compared with other life cycle steps (Section 4.2) so the very generic assumptions on transport distances and means are justified.

3.4.4 Installation and maintenance

For installation and maintenance operations, the use of vessels and barges was modelled as described in Section 3.2.3. We used the 'GLO: bulk commodity carrier' and 'EU-27: barge incl. fuel' datasets (Thinkstep 2015b).

3.4.5 End of life

For modelling the end of life (EOL) of the ocean energy devices, we assumed no environmental impacts from disassembly processes. We assumed three different EOL routes for materials used—recycling, incineration and landfilling (Table 3) taking the proportional breakdown from Zimmermann (2012).

Since no one has any real experience of disposal of ocean energy devices, this can be considered a rough estimate. For the majority of materials (e.g. steel and other metals), the recycling quota could probably be higher. We applied no credits for recycling. For landfilling and incineration, we used the relevant datasets from Thinkstep (2015b). A credit was applied for energy recovery from incineration and recycling, using the datasets from Table 2 for electricity and heat.

4 Results

4.1 Mass flows

Figure 6 shows the average volume of material used to produce the device. Device weights vary considerably between device types: from about 190,000 kg for enclosed-tip devices to 1,270,000 kg for overtopping devices. On average, tidal device types have a lower mass than wave energy devices.

For most device types, mooring and foundations contribute most to total device weight. For 12 types, the proportion is over 50 % and it can reach 86 % in the case of the vertical axis turbine. Structural components are also important, making up an average 26 % of the total weight. PTO components account for a relatively minor proportion (less than 10 % for 10 device types), but this can reach 36 % in the case of attenuators. The electrical connection contributes less than 10 % in all device types except oscillating hydrofoils.

We also calculated the specific mass of device types in terms of kilograms per kilowatt nominal capacity. Here, the difference between tidal and wave energy devices is small (Fig. 7). Specific weights range from about 470 kg kW^{-1} for enclosed-tip to about 3860 kg kW^{-1} for rotating mass devices. Interestingly, the relative weight contribution of structural components is much higher in wave energy devices than in tidal energy devices (38 and 12 %, respectively).

As regards the mass of material used, we found that steel predominates. For all device types except overtopping devices, steel accounts for over 45 % of total weight (Table 4). Concrete is an important material in overtopping devices

Table 3 Assumptions and datasets for EOL

Material	Recycling (%)	Incineration (%)	Landfill (%)
Ferrous metals	90	0	10
Non-ferrous metals	95	0	5
Plastics	80	20	0
Composites	0	100	0
Concrete	85	0	15
Sand[a]	0	0	0
Electronics	0	100	0

Source: Zimmermann (2012)

[a] Used only as ballast, assumed to remain on the seabed after use

(about 55 %) and makes up between about 20 and 30 % of the weight of eight device types. Proportions of other metals (aluminium, iron, copper) and plastics can go up to 13 % but in general are less than 10 %. Electronics make up no more than 4 %.

4.2 LCA results: base case

A wealth of LCA results was obtained from the model calculations. We will look first at the environmental impacts of the most prevalent device types, i.e. horizontal axis turbine for tidal energy and point absorber for wave energy devices.

The environmental impacts of horizontal axis turbines are shown in Fig. 8. The individual components are displayed separately, while the processes for device assembly and installation have been grouped together. For almost all impact categories, mooring and foundations contribute the most environmental impacts. Depending on impact category, the electrical connection and PTO components account for significant proportions (over 25 %). Structural components and end of life contribute very little, while assembly, installation and use do not produce significant impacts.

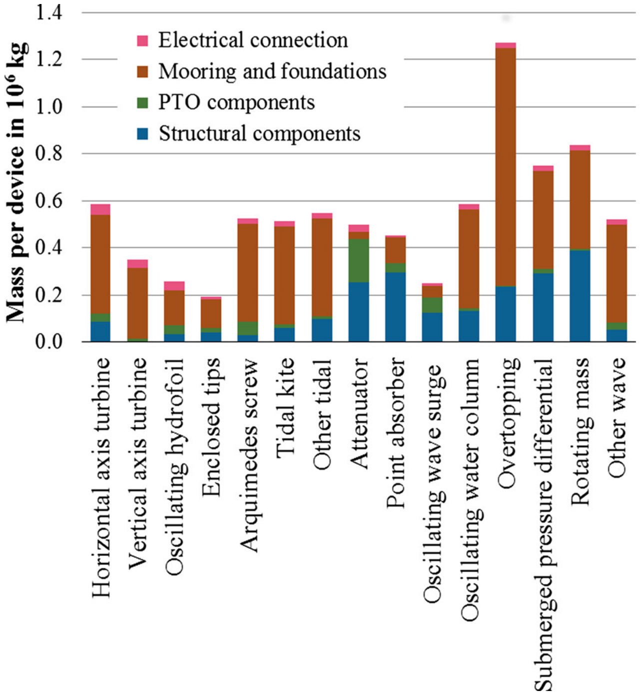


Fig. 6 Amount of materials for the production of ocean energy devices

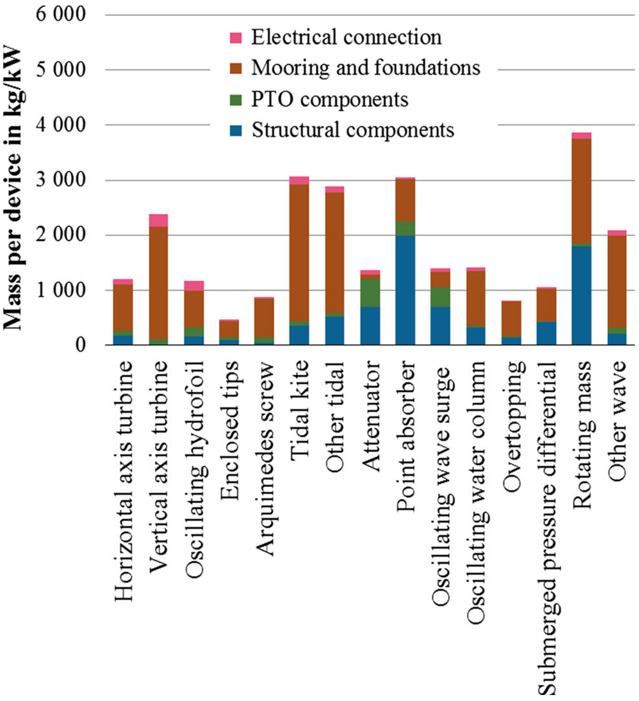


Fig. 7 Amount of materials for the production of ocean energy devices

Figure 9 shows the (somewhat different) results for point absorbers. Clearly, structural components dominate the environmental impacts; they account for over 40 % in all but two impact categories. Next, mooring and foundations but also PTO components (in two impact categories) play a significant role. Again, the impacts from assembly, installation and use are not significant.

The LCA results for these two device types closely reflect the relative contributions of the various components to the overall weight of the device as shown in Fig. 7. We analysed the correlation between the volume of material used per component (structural components, PTO components, electrical connection, mooring and foundations) and the environmental impacts per component (including end of life). As shown in Table 5, environmental impacts are closely related to mass flows. For almost all impact categories except ionising radiation and freshwater eutrophication, there are positive correlations between component mass and the environmental impacts. Correlation coefficients are greater than 60 % for the majority of impact categories and ocean energy devices.

Freshwater eutrophication impacts are dominated by some materials that have disproportionately high specific impacts: polycarbonate, copper (used for cables in the electrical connection) and stainless steel, which is used mainly in mooring

Table 4 Share of material used to produce ocean energy device in % of total weight

Device type	Steel	Other metals	Electronics	Plastics[a]	Concrete	Sand	Water
Horizontal axis turbine	50.24	6.38	0.86	6.98	32.69	0.78	2.07
Vertical axis turbine	88.40	5.52	1.47	4.60	0.00	0.00	0.00
Oscillating hydrofoil	76.99	9.70	1.81	11.21	0.30	0.00	0.00
Enclosed tips	77.82	8.02	2.85	10.86	0.45	0.00	0.00
Archimedes screw	54.52	12.52	0.34	7.59	25.03	0.00	0.00
Tidal kite	64.28	2.62	1.54	5.59	25.98	0.00	0.00
Other tidal	64.49	3.28	0.57	7.14	24.53	0.00	0.00
Attenuator	46.20	7.04	1.03	6.56	6.30	8.96	23.90
Point absorber	50.36	3.80	0.94	11.98	13.60	5.27	14.05
Oscillating wave surge	55.01	7.93	3.03	12.97	8.33	3.47	9.25
Oscillating water column	60.62	3.14	0.59	4.01	31.63	0.00	0.00
Overtopping	36.73	0.93	0.15	0.92	55.48	1.58	4.21
Submerged pressure differential	63.11	3.37	0.93	11.22	21.29	0.02	0.05
Rotating mass	46.11	2.81	0.34	4.87	20.56	6.90	18.40
Other wave	65.51	3.63	0.54	4.76	25.56	0.00	0.00

[a] Includes also composites

and foundations (e.g. piles). High ionising radiation impacts stem from the electricity demand of manufacturing processes (e.g. production of electronics, assembly process). Resource depletion impacts are linked mainly to copper and steel.

We also quantified the proportion of environmental impacts stemming from transport processes. For both horizontal axis turbines and point absorbers, this is not significant. For no impact category do the impacts from transport exceed 0.2 % of total impacts.

Since ocean energy is considered by many as a technology that will contribute to a low-carbon energy system, we looked in detail at the LCA results for global warming. Figure 10 shows the global warming potential (GWP) of device types according to life cycle step. Total greenhouse gas (GHG)

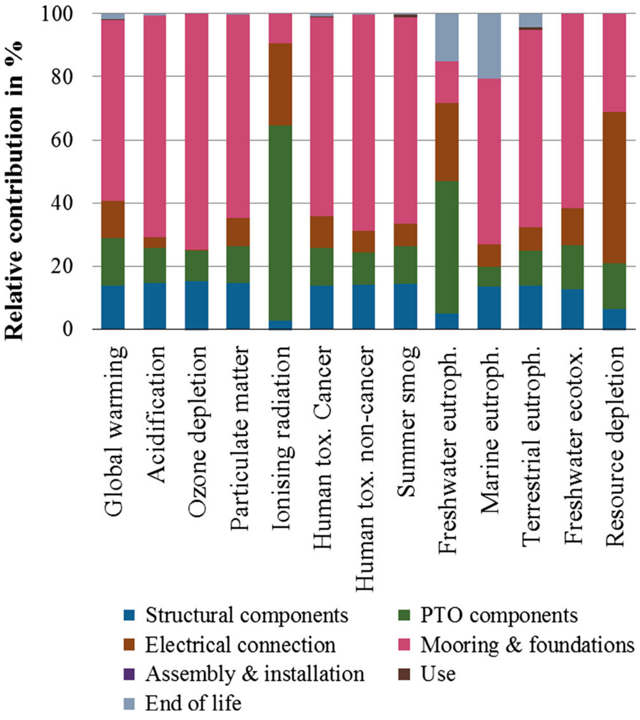


Fig. 8 Environmental impacts of horizontal axis turbines according to life cycle step

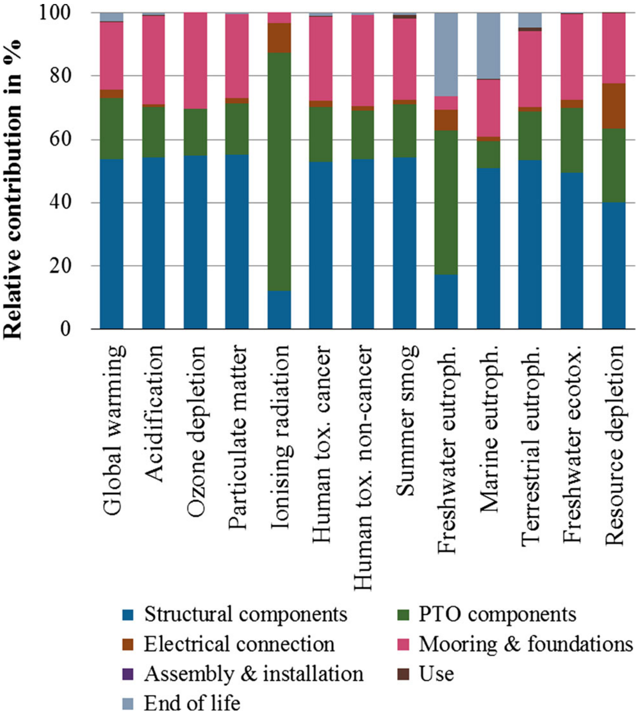


Fig. 9 Environmental impacts of point absorber according to life cycle step

Table 5 Correlation between environmental impacts and device mass per life cycle step

Impact category	HAT	VAT	OHF	ETP	AQS	TKT	TOT	ATT	PTA	OWS	OWC	OVT	SPD	RMA	WOT
Global warming	0.99	1.00	0.98	0.93	1.00	0.98	1.00	0.68	0.97	0.80	0.99	0.99	0.98	0.94	1.00
Acidification	0.99	1.00	0.98	0.99	1.00	1.00	1.00	0.60	0.98	0.87	1.00	0.98	1.00	0.89	1.00
Ozone depletion	0.99	0.99	0.97	0.99	1.00	1.00	1.00	0.57	0.98	0.88	1.00	0.97	1.00	0.87	1.00
Particulate matter	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.60	0.99	0.88	1.00	0.98	1.00	0.90	1.00
Ionising radiation	−0.24	−0.18	−0.11	−0.20	0.13	−0.25	−0.20	0.41	−0.14	0.00	−0.25	0.36	−0.37	−0.30	−0.09
Human tox. cancer	0.99	1.00	1.00	0.98	1.00	1.00	1.00	0.58	0.98	0.83	1.00	0.98	1.00	0.89	1.00
Human tox. non-cancer	1.00	1.00	0.99	0.99	1.00	1.00	1.00	0.57	0.98	0.87	1.00	0.98	1.00	0.88	1.00
Summer smog	1.00	1.00	0.99	0.98	1.00	1.00	1.00	0.62	0.98	0.86	1.00	0.98	1.00	0.90	1.00
Freshwater eutroph.	−0.13	−0.02	−0.07	−0.16	0.31	−0.18	0.12	0.53	0.46	0.22	0.06	0.78	0.01	0.47	0.24
Marine eutroph.	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	0.99	0.99	1.00
Terrestrial eutroph.	1.00	1.00	1.00	0.99	1.00	1.00	1.00	0.70	0.99	0.90	1.00	0.99	1.00	0.93	1.00
Freshwater ecotox.	0.99	1.00	0.99	0.96	0.99	0.99	1.00	0.52	0.95	0.71	0.99	0.97	0.99	0.86	1.00
Resource depletion	0.34	0.76	0.33	0.76	0.57	0.82	0.82	0.20	0.88	0.33	0.80	0.84	0.83	0.63	0.82

HAT horizontal axis turbine; *VAT* vertical axis turbine; *OHF* oscillating hydrofoil; *ETP* enclosed tips; *AQS* archimedes screw; *TKT* tidal kite; *TOT* other tidal; *ATT* attenuator; *PTA* point absorber; *OWS* oscillating wave surge; *OWC* oscillating water column; *OVT* overtopping; *SPD* submerged pressure differential; *RMA* rotating mass; *WOT* other wave

emissions range from about 15 g CO_2-eq. kWh^{-1} for enclosed-tip devices to about 105 g CO_2-eq. kWh^{-1} for point absorber and rotating mass devices. The average GWP for all device types is 53 ± 29 g CO_2-eq. kWh^{-1}.

For almost all device types, mooring and foundations contribute most to GHG emissions (over 40 % for 12 out of 15 device types). With attenuator and oscillating wave surge devices, the PTO components account for the proportion of GHG emissions; with point absorbers, the structural components are responsible for the majority. Electrical connections are not a major source of GHGs; in general, they contribute less than 10 % and are responsible for a significant proportion only in the case of oscillating hydrofoils. The proportions for other life cycle stages (assembly, installation, use and end of life) are almost negligible (2.6 % and less) for all device types.

4.3 LCA results of sensitivity analysis

We performed a sensitivity analysis for one tidal (horizontal axis turbine) and one wave energy device (point absorber) in order to identify the model parameters that have the biggest influence on environmental impacts. Each parameter of the model was varied by ±50 % and the resulting variation of the environmental impacts was calculated for each impact category.

In total, 15 parameters have a big influence on the results, i.e. varying the parameter by ±50 % led to a change of over 5 % in at least one environmental impact category (Table 6). Depending on device type, the weight of various subcomponents (e.g. nacelle, frequency converter, gravity base) has a great influence on the results. Naturally, parameters affecting the use phase have a significant influence, e.g. a 50 % decrease in lifetime will increase environmental impact by about 98 to 100 %.

A sensitivity analysis was also carried out for the type of steel modelled, since the use of steel contributes significantly to the LCA results. In the base case, it was assumed that stainless steel is used in all parts of the device (Table 2). The alternative considered in the sensitivity analysis is finished cold-rolled coil steel (Thinkstep 2015b). This carbon steel shows lower environmental impacts per kilogram (1 to 85 % less than the stainless steel modelled, depending on the impact category). The LCA results for carbon steel for the horizontal axis turbine and the point absorber showed that the potential environmental impacts would be much lower (by 47 to 99 %

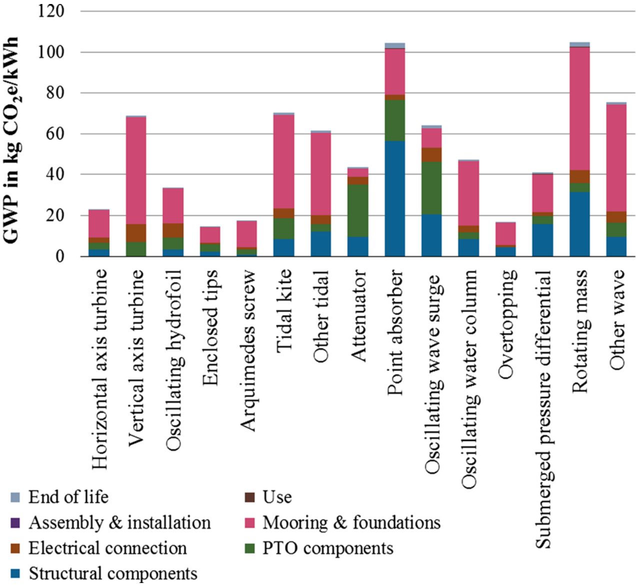


Fig. 10 Global warming potential according to life cycle step

Table 6 Range of changes in environmental impacts across impact categories for parameters; the model shows greatest sensitivity in percentage related to a change of the parameter by 50 %

Life cycle step	Component	Parameter	Horizontal axis turbine	Point absorber
Assembly	Structural component	Weight nacelle	0.75–5.60	n.a.
		Weight float	n.a.	1.44–14.82
		Weight other	n.a.	3.60–20.39
	PTO component	Weight frequency converter	0.26–9.90	0.18–6.53
		Weight control system	n.a.	0.22–7.71
		Weight auxiliaries	0.48–18.29	0.57–20.11
Installation	Mooring and foundations	Weight of lattice support tower	0.86–8.98	n.a.
		Weight of pontoon	n.a.	0.55–6.24
		Weight of gravity base	2.16–18.77	0.57–5.09
		Weight of pile	1.18–12.40	n.a.
	Electrical connection	Weight of cable	0.00–10.11	n.a.
		Weight of connector	0.06–8.85	n.a.
Use	n.a.	Nominal capacity	100.00	100.00
		Capacity factor	100.00	100.00
		Lifetime	98.87–100.00	98.49–100.00
Assembly, installation and EOL	Steel	Carbon steel[a]	1.00–53.00	1.00–54.00

n.a. not applicable

[a] In the case of the sensitivity analysis for steel, it was assumed that 100 % of stainless steel (see Table 2) is replaced with finished rolled coil steel

for the horizontal axis turbine and 46 to 99 % for the point absorber, depending on impact category). Thus, the assumptions for the base case are very much a simplification and might be considered as representing a worst-case scenario.

4.4 LCA results: scenarios

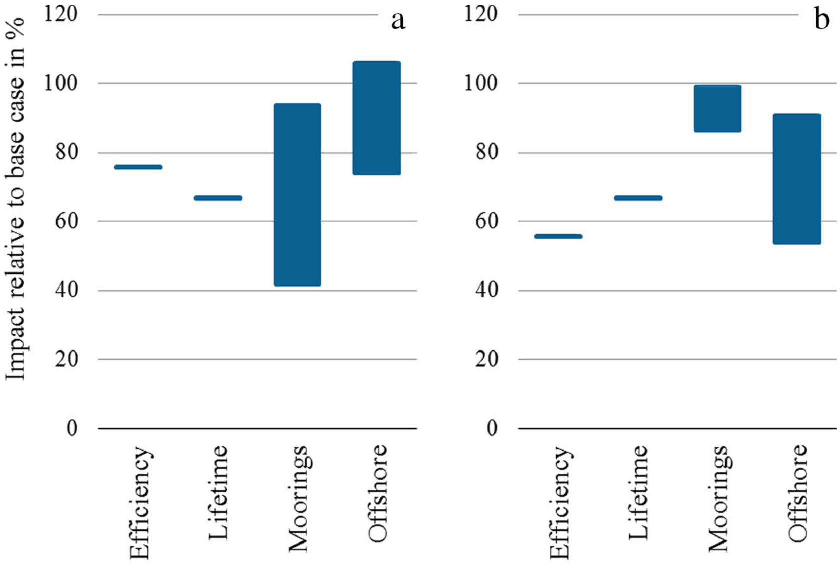
We drew up a number of scenarios (Table 7) to model potential improvements in life cycle environmental impact, reflecting the importance of individual parameters or environmental hot spots (see Section 4.3) and the ways in which technology developers can change such device- and project-specific parameters. The horizontal axis turbine was again chosen to exemplify results for tidal energy devices and the point absorber for wave energy devices. We modelled the scenarios shown in Table 7. The bars in Fig. 11 give the range of environmental impacts as compared with the baseline scenario over all impact categories. One must keep in mind that the results are indicative and to some extent hypothetical. For example, higher capacity factors might be achieved only by changes in device design that also affect environmental impacts from manufacturing, which could offset some of the potential environmental gains. Such effects have not been taken into account in this study but represent an interesting field to pursue in future assessments.

If technology developers could increase capacity factors to the maximum values stated in Carlsson (2014), the environmental impacts of horizontal axis turbines and point absorbers could be reduced to 76 and 56 %, respectively, for all impact categories (Fig. 11). Similarly, a 50 % longer device lifetime could reduce the life cycle environmental impacts of both devices by 33 % (for all impact categories), given that almost

Table 7 Scenarios modelled

Scenario	Description	Assumptions
Increased efficiency	Higher capacity factor	CF of 45 % instead of 34 % for tidal and 36 % instead of 20 % for wave
Increased durability	Higher lifetime	Lifetime of 30 years instead of 20 years
Other mooring and foundations	Using mooring lines instead of foundations	No piles, pontoon and support towers used for mooring but only anchors, mooring lines and gravity base. Values for average tidal/wave device used
Moving further offshore	Higher ocean energy resources but longer cable connection	Average distance from shore is about 2120 m for horizontal axis turbines and 260 m for point absorbers. An increased distance of 10 km is assumed in the scenario, allowing for reaching maximum capacity factors (see above, 45 and 36 % for tidal and wave energy devices, respectively)

Fig. 11 Range of environmental impacts over all impact categories relative to baseline. **a** Horizontal axis turbines. **b** Point absorbers



all impacts stem from assembly, installation and end of life and almost none occur during the use phase (Figs. 9 and 10).

The scenario for a change in mooring and foundations suggests that environmental impacts can be reduced for all impact categories. Reductions range from 6 to 58 % for horizontal axis turbines and from 1 to 14 % for point absorbers. The reduction potential for tidal energy devices is higher since they use heavier foundation systems (e.g. gravity bases) than wave energy devices. In the calculations, we did not take into account whether local (wave/tidal current climate) and device-specific circumstances allowed for a change of mooring and foundation system. Still, considering the large contribution that mooring and foundations make to environmental impacts, even small improvements will help to reduce overall impact.

The fourth scenario analysed the effects of moving devices further offshore, allowing for the use of greater ocean energy resources. This increases efficiency, but the gains in terms of environmental impact are offset by the longer cable connections to be installed in the sea. For point absorbers, there are still net environmental benefits for all impact categories, mainly thanks to high efficiency gains (Fig. 11). For horizontal axis turbines, benefits can be seen for all environmental impacts except freshwater eutrophication and freshwater ecotoxicity. Assumed increases in efficiency (capacity factor between 34 and 45 %) do not counterbalance additional impacts from the cable connection.

Another scenario we considered was the use of lightweight materials such as composites and aluminium. This could involve greater specific environmental impacts per kilogram of material but also a possible reduction in impacts due to the lower mass of material used. However, there are a number of uncertainties around this scenario, e.g. how much steel might be replaced and the extent to which the structural weight could be reduced. Also, the 'lightweighting' of ocean energy devices

Table 8 Life cycle impact assessment results from literature and this study

Device type	Impact category	Unit	Literature	This study
Attenuator	Global warming	g CO_2-eq./kWh	22.8[a]–29.8[b]	43.7
	Ozone depletion	g CFC-11 eq./kWh	2.3[b]	1.8
	Freshwater eutroph.	mg P eq./kWh	9.84[b]	0.16
	Marine eutroph.	mg N eq./kWh	21.0[b]	10.0
Oscillating wave surge	Global warming	g CO_2-eq./kWh	25[c]	64
Point absorber	Global warming	g CO_2-eq./kWh	39–126[d]	104.5
	Ozone depletion	g CFC-11 eq./kWh	1.48–4.58[d]	4.2
Horizontal axis turbine	Global warming	g CO_2-eq./kWh	15–20[e]	23.1

[a] Parker et al. (2007)

[b] Thomson et al. (2011)

[c] Walker and Howell (2011)

[d] Dahlsten (2009)

[e] Douglas et al. (2008)

does not currently seem possible, for economic reasons. Due to the uncertainties, the results of this scenario cannot be considered robust enough for a solid conclusion; this might be analysed in a further study.

5 Discussion and conclusions

The results of this analysis have shown that there is still considerable divergence in design options for ocean energy (especially wave energy) devices, as also stated in Magagna and Uihlein (2015). There are great variations in weight/power ratios, with specific device weights varying by almost an order of magnitude (from about 470 to 3860 kg/kW). Compared with other renewable energy technologies, ocean energy devices seem to demand quite a high input of materials per installed capacity. For example, according to Krauter (2006), photovoltaic systems weigh 330 to 360 kg/kW and wind turbines about 340 to 770 kg/kW (Guezuraga et al. 2012). Of course, the material intensity of ocean energy devices can be reduced when they are deployed in arrays, since they can then share some components (e.g. cable connection to the shore, foundation systems). The high power density of tidal current or waves, for example, which in principle allows high efficiencies, also places high demands on devices in terms of reliability and survivability and thus in turn on material inputs.

As mentioned above, most LCAs on ocean energy have focused on energy use and carbon dioxide emissions, to the exclusion of other environmental impact categories. The results of the LCA for the base cases for GHG emissions are in line with the results from previous studies (Table 8). Greater deviations were found for other impact categories, such as eutrophication, possibly, because our impact assessment models differed from those used in previous studies.

We concur with all previous studies that contain and disclose detailed information on the spread of impacts across life cycle phases (e.g. Walker and Howell 2011) in finding that the main environmental impacts from ocean energy devices from an LCA perspective are due to materials use, while installation, maintenance and operation do not show significant impacts.

Comparison with other renewables showed that energy and carbon intensity levels would be similar to those of large wind turbine installations (Walker and Howell 2011). For example, average GHG emissions for electricity production from other renewables are about 34 and 50 g CO_2-eq./kWh for wind and solar PV, respectively (Nugent and Sovacool 2014), 20–80 g CO_2-eq./kWh for concentrated solar power (Burkhardt et al. 2012) and 40–80 g CO_2-eq./kWh for geothermal (Frick et al. 2010). Ocean energy devices thus offer the potential to limit environmental impacts to levels associated with other renewable technologies, especially as regards global warming. Certainly, they can contribute to a more sustainable energy supply as compared with fossil fuels (Lewis et al. 2011).

Environmental impacts from ocean energy devices can be further reduced, as the scenario calculations have shown (Section 4.3). Developers are already focusing on improvements such as increased efficiency, durability and reliability and better mooring systems, in order to advance ocean energy technologies and further reduce costs (Magagna and Uihlein 2015). One approach to increasing efficiency and reducing environmental impacts is to move further offshore in order to deploy devices in areas with greater resources (e.g. higher wave energy). However, environmental benefits could be offset by the longer cable lengths needed, so this option needs to be examined carefully.

In the future, ocean energy devices will also be installed in arrays or even ocean energy farms. This will clearly reduce the environmental impacts per kilowatt-hour of electricity produced, since some components (e.g. cable, electrical hubs, substation) could be shared. Future LCAs should thus focus on whole arrays of ocean energy devices. Since ocean energy resources are variable (although very predictable, e.g. in the case of tidal currents), studies taking into account the fluctuations in electricity production would also be very useful for assessing the environmental benefits of ocean energy.

Compliance with ethical standards

Disclaimer The views expressed in this paper are those of the writer only and may in no circumstances be regarded as representing an official position of the European Commission.

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