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Life cycle assessment of a point absorber wave energy converter

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ABSTRACT

Harnessing wave energy from the oceans using wave energy converters (WECs) offers a huge opportunity to diversify Europe's future renewable energy system. Although the energy conversion of this pre-commercial technology is not directly linked to greenhouse gas emissions, environmental sustainability over the full life cycle needs to be ensured for a future-proof large-scale application of WECs. Therefore, we present a cradle-to-grave full life cycle assessment (LCA) study for a generic point absorber WEC based on a fully transparent and adaptable life cycle inventory. Within the study we assess the environmental impacts of a single point absorber device, the influence of different hull materials, hotspots in the impacts of WEC components, and variations induced by different deployment locations. For a WEC deployed in the North Sea, we found a global warming impact of 300-325$gCO_2eq./kWh$ with periphery and 52-77$gCO_2eq./kWh$ without periphery, depending on the hull material. Using an alternative fibre-reinforced concrete material for the hull can reduce the impact across all categories by between 10% (marine eutrophication) and 78% (human toxicity, carcinogenic). In addition to the WEC itself we found that the electrical cable and vessel operations, particularly for maintenance, are significant contributors. These two elements will also be relevant to other marine renewables such as offshore wind and floating solar. Overall, this study shows potential for improving environmental impacts from WECs and identifies possible levers to achieve such a reduction.

1. Introduction

The progression of anthropogenic climate change calls for a transition away from fossil fuels and towards renewable energy sources (Lee and Romero, 2023). Wind and solar are currently advancing fast but are not the only viable alternatives (IRENA, 2021; IEA, Renewables, 2023). Our oceans hold a vast amount of extractable energy, especially in the form of waves, potentially able to deliver more than the current global annual electricity demand (Satymov et al., 2024). The extractable wave resource is abundant, distributed widely around the globe and is characterised by high energy density (Lavidas and Kamranzad, 2021). In addition, it is a suitable candidate to help integrate high shares of renewables into the electricity grid (Kluger et al., 2023) due to its low seasonal variations, predictability and different intermittency pattern compared to wind and solar (Reikard, 2013; Satymov et al., 2024). Seeing this potential the European Union has included wave energy into their renewable energy strategy and targets large-scale implementation of 1 GW of wave energy by 2030 and 40GW by 2050 (European Commission, 2020).

Wave energy as a renewable energy technology can potentially contribute to a more sustainable energy supply (European Environment Agency, 2024; Uihlein, 2016). Prior assessments have shown that this is the case for mature renewables like wind and solar (Hertwich et al., 2015). As wave energy is still in its pre-commercial state (Guo and Ringwood, 2021) it can be beneficial for decision-making on further design and large-scale implementation of wave energy to now assess the technology's environmental performance over its entire life cycle, thus avoiding shifting of burdens and large efforts to implement changes later on (Cucurachi et al., 2018).

Existing wave energy converters (WEC) differ widely in their principles of energy capture and conversion, their feasible deployment locations with respect to the shore as well as their built-up and appearance (Falcão, 2010). Despite a lack of a certain favoured design until today, current developments tend to focus more on point absorber (PA) WECs, as evidenced by the number of projects developed (IRENA, 2021; IRENA, 2020; Uihlein, 2016). Consequently, this study comprises a life cycle assessment (LCA) of WECs. LCA is a method to quantitatively assess the potential environmental impacts a product is associated with over its entire life cycle (Guinée, 2002). It is widely applied for the

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List of abbreviations

General

AC	Alternating Current
AEP	Annual Energy Production
AHTS	Anchor Handling and Tug Support Vessel
CF	Capacity Factor
CLV	Cable Lay Vessel
CTV	Crew Transfer Vessel
DC	Direct Current
EOL	End of Life
HFO	Heavy Fuel Oil
HVDC	High Voltage Direct Current
L	Lifetime
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEP	Lifetime Energy Production
OSV	Offshore Support Vessel
OWC	Oscillating Water Column
PA	Point Absorber
PTO	Power take-Off Unit
RP	Rated Power
WEC	Wave Energy Converter
XLPE	Cross-Linked Polyethylene

Impact Categories

AC	Acidification
FD	Non-Renewable Energy Resource Depletion
FE	Freshwater Eutrophication
FET	Freshwater Ecotoxicity
GW	Global Warming
HTc	Human Toxicity, Carcinogenic
HTnc	Human Toxicity, Non-Carcinogenic
IR	Ionising Radiation
LU	Land Use
MD	Metals/Minerals Material Resource Depletion
ME	Marine Eutrophication
OD	Ozone Depletion
PM	Particulate Matter Formation
POF	Photochemical Oxidant Formation
TE	Terrestrial Eutrophication
WU	Water Use

assessment of renewable energy technologies (Turconi et al., 2013; United Nations Economic Commission for Europe, 2022) and is recommended for use by the European Union (Joint Research Centre, 2010).

LCA has previously been used to assess the environmental performance of wave- and ocean energy devices (Paredes et al., 2019; Uihlein and Magagna, 2016). We found 19 studies on WECs, summarised in Table 1.

Regardless of the number of studies, there is a mismatch between the number of wave energy projects under development (Uihlein, 2016; IRENA, 2021) and the number of LCAs performed on specific prototypes, suggesting the need for a greater number and more generalisable assessments of WECs. The results of prior studies are still variable, with global warming (GW) impacts ranging from 20 to $374 gCO_2eq./kWh$. This is partly due to differences in the operating principles of assessed devices, but also due to methodological inconsistencies in the studies. In particular, modelling decisions on the set system boundaries, the chosen functional unit or the inclusion of recycling credits differ widely. Further, seven of the 19 studies do not cover impact categories not related to greenhouse gases, carbon or energy.

Despite the large range of results, major drivers of impacts are apparent. Most global warming impacts stem from the used materials in the structural components and mooring and make up between 40% and 90% depending on the study. This trend is not only visible in the category of GW but also other impact categories like resource depletion (metal and fossils), aquatic eutrophication, human toxicity, water ecotoxicity, ozone depletion, terrestrial acidification, photochemical oxidant formation, particulate matter formation, land and water use (Paredes et al., 2019). This hotspot is well known, still only few studies assess viable alternative materials for comparison. Today most WECs are made of steel due to large dimensions of the structures with high requirements for survivability to withstand the harsh marine environment (WECHULL+; Guo and Ringwood, 2021). However, recently composite materials and concrete structures are explored as alternative.

The three most comprehensive LCAs to date are from Uihlein, (2016), Thomson et al., (2019) and Pennock et al., (2022) which all are methodologically consistent cradle-to-grave studies that assess a wide range of impact categories according to mature impact assessment methods. Uihlein (2016) collectively assessed 103 WECs from 50 developers, covering eight different working principles based on a European database for ocean energy projects (not public). The study provides a high-level overview over the principal impacts based on the generic structure of the WEC types but does not give further details on the underlying modelling principles. Point absorbers are found to be the most commonly developed type of WEC with 53 out of 103 devices, but also show the highest impacts in GW with $105 gCO_2eq./kWh$.

Most other studies assess existing WEC prototypes and therefore entail higher degree of detail in the assumptions made regarding the device built-up. These predominantly rely on undisclosed project data. Thomson et al., 2019 reassessed the environmental impacts of the Pelamis attenuator and identified 15–20% higher impacts in the GW category than previously found for this device (Thomson et al., 2011). This highlights the importance of assessing environmental impacts beyond carbon and energy intensities, which were not previously included, and other methodological improvements regarding the consideration of recycling credits. The study discloses detailed LCA modelling steps, approximations and parts of the used data which makes the study the most transparent to be found. Pennock et al. (2022) assessed an array of the only currently near-commercial PA WEC from CorPower Ocean. They found that the GW impacts for the composite buoy array are two to three times lower than those for PAs assessed in Uihlein's collective LCA. Although the study presents itself as methodologically consistent, data used is not disclosed and modelling assumptions are not documented transparently.

In this study, we assess the environmental impacts of a single generic WEC in different configurations and deployment scenarios, based on a holistic and detailed life cycle inventory (LCI). The LCI is transparently documented, based on publicly available or disclosed data and is consistent with the acknowledged LCA modelling practices. This fully transparent, adaptable and methodologically consistent LCI therefore serves as a reproducible framework to build upon and extend. By this, we address a lack of transparency in previous LCA studies on WECs and seek to fill a gap in the literature regarding a common approach for assessing wave energy technology using LCA. This combination of a transparent representative LCI and holistic impact assessment of different configurations and deployment scenarios makes this study one of the most open, comprehensive and detailed LCAs for WECs to date.

The paper is structured as follows: In section 2 the life cycle inventory model of a generic point absorber WEC is presented. In section 3 impact assessment results obtained with the model are shown. Findings are discussed in section 4 and main conclusions and recommendations are summarised in section 5.

Table 1
Identified LCA studies on WECs between 2006 and 2023.

Authors	Year		WEC	Installed capacity	Operating principle	Functional unit	Impact assessment method	Lifetime [yrs.]	Global warming impacts [gCo2eq./kWh]
Bastos et al.	2023	Bastos et al. (2023)	LiftWEC	100 MW	Others	1 kWh electricity	ReCiPe 2016, Cumulative energy demand	25	32
Bruno et al.	2022	Bruno et al. (2022)	Generic	na	OWC	1 year of device operation	Global warming potential	na	203–270
			Seabased		OWC				94–374
			SeadampFX		On-shore PA				105–158
Apolonia & Simas	2021	Apolonia and Simas (2021)	MegaRoller	1 MW	Wave surge	1 kWh electricity	ReCiPe Midpoint, Cumulative energy demand	20	33,8–75,1
Di Muro et al.	2021	Di Muro et al. (2021)	ISWEC	100 kW	Rotating mass	1 kWh electricity	Undefined	20	31,5-62
Pennock et al.	2022	Pennock et al. (2022)	CorPower C4	10 MW	PA	1 kWh electricity	ReCiPe Midpoint	20	25–42
Karan et al.	2020	Karan et al. (2020)	Oyster 1	315 kW	Wave surge	1 kWh electricity	EDIP2003, Cumulative energy demand	15	79
			Oyster 800	800 kW	Wave surge			20	57
Thomson et al.	2019	Thomson et al. (2019)	Pelamis	750 kW	Attenuator	1 kWh electricity	ReCiPe Midpoint, Cumulative energy demand	20	35
Patrizi et al.	2019	Patrizi et al. (2019)	OBREC	3 kW	Overtopping	1 device	Global warming potential	60	37–86
Banjaree et al.	2013	Banerjee et al. (2013)	Pelamis	750 kW	Attenuator	1 device	Carbon and energy audit	20	20
			Wave Dragon	7 MW	Overtopping			50	28
Zhai et al.	2018	Zhai et al. (2018)	Buy-rope-drum	10 kW	PA	1 kWh electricity	ReCiPe	20	89
Curto et al.	2018	Curto et al. (2018)	DEIM I	na	PA	1 device	PEF (modified)	20	143
			DEIM II		PA				67
Uihlein	2016	Uihlein (2016)	103 devices (unknown)	5–2000 kW	53 PA	1 kWh electricity	Hauschild 2012 (midpoint)	20	105
					16 wave surge				65
					6 attenuators				45
					15 OWC				50
					1 overtopping				20
					3 pressure differential				40
					4 rotating mass				105
					5 others				67
Douziech et al.	2016	Douziech et al. (2016)	Oyster 800	800 kW	Wave surge	1 kWh electricity	ReCiPe 2008	20	65.5
Dalton et al.	2014	Dalton et al. (2014)	Wavestar	1 MW	PA	1 device	Carbon and energy audit	20	47
Thomson et al.	2011	Thomson et al. (2011)	Pelamis	750 kW	Attenuator	1 kWh electricity	EDIP2003	20	30
Walker & Howell	2011	Walker and Howell (2011)	Oyster 1	315 kW	Wave surge	1 device	Carbon and energy audit	15	25
Dahlsten	2009	Dahlsten (2009)	Seabased	20 MW	PA	1 kWh electricity	PEF	20	32–152
Parker et al.	2007	Parker et al. (2007)	Pelamis	750 kW	Attenuator	1 kWh electricity	Carbon and energy audit	20	23
Sorensen et al.	2007	Soerensen et al. (2007)	Wave Dragon	7 MW	Overtopping	1 kWh electricity	EDIP	Na	Na

2. Method

The presented LCA is performed according to ISO14044 standards. The analysis and modelling are conducted using the open-source software openLCA 2.3 (GreenDelta, 2024; Ciroth, 2007). For execution of the LCA phases we followed the methodological guide from Guinée, (2002). We sourced background data from ecoinvent v.3.9. with the cut-off by classification system model applied (Wernet et al., 2016). For all foreground unit processes we used primary data or secondary sources.

2.1. Goal & scope definition

The goal of this LCA study is to determine the environmental impacts of a generic point absorber WEC made from different materials and deployed in European waters. The scope entails a detailed cradle-to-grave analysis of a single WEC connected to the grid and moored to the seabed (see Fig. 1). Its function is to deliver electricity to the onshore grid. The functional unit for this study is set to 1kWh of electricity. We assess two different structural materials for the device's hull, namely steel and a newly proposed fibre-reinforced concrete for ocean energy devices.

We primarily assume a European supply chain, though wherever evidence or a lack of specific data is required, also take into account global supply chains. The assessment is done in an attributional manner, considering no economies of scale for WEC-specific manufacturing steps due to the moderate maturity of the industry. The life cycle stages included in this study were chosen to be comparable to what is the state-of-the-art in literature (Paredes et al., 2019; Zhang et al., 2020; Pennock et al., 2022; Uihlein, 2016): Manufacturing, installation, use and end of life (EOL), making this study's approach comparable with past efforts. An overview of modelled system components and life cycle stages is given in Fig. 2.

2.2. Life cycle inventory

The following sections outline the modelling assumptions behind the LCI of the presented WEC briefly. The full LCI with used data points, their sources and underlying assumptions can be found in the supplementary material.

2.2.1. WEC specifications

According to Guo et al., (2022. p.4) a PA "comprises a floating body interacting with surface waves and a power take-off unit [(PTO)] referenced or anchored to the seabed. The floating body oscillates under the excitation of waves, and its motion drives the PTO mechanism to generate electricity". We chose a modular approach based on the WECs major technical components to resemble such device in an LCI. The point absorber WEC is broken down into a floater, the PTO for power conversion, and a foundation acting as the reference to the heaving body. A periphery including moorings for station keeping and an electrical connection to the grid is also considered (Guo et al., 2022; Curto et al., 2021). The device built-up has been shown in Fig. 1 and the related product system is presented in Fig. 2. To enhance the flexibility and representativeness of the model all major influencing factors like performance specifications (e.g. lifetime, rated power, capacity factor), specifications of the geometry (e.g. height, diameter, hull thickness), values describing the location (e.g. distance to shore and port) as well as other inputs related to installation and maintenance activities are parametrised. This allows for easy assessment of different scenarios and configurations with limited changes in the model. A full list of parameters is included in the supplementary material.

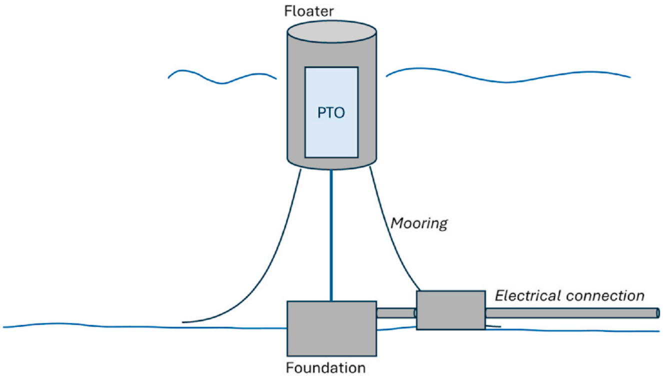


Fig. 1. Visualisation of general components of the generic PA and its periphery (cursive).

Based on ongoing PA developments we defined a baseline configuration of the PA WEC. The chosen specifications are summarised in Table 2.

We define the dimensions and rated power of the generic PA based on the CorPower Ocean C4, the only near commercial device to date (CorPower Ocean; Raghavan et al., 2024; Pennock et al., 2022). We chose the PTO type because direct-drive linear generators are expected to be more widely used in future WECs due to their low mechanical system complexity and high efficiencies (Guo et al., 2022; López et al., 2013; Yang et al., 2024). The assessment covers two different materials for the hull of the device that are being compared, namely steel and concrete. For the steel WEC, the cylindrical floater is composed of welded, hot rolled low-alloyed steel plates. The concrete floater hull is cast of a fibre-reinforced concrete mix that is proposed as new alternative structural material for ocean energy projects. The concrete consists of cement, a large portion of ground granulated blast furnace slag filler, aggregates, additives as well as steel fibres instead of traditional reinforcing, based on information received from WECHULL and WECHULL+.

We determined the capacity factor (CF) for device operation based on 30-year wave data of two proposed deployment locations in the Dutch North Sea and at the Portuguese Atlantic coast (Alday and Lavidas, 2024). The power matrix describing the power output of the defined WEC in each sea state has been provided by Raghavan et al., 2024. Specifics of the representative deployment locations are given in Table 3.

Including the North Sea in the analysis is important for understanding the environmental performance of converters in moderate wave climates compared to more common high-energy regions like the Portuguese coast. Deploying WECs in the North Sea can be vital for scale-up, as larger areas for effective wave energy utilisation are unlocked. Recent research based on long-term wave data revealed that also this milder resource can be viable when paired with the right WEC (Lavidas and Blok, 2021). Medium water depths at close distance to shore and the limited occurrence of severe extreme wave events are especially advantageous in this area (Lavidas and Blok, 2021). Furthermore, the already ongoing developments for large-scale offshore wind implementation pose potential for synergies (Chozas et al., 2010; Raghavan et al., 2024)

In the following sections modelling assumptions for each of the stages are explained. A full flow diagram for the purpose of working with the presented LCA model can be found in the supplementary material.

2.2.2. Manufacturing & assembly

In the manufacturing stage the floater is assembled from its hull materials and coupled with the major pre-manufactured components in an industrial hall at an assembly site at a port close to the deployment location. The steel hull is produced from low-alloyed hot rolled steel plates that are welded together on site. The concrete floater is cast from fibre-reinforced concrete (Section 2.2.1) that is mixed at the assembly site by a diesel-powered concrete mixer. Assembly is assumed to consist of mostly manual labour and lift operations by a mobile diesel-powered crane. Lighting and heating for the assembly hall are not considered.

Pre-manufactured components of the floater are a transformer, the PTO as well as an anti-corrosive glass-flake paint (applicable for the steel hull). A brief description of the WEC components is given in Table 4. These components are assumed to be produced at an unknown site in Europe and transported as one piece to the port site. Inter European transport is modelled according to the average modal split (Eurostat, a) and average transport distances of 140 km for transport by road (Eurostat, b), and 1000 km for rail and inland water (Uihlein, 2016) are applied. For steel and ferrous metals, a product-specific modal split with increased shares of rail and barge transport is used (Eurofer, 2003).

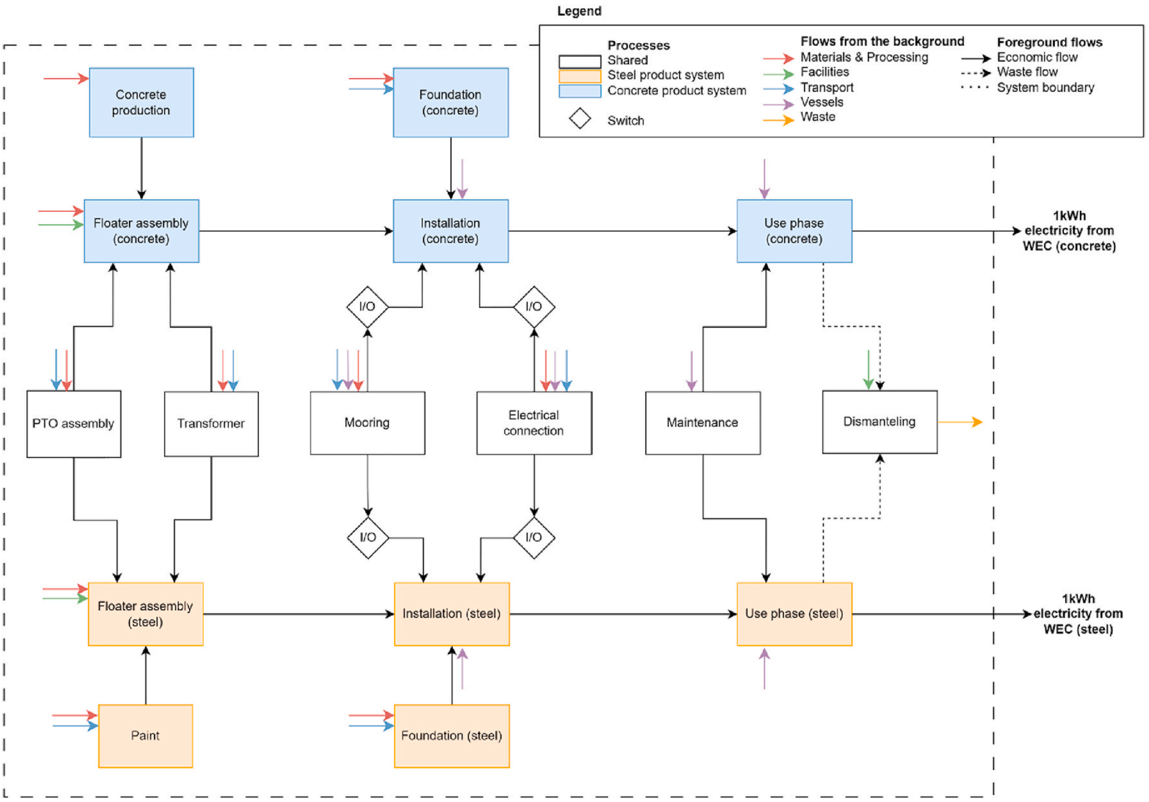


Fig. 2. Modelled product system for the steel and concrete WEC.

Table 2
Baseline configuration of the generic PA.

Type	Single-body, fixed reference heaving buoy	
Floater	Cylindrical	
Floater dimensions	D9mx18m	
PTO	Direct-drive linear generator placed in the floater	
Rated power	400 kW	
Lifetime	20 years	
Hull material	**Steel**	**Concrete**
Wall thickness	50 mm	40 mm
Foundation	Steel vertical anchor	Concrete gravity foundation

Table 3
Specifics of two representative deployment locations in European waters.

Location	North Sea (NL), coast of Vlieland	Atlantic (PT), coast of Aguçadoura
Water depth	25m	45m
Distance to shore	40 km	10 km
Nearest capable port	Den Helder (Distance: 70 km)	Viana do Castelo (Distance: 25 km)
Device CF	32%	47%

Table 4
Description of (pre-manufactured) WEC components.

Component	Description	Source
Transformer	Low to medium voltage transformer for processing the unregular power produced by the linear generator. Made from steel, aluminium, porcelain and insulated with paper and transformer oil.	Thomson et al. (2019) Jorge et al. (2012)
Paint	Protective paint for the highly corrosive environment of the WEC. Epoxy based, with glass flakes as proposed for the Pelamis device.	Thomson et al. (2019) Momber and Marquardt (2018)
PTO	Modular direct-drive linear generator based on an iron core, copper coils and Neodymium permanent magnets (NdFeB) as proposed for the archimedes waveswing device. The generator for the archimedes waveswing has a 2 MW capacity and is built of two 8m high modules. For this study a 100 kW module is modelled that can be scaled to the rated power of the assessed WEC.	Hodgins et al., (2012) Prado and Polinder (2011)
Connection rod	Connection of the floater to the later foundation represented by a hollow steel pipe depending on the water depth and draft of the floater in its length.	
Internal structure	Fixed amount of steel representing a generic internal structure of the device e.g. end-stop springs, rods, bolts and nuts, in line with typical design specifications.	
Control	Electrical control system resembled by generic electronics common for generator control.	Bauer (2004)

Inputs to the pre-manufactured components are represented by global market processes (transport included in the datasets). Direct inputs to the floater are represented by market processes of the closest available geography.

As for the direct steel input to the floater no European market process exists in ecoinvent, the global steel market process (ecoinvent) has been adapted to match the European ratio of domestically produced and imported steel according to Eurofer, 2023.

2.2.3. *Installation*

After assembly at the port site, the floater is brought to the deployment site offshore and coupled with its foundation and periphery.

The export cable, moorings, and anchors as well as the steel foundation are pre-manufactured components where the same modelling rules for trans-port and geography apply (Section 2.2.2). Table 5

Table 5
Modelling of external floater components and periphery.

Component	Description	Source
Foundation (steel product system)	40t steel vertical anchor - Based on the CorPower Ocean UMACK anchor - Installed in one piece - Fully retrievable	CorPower Ocean, 2022
Foundation(concrete product system)	800t gravity foundation (d10mx3m) - Poured in place	
Transmission	33 kV medium voltage AC cable to shore - Suitable system for short distances to shore (<70 km) and small plant sizes <1 MW due to lower losses and lower cost than e.g. HVDC transmission – 15cm diameter XLPE (polymer) insulated copper conductor cable with galvanised steel mantel, and lead (total cable weight of 26,4 t/km) - Three core cable due to lower cost and suitable mechanical properties compared to single core cables when used for low to medium voltage transmission - Copper as conductor material as widely applied for submarine cables due to lower cross sections suitable for offshore handling and less required insulation material compared to similar aluminium conductors - Transmission efficiency of ~94% of the produced electricity - Losses are seen as constant within the applicable range of the model	Lopez et al., (2010) Li et al. (2022) Birkeland (2011) Arvesen et al. (2013) Georgallis (2021) Argaut (2021)
Mooring	Catenary 3-line spread chain mooring with drag embedment anchors – 48mm diameter chain (50 kg/m) – 15t weight of anchors - Chain length of ~5,5 times the water depth, for catenary mooring - Optional in the model as not all PAs require mooring in addition to the connection to the seabed	Cerveira et al. (2013) Depalo et al. (2021) Pecher et al. (2014) Harris et al. (2006)

Table 6
Used vessels, their fuel consumption and representation in the model.

	Description	Fuel Type	Fuel [kg/h]	Source	Representation in ecoinvent
AHTS	Anchor Handling & Tug Support Vessel	HFO	600	Adland et al. (2019)	Transport, freight, sea ferry
OSV	Offshore Support Vessel	HFO	400	Adland et al. (2019)	Transport, freight, sea ferry
CLV	Cable Lay Vessel	HFO	560[a]	Li et al. (2022)	Transport, freight, sea ferry
Tug	Tugboat	HFO	600	Garcia-Teruel et al., (2022); Brussa et al., (2023)	Transport, freight, sea ferry
CTV	Crew Transfer Vessel	Diesel	300	Garcia-Teruel et al., (2022); Brussa et al., (2023)	Transport, freight, inland waterways, barge [b]

[a] value was translated from l/h with a HFO density of 983kg/m3 (Arvesen et al., 2013).

[b] adapted to not include canal infrastructure.

Table 7
Installation steps, duration and vessel requirements.

	Description	Duration	Vessels	Source
Mooring pre-lay	Installing anchors and chains on the seabed	12h/line	1xAHTS 1xOSV	Statoil (2015)
Foundation installation	Installing the UMACK anchor/pouring the gravity foundation	13h	1xOSV	Pennock et al. (2022)
Cable laying	Ploughing and laying the export cable at ~1m depth in the seabed	3,5h/km to shore	1xCLV	Li et al. (2022)
Towing of floater	Towing the assembled floater from port to deployment site	0,1h/km to port	1xTug	Pennock et al. (2022)
Hook-up (mooring)	Connecting the floater to a pre-layed mooring line	8h/line	1xOSV 1x Tug	Statoil (2015)
Hook-up (foundation)	Connecting the floater to the pre-installed foundation and cable	10h	1xOSV 1xTug	Pennock et al. (2022)

provides a description of the modelling of external components and periphery.

As the cable system for the generic device is not specifiable, an average of the material compositions for medium voltage submarine cable types most commonly used according to mechanical-, cost- and loss-properties is taken (Argaut, 2021; Georgallis, 2021; Li et al., 2022). The average material composition of the cable has been derived from Arvesen et al., (2013) that provides information on material compositions of five different medium voltage copper conductor cables with different cross sectional areas currently available on the market. A similar approach is taken in Li et al., (2022).

The floater and periphery need to be installed at sea by offshore vessels (see Table 6). Installation happens in several different steps specified in Table 7. The large slow propelled vessels are assumed to consume heavy fuel oil (HFO) while the smaller fast vessels are assumed to consume diesel.

Due to the lack of operational experience with WECs, data on installation practices is scarce and not publicly available in good quality. The made assumptions on duration of activities and fuel consumptions underlie uncertainty regarding the applicability of the referenced vessels and operating modes for WEC related activities as information was partially sourced from other industries (see supplementary material).

Furthermore, background processes representing the used specific offshore vessels are not available in ecoinvent (Arvesen et al., 2013). Therefore, existing processes for transport of goods are used. The ecoinvent dataset for “transport, freight, sea ferry” (Notten, 2018) is considered applicable for larger HFO propelled vessels in view of the comparable deadweight tonnage of the ferry (10,000t) and the used sea vessels (4,000t) (Boskalis, Maersk Supply Service, van Oord). However, the fuel consumption does not match the ones presented in Table 6. The existing dataset has been used regardless as it allows the entire supply chain of the vessel, including production, maintenance and port facilities, as well as combustion emissions and the supply chain of the fuel used, to be included in the analysis. To address the discrepancy in fuel consumption between the installation vessel and the ecoinvent ferry, the total amount of fuel for an installation activity was rescaled by the fuel consumption of the ferry per kilometre of transported tonne of goods (Eq. (1)). This is similar practice to other LCA studies on offshore renewables (Thomson et al., 2019; Arvesen et al., 2013; Pennock et al., 2022). The small and fast CTV is represented as a smaller diesel-powered barge with the dataset “transport, freight, inland waterway, barge” (Spielmann, 2007). Alignment of the different fuel consumptions is done in the same manner as for the ferry.

$$transport, freight, ferry \Big/ barge\ [t\ of\ goods * km] = \frac{\Sigma fuel\ consumption\ vessel(s)\ [kg\ of\ fuel/h] \times duration\ of\ activity\ [h]}{fuel\ consumption\ ferry/\ barge\ [kg\ of\ fuel/t\ of\ goods{*}km]} \quad (1)$$

2.2.4. *Use phase*

Once installed, the device produces electricity from ocean waves without any direct emissions related to the power conversion. Interactions with the marine environment are considered in terms of the space occupied by the device and its periphery. For all components in touch with the seabed, land use in the form of transformation (habitat loss) and occupation until removal (land competition) (Guinée, 2002) is taken into account.

Only a part of the WEC system can be attributed to the production of 1 kWh of electricity. Therefore, the life cycle inventory is scaled to the reference flow as shown in Eqs. (2)–(4).

$$AEP\ [kWh\,/\,yr] = RP\ [kW\,] \cdot CF \cdot 8760[h\,/\,yr] \quad (2)$$

$$LEP\ [kWh/device] = AEP\ [kWh/yr] \cdot L\ [yr/device] \cdot effE \quad (3)$$

$$Inventory\ [1/kWh] = \frac{Inventory\ of\ Inputs\ [1/device]}{LEP\ [kWh/device]} + \frac{Inventory\ of\ outputs\ [1/device]}{LEP\ [kWh/device]} \quad (4)$$

All in- and outputs to the use phase are divided by the lifetime electricity production of the device (LEP - Eq. (3)). The LEP depends on the annual energy production (AEP), the devices lifetime (L) as well as the transmission efficiency (effE). The transmission efficiency determines the share of produced electricity reaching the grid and depends on the modelled transmission system. For this study a transmission efficiency of 94% is assumed (Lopez et al., 2010) based on the AC medium voltage cable type, the distance to shore and the low transported power from one single device (see Table 5). The AEP is defined by the dimensionless capacity factor (CF), the rated power of the device (RP) as well as the number of operating hours in a year (Eq. (2)). The mentioned values are all parameters adaptable in the model.

To ensure continuous operation over the device's full lifetime, maintenance is required. Due to the lack of operational experience, specific maintenance strategies have not yet been proven for the wave energy sector (Ambühl et al., 2015; Guo and Ringwood, 2021). Due to this uncertainty, different maintenance scenarios based on component failure rates from other applications (Rinaldi et al., 2018; Mueller et al., 2016) and reports from the CorPower point absorber (Pennock et al., 2022) were considered in the analysis (Table 8).

Influences of downtime because of failures and maintenance periods on the annual energy production are not considered. This is because of the large range of possible scenarios depending on the weather at the location, vessel availability and the specific components responsible for failures (Ambühl et al., 2015).

Table 8
Maintenance scenarios for sensitivity analysis.

	Inspection [x/year]	Corrective maintenance [once x years]	Description
Baseline	1	4	Corrective maintenance based on component failure rates of components in comparable use, from Rinaldi et al., (2018).
Optimistic	1	0	Best case scenario
Pessimistic	6	1	Corrective maintenance based on representative component failure rates presented in Mueller et al., (2016). Inspection interval based on Pennock et al., (2022).

Material and process requirements for repairs (spare parts, energy) are also excluded from the analysis for the same reasons (Mueller et al., 2016; Thomson et al., 2019; Uihlein, 2016). A description of the related activities is given in Table 9.

2.2.5. *End of life*

After the lifetime of the WEC, it is towed to shore for dismantling. The moorings and steel foundation are assumed to be removed, and the materials recovered for EOL treatment or recycling. The gravity foundation as well as the electrical cable are assumed to stay in place as removal is not common practice and no negative effects on the sea bed are suspected (Topham and McMillan, 2017; Bonar et al., 2015; Al-Sallami, 2021; Taormina et al., 2018). Further justification is given in the supplementary material. The materials of the components left in the seabed are lost and therefore do not appear in the dismantling process.

The process efforts (sea vessel operations) required for the removal of the WEC are assumed to be the reversed installation and added to the model in the use phase. Once the floater reaches the shore it is being dismantled at the former assembly site at the closest port. Energy and process inputs are assumed to be the same as for the assembly stage. The regained materials are assumed to be partially recycled and partially disposed of through incineration or landfilling. Table 10 gives an overview over the EOL treatments for all the recovered materials of the WEC, including PTO, steel foundation, mooring, control and transformer.

In this study we apply the cut-off allocation method, EOL recycling processes are therefore considered to be outside the system boundary, and no recycling credits are given. This approach is chosen in line with the used background dataset and system model to avoid double counting and is commonly used in LCA for WECs (Thomson et al., 2019; Pennock et al., 2022; Uihlein, 2016). The recycled material contents as shown in Table 10 only reduce the amount of material that is e.g. incinerated or landfilled otherwise.

2.3. *Life cycle impact assessment*

For the assessment of potential environmental impacts from the modelled WEC, we consider all quantifiable environmental extensions to and from the environment that occur during its lifetime these life cycle stages including space use, resource use, emissions to air, land and

Table 9
Modelling of maintenance activities.

	Description	Duration	Vessel	Source
Inspection	Inspection of the device from the outside with manual underwater equipment from a CTV with station keeping system.	6h stationary 0,036 h/km	1xCTV	Garcia-Teruel et al. (2022) Brussa et al. (2023)
Towing	2x towing (to and from port) 2x hook up (latching & unlatching from mooring and foundation)	See Table 7	See Table 7	Thomson et al. (2019)

Table 10
EOL treatment of recovered materials.

Values in [t]	Steel WEC	Concrete WEC	EOL treatment
Steel[a]	402,18	112,49	10% steel scrap (partial incineration and landfilling) 90% recycling [b]
Fibre-reinforced concrete	0,00	66,67	inert waste (landfilling)
Iron	1,50	1,50	iron scrap
Copper	1,44	1,44	40% copper scrap (incineration), 60% recycling [b]
Plastics	0,08	0,08	Inert waste (landfilling)
Others	0,07	0,07	Inert waste (landfilling)
Magnets	0,90	0,90	Inert waste (landfilling) [c]
Electronics	0,44	0,44	Inert waste (landfilling)
Aluminium	0,20	0,20	Aluminium scrap (incineration)
Transformer oil	0,34	0,34	Waste mineral oil (hazardous waste incineration)
Total	**407,15**	**184,13**	

[a] does not include steel fibres in hull concrete.
[b] (EuRIC aisbl, 2020).
[c] (Kumari et al., 2018).

water. The study cannot cover direct interactions with the marine environment such as underwater noise, magnetic and electrical fields as well as flow alternations as for these impacts no mature impact assessment models and quantifiable data are available (Paredes et al., 2019; Bonar et al., 2015). In regard of the location of analysis we assess the environmental impacts on a midpoint level with the environmental footprint declaration method EF 3.1. The method is provided by the European joint research centre and is in line with the European environmental footprint measurement and reporting regulations (European Commission, 2021; Damiani et al., 2022).

3. Results

3.1. Impact assessment analysis

With the LCI and impact assessment method described in the previous section we found global warming impacts of 300-325$gCO_2eq./kWh$ for a WEC deployed in the North Sea with its periphery considered. Full impact assessment results across all 16 included categories are presented in Table 11. In the context of already existing WEC literature, the GW impact found for the steel and concrete WEC with periphery is roughly double what previous.

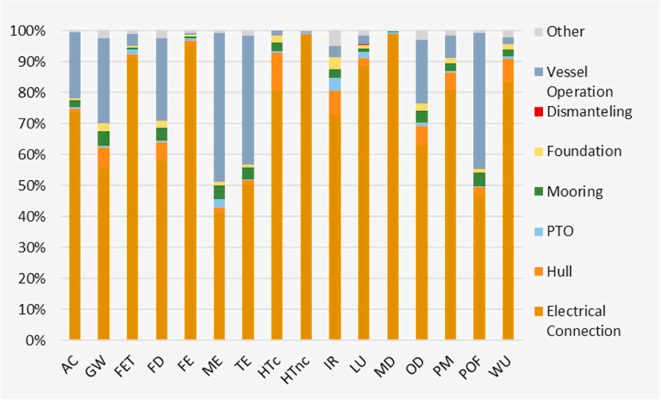


Fig. 3. Contribution analysis of the baseline steel WEC deployed in the North Sea.

Table 11
Comparison of impact assessment results of the baseline WEC in the North Sea with different hull materials and system boundaries, with description of impact categories and characterization factors in EF 3.1

			With periphery		Without periphery	
			Steel WEC	Concrete WEC	Steel WEC	Concrete WEC
AC	Acidification - accumulated exceedance (AE)	mol H + -Eq	1,10E-02	1,10E-02	1,05E-03	9,12E-04
GW	Climate change - global warming potential (GWP100)	gCO2-Eq	325,4	299,9	77,7	52,2
FET	Ecotoxicity: freshwater - comparative toxic unit for ecosystems (CTUe)	CTUe	11,9	11,8	0,6	0,5
FD	Energy resources: non-renewable - abiotic depletion potential (ADP): fossil fuels	MJ, net calorific value	4,2	3,9	0,9	0,6
FE	Eutrophication: freshwater - fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq	5,90E-04	5,80E-04	2,37E-05	1,05E-05
ME	Eutrophication: marine - fraction of nutrients reaching marine end compartment (N)	kg N-Eq	1,30E-03	1,30E-03	3,19E-04	2,87E-04
TE	Eutrophication: terrestrial - accumulated exceedance (AE)	mol N-Eq	1,70E-02	1,70E-02	3,11E-03	2,79E-03
HTc	Human toxicity: carcinogenic - comparative toxic unit for human (CTUh)	CTUh	2,00E-09	1,70E-09	3,37E-10	7,77E-11
HTnc	Human toxicity: non-carcinogenic - comparative toxic unit for human (CTUh)	CTUh	1,00E-07	1,00E-07	1,35E-09	9,03E-10
IR	Ionising radiation: human health - human exposure efficiency relative to u235	kBq U235-Eq	2,00E-02	1,70E-02	4,51E-03	2,32E-03
LU	Land use - soil quality index	dimensionless	2,8	2,7	0,2	0,2
MD	Material resources: metals/minerals - abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq	1,00E-04	1,00E-04	1,07E-06	8,84E-07
OD	Ozone depletion - ozone depletion potential (ODP)	kg CFC-11-Eq	6,60E-09	6,00E-09	1,38E-09	8,52E-10
PM	Particulate matter formation - impact on human health	disease incidence	3,30E-08	3,10E-08	3,91E-09	1,86E-09
POF	Photochemical oxidant formation: human health - tropospheric ozone concentration increase	kg NMVOC-Eq	4,30E-03	4,20E-03	9,08E-04	7,69E-04
WU	Water use - user deprivation potential (deprivation-weighted water consumption)	m3 world eq. deprived	0,1	0,1	0,02	0,01

LCAs on point absorber WECs suggest (25-158$gCO_2eq./kWh$). Most of the LCA results from studies on other types of WEC also fall into this much lower range except for one outlier that presents up to 374$gCO_2eq./kWh$ (Bruno et al., 2022).

To understand drivers of the high impacts, a contribution analysis of the baseline scenario aggregated at the component level was performed (Fig. 3). This reveals that significant shares of the large impacts stem mainly from the electrical transmission cable ranging from 40% in ME up to 99% in MD. Impacts within the cable stem mainly from the large amounts of copper used in the cable (6t per km). Copper is a material with high impacts across several categories coming largely from inefficient extraction process as well as associated tailings and their treatment (Tao et al., 2022).

The cabling potentially overshadows impacts within the WEC, such as the influence of the hull material. Therefore, we assessed an additional scenario of the steel WEC deployed in the North Sea with narrowed system boundaries, omitting the periphery. The found GW impacts are much lower with 52,2–77,7$gCO_2eq./kWh$ depending on the hull material (see Table 11). This lies in the middle of the range found for point absorber WECs in previous studies.

Looking at the WEC alone, a strong reduction potential of the alternative hull material becomes apparent. As shown in Fig. 4, using fibre-reinforced concrete as hull material instead of steel can reduce the impact of the WEC without periphery from 10% in ME up to 78% in HTnc. GW impacts can be reduced by 35% (25,5$gCO_2eq./kWh$).

As can be seen in the contribution analysis of the concrete WEC without periphery, the impact of the hull is reduced to a minimum (Fig. 5b). This is due to the concrete having a very low embodied impact on a weight basis compared to structural steel. Nevertheless, the overall impact reduction potential of the concrete hull varies between impact categories (Fig. 4). For a category dominated by emissions associated with metal (FET, FE, HTnc, HTc, IR, LU, MD, PM, WU) the reduction potential is higher than for one that is dominated by emissions from burning shipping fuel during sea vessel operations (AC, FD, ME, TE, POF). For GW and OD emissions associated with metals and vessel operations contribute to the impact category in relatively equal magnitude.

The impacts of sea vessel operations for installation, maintenance and decommissioning, represent another significant contributor to the overall results for both WEC configurations, accounting for up to 83% of TE (see Fig. 5a). 80% of the impacts from offshore vessels stem from activities related to maintenance, due to the time consuming and vessel-intensive un- and re-latching actions that are required for towing when corrective maintenance is needed.

Transport and material processing are not shown specifically in Fig. 5 as they are included within the different components. The contribution of these activities to the different impact categories has been evaluated separately and is overall low, with a percentage of less than 10% for processing and less than 2% for transport.

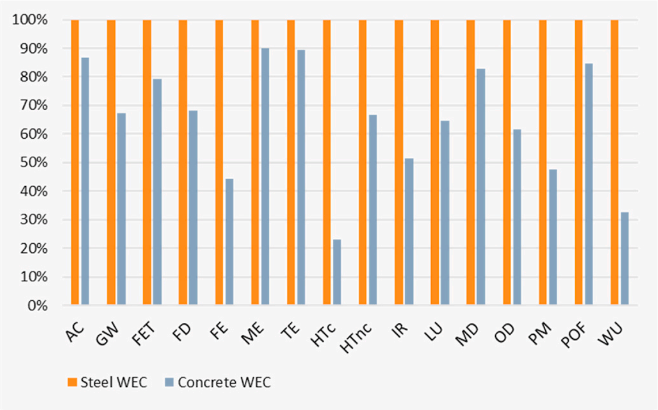
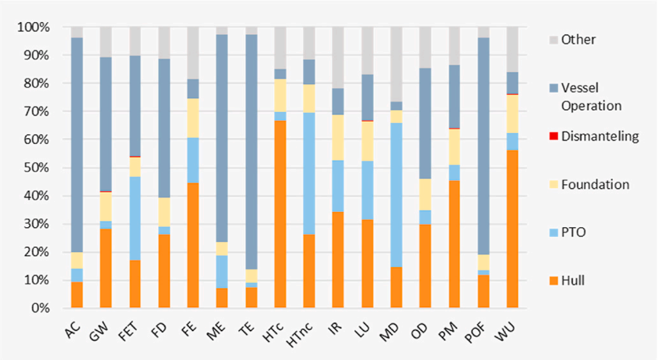
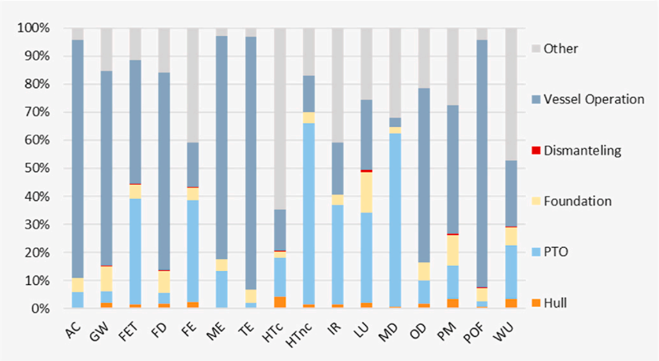


Fig. 4. Relative impact assessment results for the baseline WEC without periphery in the North Sea.



(a) Steel floater



(b) Concrete floater

Fig. 5. Contribution analysis of the baseline WEC without periphery in the North Sea.

3.2. Sensitivity analysis

To verify the validity of results based on assumptions with underlying uncertainty, especially the ones presented with large contribution to the results, sensitivity analysis was performed.

The results have shown a high impact from vessel operations for maintenance and underlying assumptions on procedures are still uncertain. Therefore we evaluated the sensitivity of the results to assumptions on maintenance intervals by assessing three different scenarios. The three scenarios have been defined in section 2.2.4 Table 8. The pessimistic scenario leads to almost quadrupled impacts in the vessel-dominated impact categories compared to the baseline assessment. For the optimistic scenario a possible decrease of impacts up

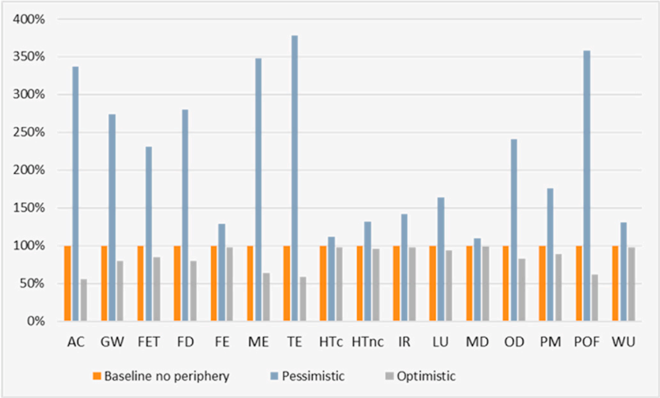
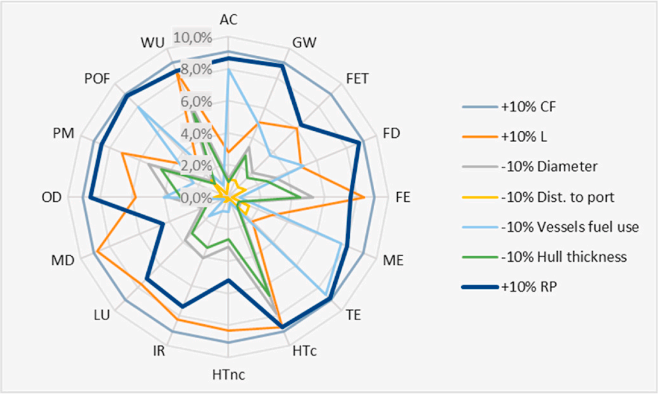
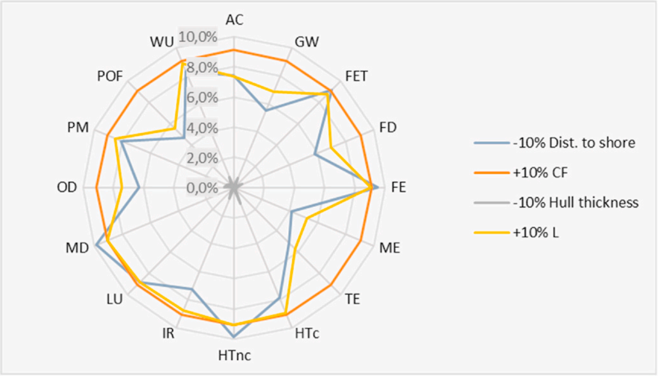


Fig. 6. Changes in impact assessment results of the steel WEC with different maintenance scenarios.



(a) Steel WEC without periphery



(b) Steel WEC with periphery

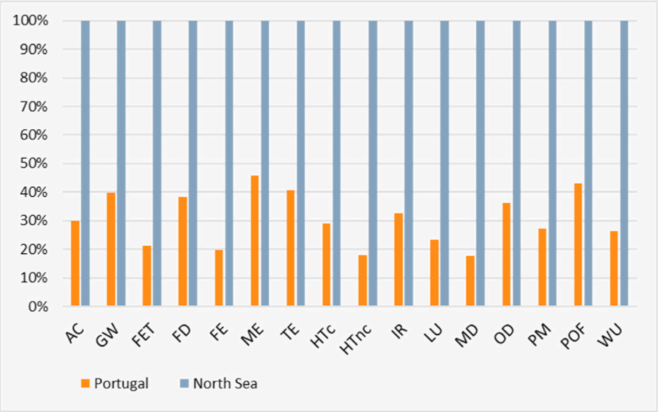
Fig. 7. Sensitivity analysis on a selection of parameters, showing the decrease in impacts per category.

to 44% is found (see Fig. 6).

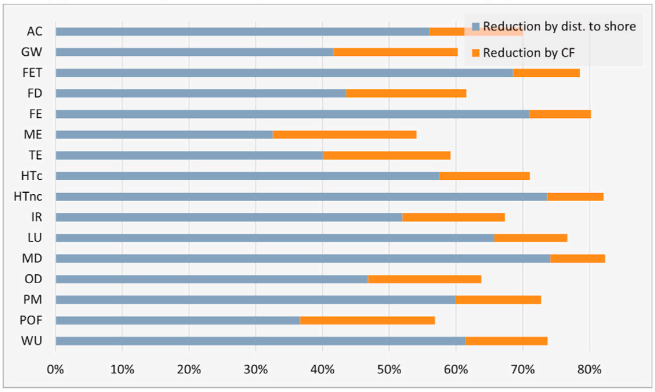
Furthermore a simple sensitivity analysis on the impact of single parameters on the results was performed. Fig. 7 shows the sensitivity of the results to key parameters related to floater geometry namely the hull diameter and its thickness, device performance defined by the CF and the RP, the distance to the nearest port sea vessels have to travel as well as their fuel consumption. For the scenario considering the WECs periphery additionally the sensitivity of the results on the distance to shore is assessed. It must be noted that the shown changes in CF and RP are purely theoretical to showcase their influence on the results. These parameters are physically dependent on each other as well as on the wave resource at a specific deployment location and cannot be altered independently of each other for real assessments.

Increasing the CF has the highest potential influence in all impact categories as it affects all parts of the inventory equally in a linear manner. The sensitivity to the lifetime and the RP varies between categories despite their relevance in determining the reference flow. This is because the lifetime additionally determines total maintenance needs while the RP also drives material requirements for the PTO. The results are insensitive to the distance to port as most vessel activities are modelled with fixed durations as they take place on the spot and do not require transit (e.g. latching). Vessel-dominated impact categories are more sensitive to changes in fuel consumption and travelled distance while parameters related to the device's geometry influence the metal-dominated categories to a higher degree. For a WEC with periphery, the sensitivities present themselves similarly but the distance to shore is of higher importance as it directly drives the length of the impactful cable. Also, in line with earlier results the geometry of the floater (e.g. steel thickness) is of lower importance for the results of the baseline scenario due to the domination of the cable, unaffected by these changes.

The result's sensitivity to device performance, depending strongly on local wave climates suggests that an alternative deployment location can influence environmental impacts significantly. Therefore, we finally assessed an alternative possible European WEC deployment location at the coast of Aguçadoura and close to the port of Viana do Castelo (section 2.2.1). This location marks a higher energy resource closer to shore. Results of the analysis of a steel WEC with periphery at the described site are presented in Fig. 8.



(a) Relative comparison of impacts of the steel WEC in two deployment locations



(b) Breakdown of drivers of the achieved impact reduction

Fig. 8. Reduction in impacts by deployment of the steel WEC with periphery in higher energy regions seen on the example of the Portuguese coast.

The impacts of the steel WEC with periphery can be reduced between 54% and 82%. The improvement stems mostly from the reduced cable length due to the reduced distance to shore (32–47%). An additional impact reduction of 10%–20% is achieved by the increased CF.

Table 12
Comparison between key assumptions in this study and other relevant LCAs on WECs.

	Pennock et al., (2022)	Uihlein, (2016)	Thomson et al., (2019)
Differences in key assumptions on. …			
… electrical transmission	10 km export cable Shared between 28 WECs	Average of 3 km export cable length	Unknown
… others	Array Composite hull Mechanical, geared PTO	Data from prototype database Lower CF Generic (low) estimation of vessel operations	Higher CF Higher estimation of vessel operations
GW results	23-47gCO$_2$eq./kWh	105gCO$_2$eq./kWh (for PAs)	35gCO$_2$eq./kWh

4. Discussion

The results of this analysis have shown that the potential impacts of a single WEC highly depend on its electrical transmission system, vessel operations, maintenance regimes and hull material. The following sections place these findings in the context of previous LCA studies on WECs and electricity generation. The applicability and limitations of this model are also discussed.

The environmental impacts found for the full functional WEC including the electrical transmission cable have shown to be much higher than what previous WEC LCAs have proposed. The remarkably high contribution of the export cable to the overall impacts of a WEC has not yet been pointed out by any other study. In Table 12 therefore key assumptions of other relevant studies in that field are compared.

Table 12 shows that comparable studies model much shorter cable connections and/or consider infrastructure sharing. Their obtained results are therefore closer to the results of a WEC without a periphery assessed in this study than one with the 40 km transmission cable for a single device. Nevertheless, it must be noted, that the results of the WEC without periphery in this study may not be seen as final results because a WEC without cable cannot fulfil the function of delivering electricity to the grid. The scenario rather resembles a WEC that is theoretically located very close to shore.

Using the no-periphery scenario as a basis for comparison with studies modelling near-shore deployment locations, the range of results found for WECs is similar. The contributions found for structural materials and vessel operations, as well as the negligible impact of transport, are also in line with those suggested by Thomson et al., (2019) and Pennock et al., (2022). In Uihlein's study (Uihlein, 2016) the results for GW are higher and the contribution of vessel operations was found to be negligible. In this case this is suspected to be due to the generic assumptions used for the vessel operations. More detailed assumptions were made in our LCA. Pennock et al., (2022) finds the lowest results for GW in WEC literature but is assessing an array of 28 WECs made from a composite material with a different PTO to the one assessed here. Their contribution analysis does not further distinguish between impacts of subcomponents, so no direct comparison on the impact of the different PTO and hull types with this study is possible. It is visible though that the contribution of the cable system (inter-array cables and 10 km export cable) to the overall results is less then what we found in this study for the Atlantic location with reduced distance to shore. This suggests arraying of WECs can reduce the parts of the impacts of a kWh of electricity associated with the export cable. Further it is expected that combined installation, operation and maintenance actions can also reduce the amount of vessel operations per kWh (Pennock et al., 2022; P'erez-Collazo et al., 2015). Other positive effects of arranging wave energy converters in arrays are potentially reinforcing hydrodynamic interactions between the single devices leading to increased capacity factors depending on the location and layout of an array (Raghavan et al., 2024.; Lavidas and Blok, 2021). More transparent and broader LCAs are suggested to quantify overall trade-offs between potential reduction of impacts due infrastructure sharing, higher energy yields and increase because of additional required transmission infrastructure (inter array cables, substations, higher voltage/more cables and potential DC conversion). The presented LCA model for a generic single device can be scaled and adapted for such advanced assessment.

When comparing the impacts of a WEC with other electricity generation technologies, we find that significant improvements to fossil based technologies in terms of global warming impact are made (natural gas 403-513$gCO_2eq./kWh$ and coal 753-1095$gCO_2eq./kWh$ (United Nations Economic Commission for Europe, 2022). Other mature renewables still show lower global warming impacts with 12-37$gCO_2eq./kWh$ for offshore wind (United Nations Economic Commission for Europe, 2022; Garcia-Teruel et al., 2022) and 7-83$gCO_2eq./kWh$ for onshore solar photo-voltaic (United Nations Economic Commission for Europe, 2022). However, a single pre-commercial concrete WEC deployed in the North Sea without cable and mooring considered already reaches upper impact levels of onshore solar photovoltaic.

As comprehensive LCA assessments for WECs are not abundant yet this study serves the purpose of providing a baseline framework for the assessment of environmental impacts of WECs. Due to the parametrised and transparent nature of the presented LCA model, further analysis of environmental impacts of different device configurations and deployment scenarios can be directly performed by customising the used parameter sets. To do so the following limits of applicability should be considered: First, the modelled transmission system as well as its efficiency are only representative for distances to shore, shorter then 70 km and small plants (single devices). Although the distance to shore is parametrised the physical relationship between losses in the electrical cable and the cable length is not represented in the model. Further, WEC arrays or devices located further offshore potentially require higher voltage cables, or a DC system with the adequate conversion infrastructure in form of substations which are not included in the presented model. Second, in the model the RP and CF can be adjusted freely. For explorative purposes this can be a useful feature. However, these parameters are physically dependant on each other and on the resource at a certain location. For an assessment of specific cases these values therefore must be determined quantitatively outside of the provided LCA model. For potential further sustainability assessment outside of the scope of this study (e.g. arrays or different types of WECs) the given LCI can be easily adapted e.g. by adding more modules like an array transmission system or different PTOs.

This study comprised a full impact assessment of a PA device deployed in European waters, consistent with the goal and scope definition. A complete inventory of processes and materials for the floater and components, as well as background supply chains for used fuels, vessels and other energy sources are included in the LCI. All economic flows are followed through until they end up as an environmental flow. All flows from and to the environment are taken into account with the exception of direct marine interactions like electromagnetic fields, changes in currents, noise and vibrations. These do not have assessment models within mature impact assessment methods such as EF, Recipe and others and have therefore not yet been considered in marine energy studies (Paredes et al., 2019; Guo and Ringwood, 2021; Uihlein and Magagna, 2016). This is creating a space of unknown impacts of marine renewables, potentially misrepresenting trade-offs between impacts on the marine environment and more common impact categories like global warming. As the use of our oceans for renewable energy generation increases, LCA methodology should also develop assessment models capable of representing these actions.

The impact assessment results obtained using the presented model are subject to uncertainties due to the absence of reliable data on industry practices. Wave energy technology is still pre-commercial and operational experience is limited to a few temporary sea trials. This leads to a severe lack of disclosed data on manufacturing, installation and maintenance practices. Assumptions in these areas made within this study are based on data from other industries or pre-commercial estimations. In order to be able to assess the impact of these uncertainties on the results, a sensitivity analysis was carried out. Most of the parameters have a limited individual impact on the results, while the assumptions made on maintenance intervals and techniques proved to be highly influential. The combination of high uncertainty with large impact on the results marks a hotspot and highlights the need for further research or trials adequately quantifying required sea vessel operations and gaining experience on lifetime WEC survivability to accurately determine the environmental impacts of this technology – especially when scaled up.

5. Conclusion

In this study, we presented a fully disclosed, adaptable LCI of a generic point absorber WEC, filling a gap in the literature regarding comprehensive and transparent LCA assessments of the regarded technology. With this model we created a basis for possible further assessment of the environmental impacts of different PA configurations, different WEC working principles and deployment scenarios e.g. in more deployment locations or arranged as arrays. For a single PA WEC deployed in the Dutch North Sea, we found GW impacts for 1kWh electricity between 55 and $77gCO_2eq.$ without considering its periphery and 300 to $325gCO_2eq.$ with cable and mooring considered. The lower ends of the range in both configurations are the result of exchanging the conventional steel hull with a newly proposed fibre-reinforced concrete for ocean energy devices. This alternative material can reduce environmental impacts significantly (10–78%) across all impact categories. In addition to structural materials, we found that vessel operations contribute between 4% and 85% to the impact of a WEC without periphery, mostly in categories dominated by fuel combustion. Towing the floater back to shore for maintenance has the largest impact on the results of all other vessel operations.

As shown by the assessment of an alternative WEC deployment scenario in the Atlantic at the coast of Portugal, the location also has considerable influences on the environmental performance of a WEC. Compared to a deployment in the North Sea a steel WEC with periphery can reduce its impacts across all categories between 54 and 80%. The stronger wave resource at this location paired with a suitable WEC can leverage higher capacity factors decreasing the impacts of 1kWh of electricity in a linear manner across all impact categories. Closer distances to shore decrease the required length of the impactful cable, strongly decreasing environmental impacts driven by metals.

Based on the results of our study, we recommended to shift the development of WECs from steel towards innovative concrete compositions. In addition as much emphasis should be placed on the development of efficient maintenance procedures that minimise tow backs and less material intensive electrical transmission systems as on the WEC device itself. When scaled up, the technology could also benefit from sharing the transmission infrastructure and vessel requirements with multiple devices or other offshore renewables deployed in close proximity, potentially reducing the resulting impact per unit of electricity. Advancements in these regards are also suspected to be beneficial for the environmental performance of other offshore renewables like floating wind and solar installations due to their similar infrastructure and operation and maintenance requirements.

The impact assessment results presented in this study already qualify WECs as a more sustainable alternative electricity generation technique compared to fossil-based conventional technologies. Pulling the recommended levers to decrease environmental impacts will ensure that the technology in the near future will reach impact levels similar to or even below more mature renewables like wind and solar and unlock its full potential for a future sustainable European energy system. The deployment of WECs has wider system benefits beyond reducing its environmental impact. Due to the properties of the resource, the role of WECs is not to replace mature renewables but rather to function as an important addition and diversifying component in the energy system. The resources intermittency pattern different to wind and solar and low variability create smoothened power output in multi-source systems and by that create power security and quality with overall reduced storage demand.

Based on the results of this study scaling up wave energy deployments up to 40GW in 2050 as targeted by the European union in the renewable energy strategy can be seen as a significant advancement in sustainability of its energy system.

CRediT authorship contribution statement

Tabea Engelfried: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stefano Cucurachi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **George Lavidas:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi: mmcdoino

Data availability

Data for the LCI is made available in the supplementary material

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