Life Cycle Assessment of a Point Absorber Wave Energy Converter

Tabea Engelfried

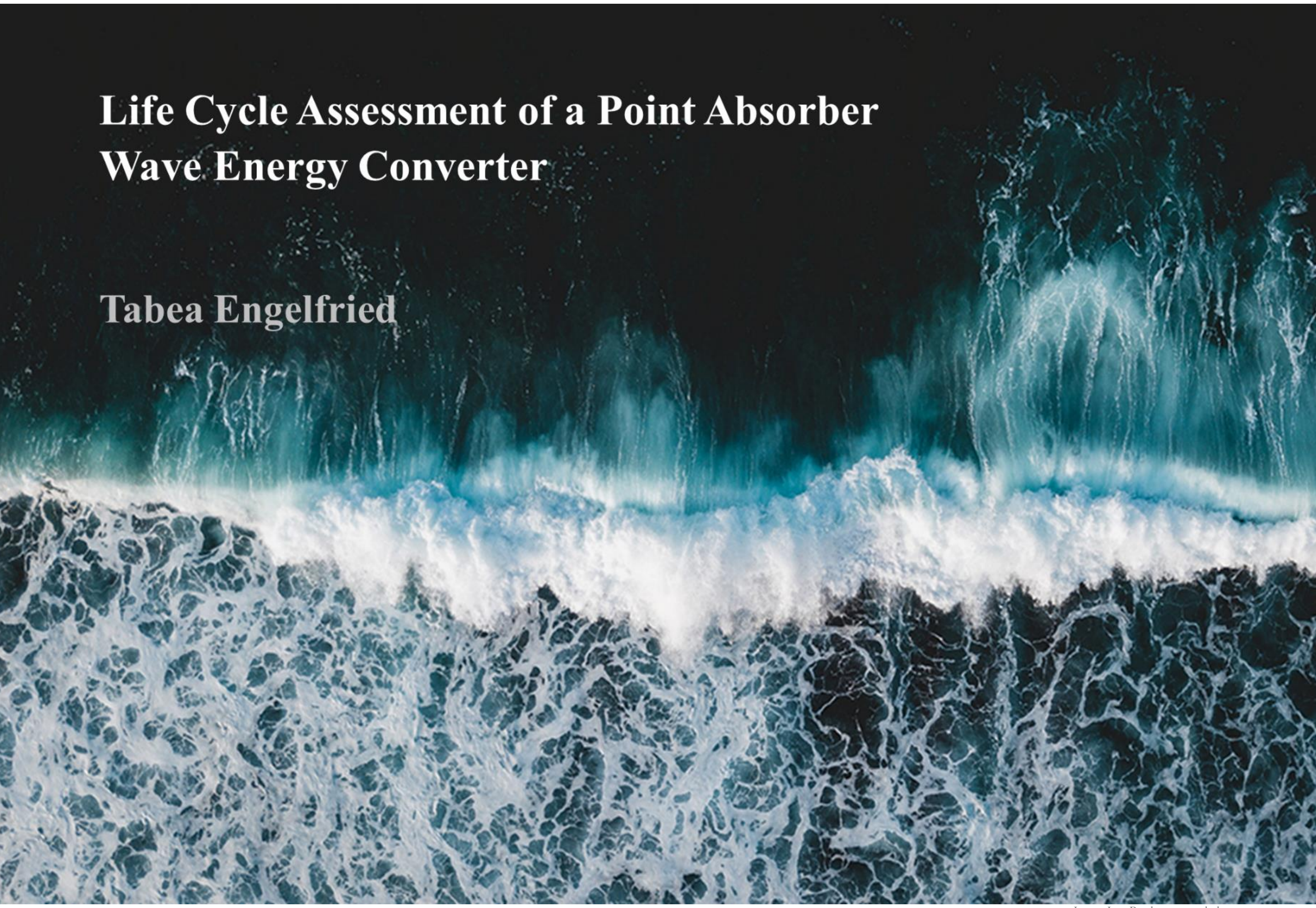

Image: Ivan Bandura on unsplash

Industrial Ecology Master Thesis

Supervised by

Dr. George Lavidas — TU Delft
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February 5th, 2024 – July 23rd, 2024

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Life Cycle Assessment of a Point Absorber Wave Energy Converter

by

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Preface

With this master thesis, my time as an Industrial Ecology student, and probably my time as a student in general, comes to an end. And as I am leaving university now, I feel more inspired than ever.

The Industrial Ecology programme has reignited my passion for learning after a challenging bachelor's degree and widened my previously narrow, purely engineering driven perspectives. The programme encouraged me to strive to understand the whole system, to continuously question what constitutes truly sustainable solutions and provided me with the tools to do so. During the studies my curiosity was sparked every day, and I was able to deepen my knowledge in existing areas of interest and to develop new ones. After two years, I can say that especially the energy transition, offshore renewable energy technologies and life cycle assessments have grown to be my main areas of interest. I can see myself pursuing my upcoming professional career within this context.

Also, this thesis project resembles these interests of mine, and I want to thank my supervisors George Lavidas (TU Delft) and Stefano Cucurachi (Leiden University) for giving me the opportunity to work on this exciting and relevant topic. They empowered me to work independently while providing support whenever needed, making this journey a great learning experience and very enjoyable for me.

Carried by this professional support of university staff but also my social support system – new friends, old friends, family, my great roommate, an inspiring workplace… - I was able to pursue my studies while feeling at home in this new country and without ever having to neglect any of my many personal interests. Thanks to this, I have been able to make the most of the programme and also of this thesis project, and I hope by that I have created something that can be of further use for the research at the TU Delft Marine Renewable Energies Lab and for the sustainable development of wave energy technology.

Tabea Engelfried, Delft, July 2024

Abstract

Harnessing wave energy from the world's oceans provides an enormous chance to fulfil substantial parts of the energy transition's demand for electricity from renewable sources. The technology that makes this possible is wave energy converters (WECs) - offshore structures that can convert the energy in waves into electricity. Although the energy conversion of this precommercial technology is not directly linked to greenhouse gas emissions like in other conventional power plants, environmental sustainability over the whole life cycle of the device needs to be ensured for a sustainable large-scale application. To assess this, in recent decades some Life Cycle Assessment (LCA) studies have been carried out on different WECs. However, there is still a gap in terms of number, quality, coverage of more sustainable design alternatives as well as impact assessment beyond greenhouse gas (GHG) emissions. Therefore, in this study a specific type of WEC – the point absorber – is assessed for its environmental sustainability by means of LCA. A parameterized cradle-to-grave LCA model of a single representative point absorber is implemented to assess the environmental impacts of a WEC, the influence of different hull materials, hotspots in impacts of WEC components as well as variations induced by different deployment locations. A GHG-intensity of 300-325gCO2eq./kWh with periphery and 52-77gCO2eq. without periphery is found for a WEC deployed in the Dutch North Sea depending on the hull material. Using an alternative fibre reinforced concrete material for the hull can reduce impacts across all impact categories between 10% and 78%. Next to the structural materials in the WEC the electrical cable and vessel operations, especially for maintenance, were found to contribute significantly. This study showed that impacts of electricity from WECs have to decrease to reach the level of other renewable electricity generation technologies but revealed possible levers to achieve such a reduction.

Keywords: Wave Energy, Life Cycle Assessment, Ocean Energy, Environmental Sustainability, Point Absorber

Contents

List of Abbreviations

AC/DC	Alternating Current/ Direct Current
AEP	Annual Electricity Production
AHTS	Anchor Handling and Tug Support Vessel
BOM	Bill of Materials
CCA	Cross Consistency Analysis
CF	Capacity Factor
CLD	Causal Loop Diagrams
CLV	Cable Lay Vessel
CTV	Crew Transfer Vessel
DC	Direct Current
EF	Environmental Footprint
effE	Electrical System Efficiency
EOL	End-of-Life
EU	European Union
GGBS	Granulated Ground Blast Furnace Slag
GHG	Greenhouse Gases
GMA	General Morphological Analysis
HFO	Heavy Fuel Oil
JRC	Joint Research Centre
L	Lifetime
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCOE	Levelized Cost of Electricity
MREL	Marine Renewable Energies Lab
NdFeB	Neodymium-Iron-Boron Magnets
NL	Netherlands
O&M	Operation and Maintenance
OB	Oscillating Body
OD	Overtopping Devices
OET	Ocean Energy Technology
OSV	Offshore Support Vessel
OTEC	Ocean Thermal Energy Conversion
OWC	Oscillating Water Column
PA	Point Absorber
PTO	Power Take of unit
PV	Photovoltaic
REE	Rare Earth Element
RP	Rated Power
RQ	Research Question
SPM	Submerged Pressure Differential
WEC	Wave Energy Converter

AC	Acidification
GW	Global Warming
FET	Freshwater Ecotoxicity
FD	Fossil Energy Source Depletion
FE	Freshwater Eutrophication
ME	Marine Eutrophication
TE	Terrestrial Eutrophication
HTc	Human Toxicity – carcinogenic
HTnc	Human Toxicity- non carcinogenic
IR	Ionising Radiation
LU	Land Use
MD	Metal/Mineral Depletion
OD	Ozone Depletion
PM	Particulate Matter Formation
POF	Photochemical oxidant formation
WU	Water use

1. Introduction

Ocean waves are a huge renewable energy resource, alongside conventional renewables such as wind and solar. Their global energy resource potential is estimated to be around 29000 TWh per year (IRENA, 2021) – more than the world's electricity demand in 2022 (IEA, 2024). In a time when "greenhouse gas emissions remain at record levels and the accumulation of emissions is increasing physical climate risks" (IEA, 2023, p.79), the issue of transitioning our energy system away from fossil fuels is becoming increasingly urgent. Harnessing even a percentage of the natural resource of waves with WECs could play a significant role in delivering the amounts of renewable electricity required by the accelerating energy transition (Gunn & Stock-Williams, 2012; IRENA, 2021).

The energy in ocean waves is present in 13 times higher density than in wind and suitable sites for extraction are distributed widely over the two hemispheres (Guo et al., 2021). In addition to the abundance and density of the resource, the deployment of WECs can be motivated from an energy systems integration perspective: Waves have high availability of up to 90% on an annual basis, low seasonal variations, are well predictable and have a different intermittency pattern then wind and solar (Guo et al., 2021; Reikard, 2013). Because these features WECs can potentially smooth out power output and reduce storage requirements when combined in multiple-source renewable energy systems (Friedrich & Lavidas, 2017). This makes wave energy a suitable candidate to help integrate high shares of renewables into the electricity grid (Kluger et al., 2023).

To harness the energy source a variety of wave energy converters has been developed since the late 1900es. As of today, the technology remains in a precommercial state. Due to the above-mentioned reasons together with the growing pressure to replace conventional power generation with renewables, developments are ongoing and accelerating once more: The European Union (EU) plans to exploit the North Sea as the renewable power plant of the future and diversify renewable energy sources with ocean energy. In the "EU strategy to harness the potential of offshore renewable energy for a climate neutral future" a deployment of 40GW of ocean energy consisting of mostly wave energy is envisioned (European Commission, 2020).

In the context of expanding the deployment of wave energy converters, it is crucial to consider their potential environmental impacts and prove that replacing conventional electricity generation techniques by WECs actually reduces the energy system`s pressures on the environment. Also, the European Union is shifting more and more focus on this aspect of new technology and promotes the measurement and communication of product's environmental footprints based on life cycle assessment (Official Journal of the European Union, 2021). Consequently, this study performs an LCA on wave energy converters deployed in Europe. The LCA examines all inputs and outputs from and to the environment throughout the device's lifecycle and quantifies the associated potential impacts.

In the following chapter wave energy technology and its current state as well as the literature landscape on WEC LCAs is introduced. In chapter 3 insights on the method and modelling of a representative WEC for LCA are given. Results are presented in chapter 4 and discussed in chapter 5, leading up to the conclusion in chapter 6.

2. Context

2.1. Introduction to Wave Energy

Despite the advantages of harnessing ocean wave energy, there are inherent challenges associated with the nature of the wave resource. Firstly, the wave resource itself is characterised by a broad spectrum of parameters, which are highly variable in time and space. Secondly, the low frequency and high amplitude of the wave-induced motion is not optimal for general generator design. Moreover, the offshore environment is harsh and hard to reach. In order to perform in such a dynamic environment and to withstand the extreme conditions, devices must have high reliability and survivability requirements. This leads to high costs for installation, operation and maintenance (O&M) compared to any installation on land (Guo et al., 2021).

Early wave energy development started in the 1970s. Since then, a variety of devices and working principles were developed in parallel, trying to overcome the mentioned challenges. Different converters have been tested at different scales in sea trials, but no long-lasting commercialization could have been achieved due to failure or economic issues (Falcao, 2010). Despite the long history, there has been no convergence towards a specific technology. This lack of convergence poses additional challenges for commercialization as it diffuses efforts and investments, slows down the learning curve and prevents economies of scale (Guo & Ringwood, 2021).

Previously developed WECs can be classified into three major types according to Falcao (2010): Oscillating water columns (OWC), oscillating bodies (OB) and overtopping devices (OD). Especially in the OB category further sub classifications are observable that are presented in the following figure. This classification is based on the European Marine Energy Centre (EMEC, 2024) and is not exhaustive, but sufficient for the purpose of this study.

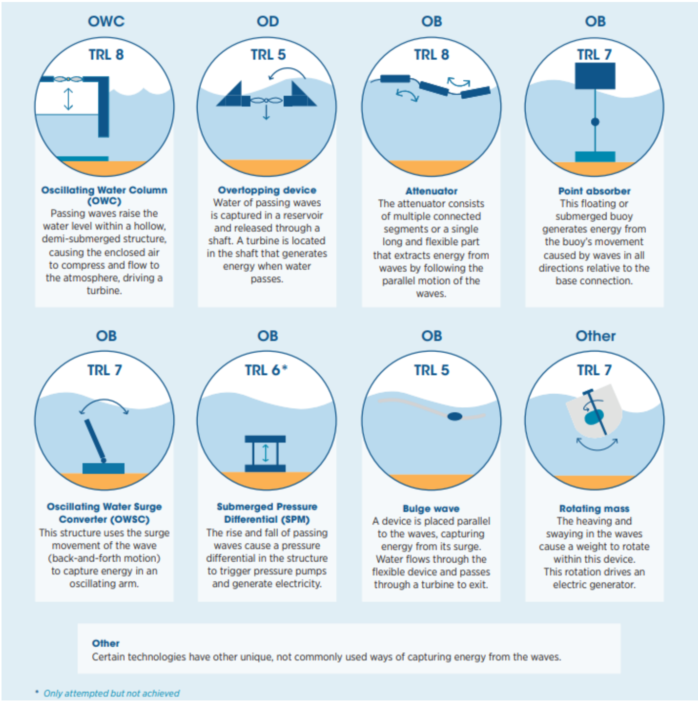


Figure 1 Categorization of wave energy devices according to EMEC (Source: IRENA, 2020)

WECs cannot only be characterized by their working principle but also by their favourable deployment conditions either onshore, near-shore or offshore. This additionally determines the performance and requirements of a deployed WEC as location parameters like water depth and distance to shore directly impact the infrastructure, material, process and cost requirements for installation, maintenance and operation (Curto et al., 2021).

Despite the lack of a certain favoured design, developments today tend to focus more on point absorber (PA) WECs, as evidenced by the number of projects developed (IRENA 2021, IRENA 2020, Uihlein, 2016). 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." From this definition the major technical components of the device are derived: a **floater** as power capture unit, the **PTO** for power conversion, a **control system** to tune the device response to the waves, a so-called **reactor** acting as the reference to the heaving body (later also called foundation), **moorings** for station keeping and the **electrical connection** to the grid (Guo et al., 2022; Curto et al., 2021).

As point absorbers work through being in resonance with the incoming wave the specific design and geometry of the floater is highly dependent on the particular wave characteristic at a given location. This relationship is complex as the extractable power in a wave at one position does depend on several spectral parameters such as the significant wave height and the wave period. These are results of wind-wave interaction and the geographical conditions like water depth and distance they travelled, as well as other non-linear interactions. The conditions change between sea states, over time and between years defining the potential of the wave resource at a certain location (Pecher & Kofoed, 2017; Cruz, 2008). This variety of determining factors of the power extractable from a wave makes waves a more complex resource then e.g. wind (Guillou & Chapalain, 2018; Guillou et al., 2020). Besides that, a deployment location is characterised by its reachability, occurrence of extreme events, seasonal and annual variations. A suitable WEC needs to be fitted to all the above-mentioned influences to survive and produce electricity in an efficient manner.

2.2. Literature Review

Various prototypes of WECs have been developed in the industry since the 1970s (Falcao, 2010), with technical literature on them ever increasing. The current state of research is shown in Figure 2: Most research & development activities focus on the technical dimensions of wave energy converters such as converter concepts, PTO systems, control strategies and resource characterization, located in the inner ring. Less efforts are spent on the outer two rings, although all the aspects are required for the pathway towards commercialization (Guo & Ringwood, 2021). Environmental aspects are located in this underrepresented outer ring as well. Also, Uihlein & Magagna (2016) shed light on research aspects currently underrepresented. Among others they highlight gaps in the field of understanding direct interactions of offshore structures with the marine environment e.g. through alternations in flow patterns entanglement, collision, noise and electromagnetic fields of sea cables.

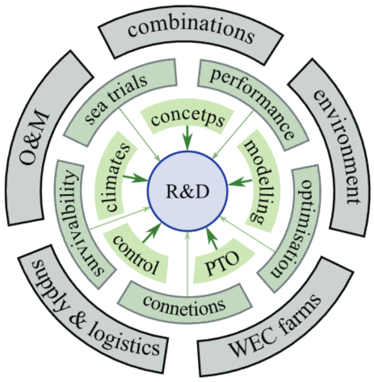


Figure 2 The current research field around wave energy technology (Source: Guo & Ringwood, 2021)

In the last 20 years the assessment of environmental impacts of ocean energy technologies (OET) by means of LCA gained momentum to prove the motivation for this renewable energy alternative. A literature review from Paredes et al. (2019) on LCA studies covering all OETs (wave, tidal, OTEC and salinity gradient) found 18 studies in the time span from 2007 until 2019. From this, 11 studies assess WECs. Only seven of all OET studies performed a full LCA with impact assessment covering more than Carbon, GHG emissions or embodied energy. Also, Paredes et al. (2019) points out a gap in the coverage of marine interactions and LCA studies on coating, antifouling and electromagnetic fields of sea cables.

In this study we found 19 LCAs on wave energy until the end of 2023 which are in line with the one presented in Paredes et al. (2019) but also include eight studies published in or later then 2019. Despite the number of studies found, there is a mismatch between wave energy projects in development (45 ongoing projects with sea testing maturity have been identified by the European Joint Research Centre (JRC) in Europe alone in 2016 (Uihlein, 2016) and 49 by IRENA in 2021) and the amount of performed sustainability assessments by means of LCA suggesting the need for a more comprehensive sustainability assessment of different WEC projects.

Table 1: LCA studies on WECs between 2006 and 2023 identified in this study

Authors	Year	WEC	Installed Capacity	Operating Principle	Functional Unit	Impact Assessment	Lifetime [yrs.]	GWP Results [gCO2 eq./kWh]
Bastos et al.	2023	LiftWEC	100MW	others	1 kWh electricity	RECiPe 2016, CED	25	32
Bruno et al.	2022	generic Seabased SeadampFX	na	OWC On-Shore point absorber point absorber	1 year of device operation	GWP	na	203-270* 94-374* 105-158*
Apolonia & Simas	2021	MegaRoller	1MW	wave surge	1 kWh electricity	ReCiPe Midpoint, CED, GWP	20	33,8-75,1
Di Muro et al.	2021	ISWEC	100kW	rotating mass	1 kWh electricity	undefined	20	31,5-62
Pennock et al.	2022	Cor Power Ocean	10MW	point absorber	1 kWh electricity	RECiPe v.1.31 Midpoint	20	25-42
Karan et al.	2020	Oyster 1 Oyster 800	315kW 800kW	wave surge	1 kWh electricity	EDIP2003, CED	15 20	79 57
Thomson et al.	2019	Pelamis (1st gen)	750kW	attenuator	1 kWh electricity	ReCiPe Midpoint, CED, GWP	20	35
Patrizi et al.	2019	OBREC	3kW	overtopping	1 Device	GWP	60	37-86
Banjaree et al.	2013	Pelamis Wave Dragon	750kW 7MW	attenuator, overtopping	1 Device	GHGs, Carbon and Energy intensity	20 50	19,49 28,23
Zhai et al.	2018	buy rope drum	10kW	point absorber	1 kWh electricity	ReciPE	20	89
Curto et al.	2018	DEIM I DEIM II	na	point absorber	1 device	PEF (modiefied)	20	143 67
Uihlein	2016	103 devices	5 - 2000kW	53 point absorber 16 wave surge 6 Attenuators 15 Oscillating Water Columns 1 Overtopping 3 Pressure Differential 4 Rotating mass 5 others	1 kWh electricity	Hauschild, 2012 (midpoint)	20	105 65 45 50 40 105 67
Douziech et al.	2016	Oyster	800kW	wave surge	1 kWh electricity	ReCiPe 2008	20	65.5
Dahlton et al.	2014	Wavestar	1MW	point absorber	1 device	Carbon and Energy audit	20	47
Thomson et al.	2011	Pelamis	750kW	attenuator	1 kWh electricity	EDIP 2003	20	30
Walker & Howell	2011	Oyster 1	315kW	wave surge	1 device	Carbon and Energy audit	15	25
Dahlsten	2009	Seabased	20MW	point absorber	1 kWh electricity	PEF	20	32-152
Parker et al.	2007	Pelamis	750kW	attenuator	1 kWh electricity	Carbon and Energy audit	20	23
Sorensen et al.	2006	Wave Dragon	7MW	overtopping	1 kWh electricity	EDIP	50	na

**t/1 year of device operation (no values for kWh given)*

Table 1 gives an overview over the studies performed until this day. Seven studies covered point absorbers, five attenuators, five wave surge devices, two overtopping devices and the rest others like rotating mass, OWC, and undefined principles. Seven of 19 studies do not provide a full impact assessment. The rest miss assessment criteria besides GHG emissions, and no study incorporates the direct interactions of the device and required support vessels with the marine environment in a quantitative way.

The results of studies carried out to date are still variable, with found GHG intensities ranging from 23 to 152 gCO2eq./kWh. The high variations stem mainly from the different types of assessed WECs as they differ largely in structure, power output, and material requirements. Further differences in methodological choices such as the inclusion of recycling credits add to the large span.

The three most comprehensive LCAs to date are from Uihlein in 2016, Thomson et al. in 2019 and Pennock et al. in 2022 which all are methodologically consistent cradle to grave, full impact assessment studies that document assumptions well and use primary data. Thomson et al. (2019) reassessed the environmental impacts of the Pelamis attenuator and revealed ~15-20% higher impacts in the global warming category (GW) than previously assessed for this device (Thomson et al., 2011). Thereby they highlight the importance of assessing previously not included environmental impacts beyond carbon and energy intensities and other methodological improvements regarding the use 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. Uihlein (2016) collectively assessed 103 WECs from 50 developers, overarching eight different working principles based on a European database for ocean energy projects (not public). The study provides a broad overview over the principal impacts of the WEC types due to their generic structure. Point absorbers are with 53 out of 103 devices, the most commonly developed type WEC but also show the highest GHG intensities with 105 gCO2eq./kWh. Pennock et al. (2022) assessed an array of the only currently commercially available point absorber WEC from CorPower Ocean and shows that this specific PA incorporated two to three times lower GHG intensity then PAs assessed in Uihlein's collective LCA. Although the study presents itself as methodologically correct, data used is not disclosed and modelling assumptions are not documented transparently.

Regardless of their comprehensiveness, the studies from Thomson et al., Uihlein and Pennock et al. all come with limitations either by considering only one specific prototype (Pennock et al., 2022; Thomson et al., 2019) or a whole variety of different working principles (Uihlein, 2016). The narrow focus leads to limited applicability to other devices, the broad focus comes with limitations regarding the degree of detail presented in the model, compromising the useability and comparability of the results as various smoothing assumptions made. Further none of the studies is documented well enough to make it fully reproducible. This highlights the need for a transparent, representative and adjustable model of one technology making it widely applicable without losing the required degree of detail for it to be representative of the reality.

In earlier years several LCA studies on different versions of WEC prototypes such as the wave surge converter Oyster1 and Oyster800 (Walker & Howell, 2011; Douziech et al., 2016; Karan et al., 2020) or the attenuator Pelamis P1 and P2 (Parker et al., 2007; Thomson et al., 2011; Thomson et al., 2019) have been conducted including adjustments to the LCA method (omitting recycling credits, broader impact assessment). The consecutive studies mostly with a more detailed assessment scope and advanced LCA methodology revealed higher values for GW for both devices. This shows that thorough assessment is required to estimate the full impacts of a device in a representative way.

Although newer studies generally have shown an increase in methodological completeness (broader impact assessment, adjustment of recycling credits) this does not hold for all aspects of the studies: Regardless of the year of publication a general lack in quality regrading made assumptions, use of non-disclosed data, transparent documentation and a holistic view on the system can be pointed out (Bruno et al., 2022; Karan et al., 2020; Soerensen et al., 2006; Dahlton, 2014; Douziech, 2016; Curto et al. 2018).

Despite the variations in quality and assumptions between the studies, dominant conclusions throughout the field are apparent: The largest contribution to the total impact stems from the used materials in the structural components and mooring and make up between 40% and 90% of total impacts depending on the study. This trend is not only visible in the category of global warming (GW) but also various other impact categories (Paredes et al., 2019). Today WECs are mostly steel or composite, and recently concrete structures with large dimensions and high requirements for lifetime, structural integrity, and corrosion resistance to withstand the harsh marine environments. This hotspot is well known, still only few studies assess or consider viable alternative materials for comparison.

Conclusions from this review are that available LCAs on WECs lack in quality and are not enough in number compared to the developments going on. Studies so far found a high contribution of structural steel to overall impacts, but do not assess alternative feasible materials. Further comparability and applicability are limited due to the use of disclosed data, very case specific assumptions or too broad assessments lacking a proper degree of detail.

3. Method

3.1. Approach

For a future proof sustainable energy system, it is required that electricity can be provided without creating new systematic impacts on the environment. In the future, measures other than the pure cost of energy will become increasingly important in technology selection for energy system integration; environmental performance is set to become one determining factor, especially in the EU (European Commission, 2020). To assess the environmental impacts of an electricity generating device, context must be created between the possible environmental benefits by the displacement of fossil fuels and the environmental impacts it is associated with. Therefore, the field of view needs to be widened from the matter of energy conversion to the whole life cycle of the conversion device. To do so, in this study an LCA according to ISO14044 standards is performed. LCA considers all flows to and from the environment over a product's life cycle and quantifies their potential impact on the environment (International Organization of Standardization, 2006).

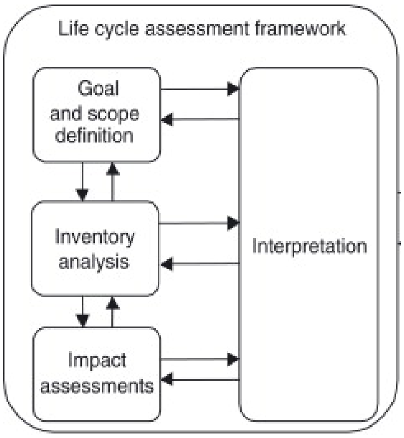


Figure 3 Methodological framework of LCA (adapted from: International organisation of Standardization, 2006)

All necessary steps included in an LCA (Figure 1) will be followed to answer the following research questions (RQs):

i. *What is the environmental impact of electricity from a representative point absorber wave energy converter considering its full life cycle?*
ii. *How does the choice of hull material affect these impacts?*
iii. *How do the single components of a WEC contribute to the overall impacts?*
iv. *How does the deployment location of a device influence environmental impacts?*

3.2. Goal & Scope Definition

The goal of this LCA is to determine the environmental impacts of a representative point absorber WEC made from different materials and deployed in the North Sea. The research is carried out at TU Delft Marine Renewable Energies Lab (MREL) and in cooperation with Leiden University. The aim is to use the results in the context of supporting decision making on possible future commercial application of WECs as a part of a renewable energy system in Europe as well as to deliver inputs to the WEC development community in early stages of commercialization to make future WEC developments more sustainable – one piece that can contribute to the road to large-scale wave energy utilization.

The scope of the study is a detailed cradle-to-grave analysis of a single representative PA device connected to the grid and moored to the seabed. Its function is to deliver electricity to the onshore grid, the functional unit for this study is set to **1kWh of electricity**. This allows for comparability to other WEC studies as well as renewable energy generation technologies (Zhang et al., 2020). Two different structural materials for the floater hull are assessed, namely steel and a newly proposed fibre reinforced concrete for ocean energy devices.

Primarily a European supply chain is assumed though wherever evidence or a lack of specific data requires, global supply chains are taken into account. The assessment is being done in an attributional manner, considering the current pre-commercial status quo of the technology of analysis as well as state of the art background technology for subcomponent manufacturing. Due to the low maturity of the industry no economies of scale for WEC specific manufacturing steps are accounted for. Further a lack of long-term operation of WECs in real seas creates a lack of data regarding installation and maintenance procedures. This can cause uncertainties in the LCA results that have to be addressed carefully in the interpretation. To compensate that lack and limit uncertainties the knowledge gained from short sea trials as well as from other more mature offshore energy generation like wind might be referred to.

The operational lifetime of the device is set to be 20 years, as it is common for LCA studies of WECs. Further the life cycle stages included in this study are chosen to be comparable to what is the status quo in this literature segment (Paredes et al., 2019, Zhang et al, 2020; Pennock et al., 2022; Uihlein et al., 2016): Manufacturing, Installation, Use and End of Life (EOL). The following figure gives a rough overview over the modelled system. All components of the WEC relevant to its function as well as all required services and facilities are represented along the full life cycle of the device. A flow diagram of all modelled LCA processes for purposes of working with the model can be found in the appendix D.

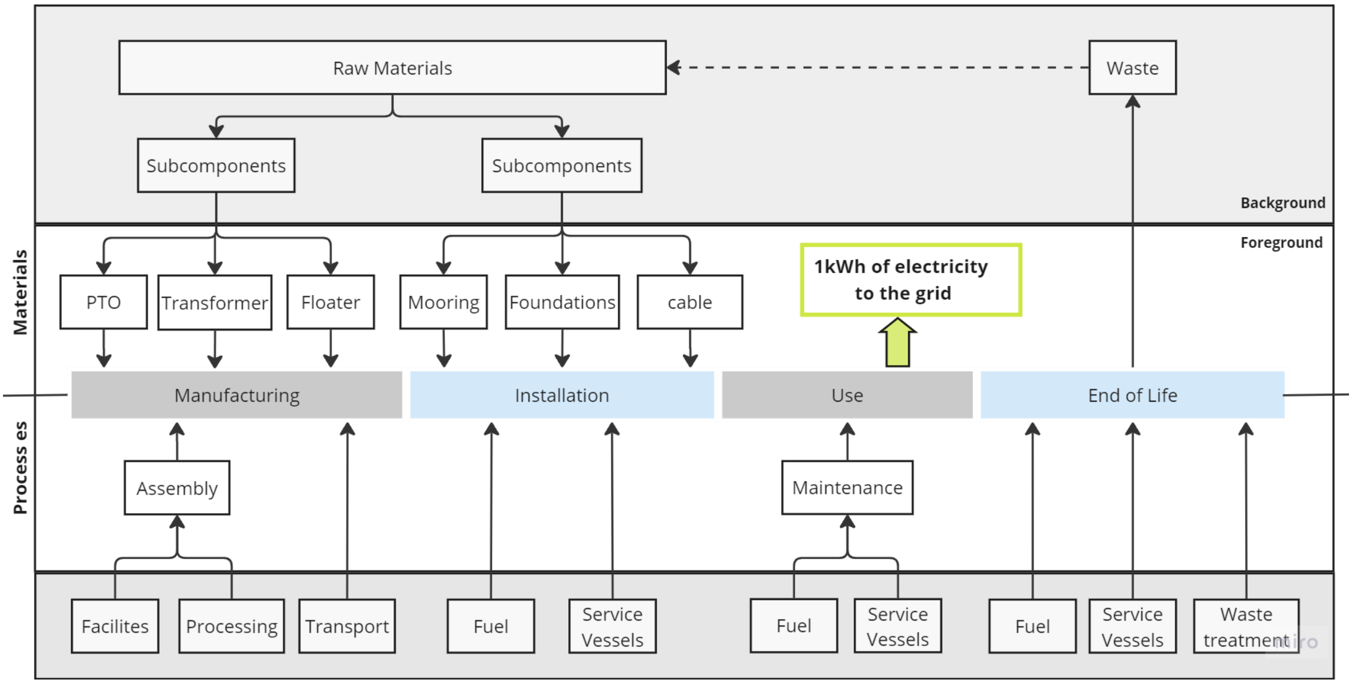


Figure 4 Modelled product system

To give a holistic assessment of the environmental performance of a PA WEC all quantifiable environmental extensions to and from the environment that occur during the life cycle stages are considered including space use, resource use, emissions to air, land and water. The model cannot cover direct interactions with marine environment such as underwater noise, magnetic and electrical fields as well as flow alternations as for these impacts no mature impact assessment models as well as data is available. Environmental impacts are assessed on a midpoint level with the environmental footprint declaration method EF 3.1. in line with the EN15043. The LCA will be modelled in the open source openLCA software that allows for parametrization of the inventory. For execution the methodological guide from Guinée, 2002 is followed. Background data is sourced from ecoinvent v.3.9. (Wernet et al., 2016).

3.3. Life Cycle Inventory

In this chapter the modelling assumptions behind the life cycle inventory (LCI) of the representative PA are described briefly. A full documentation of all modelled processes, used data points, their sources and underlying assumptions can be found in the supplementary material 1.

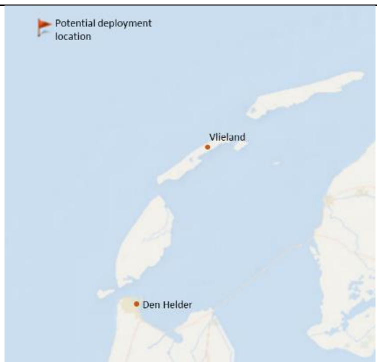
3.3.1. Representative Point Absorber

The representative PA has been determined by means of a qualitative morphological analysis (Appendix B) as the physical relations between the wave resource and device design are complex (Guillou et al. 2020) and a technical and hydrodynamic modelling is out of scope for this work.

To resemble the representative PA in the LCA model, main influencing factors like performance specifications (e.g. lifetime, rated power, capacity factor), specifications of the geometry (e.g. height, diameter, hull thickness), parameters describing the location (e.g. distance to shore and port) as well as other inputs related to installation activities are parametrized. This allows for assessment of different configurations and scenarios as well as a potential further use of the model for more specific cases. To understand influences on device design and determine parameters resembling these, a socio-technical system analysis (Appendix A) was performed beforehand. A full overview of all parameters used and their relations with each other is provided in appendix C.

Table 2: Representative WEC deployment location in the Dutch North Sea

Area	North Sea (NL), coast of Vlieland
Water depth	25m
Distance to shore	40km
Nearest capable port	Den Helder (~70km)

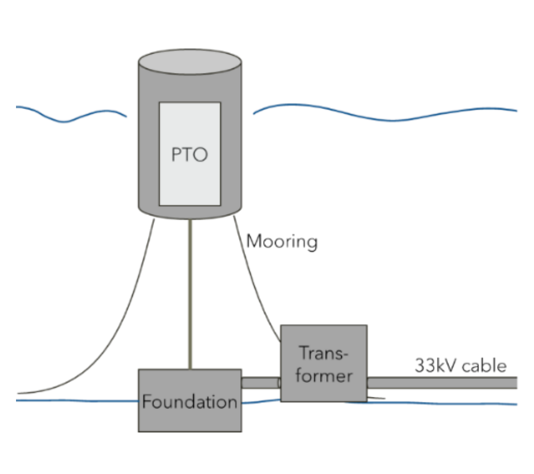


The device modelled for this study based on the prior analysis is a stand-alone PA for the utility market, deployed in the Dutch North Sea. So far, the North Sea's potential for wave energy deployment has often been underestimated due to its milder resource strength. However recent research based on long-term wave data revealed that also this milder resource can be viable when paired with the right WEC (Lavidas & Blok, 2021). Medium water depths (~30m) at close distance to shore (>100km) and the limited occurrence of severe extreme wave events are especially advantageous in this area (Lavidas & Blok, 2021). These characteristics can maximize periods where a suitable WEC can operate optimally and minimize the risk of destruction (Guillou & Chapalain, 2018; Guillou et al., 2020). Specifics of the representative deployment location are given in Table 2.

The specifications of the modelled PA for such a resource are given in Table 3. Two different materials for the hull of the device are assessed and 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 (GGBS), filler, aggregates, additives as well as steel fibres instead of traditional reinforcing. Information on the composition of the material has been provided by MREL for the purpose of this LCA.

Table 3: Baseline configuration of the representative point absorber derived from the system- and morphological analysis

Type	Single-body, fixed reference heaving point absorber	
Floater	Cylindrical	
Floater Dimensions	D9mx18m	
PTO	Direct-drive linear generator placed in the floater	
Control	Electrical control	
Mooring	3-line catenary chain mooring with drag-embedment anchors	
Reactor	Rod connection to foundation	
Electrical connection	Direct AC medium voltage transmission (33kV) to shore Low to medium voltage transformer in the device	
Capacity Factor	32%	
Rated power	400kW	
Lifetime	20 years	
Hull Material	**Steel**	**Concrete**
Wall thickness	50mm	40mm
Foundation	Steel Vertical Anchor 40t	Concrete-Magnetite gravity foundation 800t



For the representative device at the proposed deployment location the mentioned capacity factor was determined based on 30-year wave data and the power matrix of a PA device with the modelled dimensions, both provided by MREL. The power matrix, the occurring sea states, and the resulting production matrix of the representative device at the chosen location is shown in Figure 5 a-c.

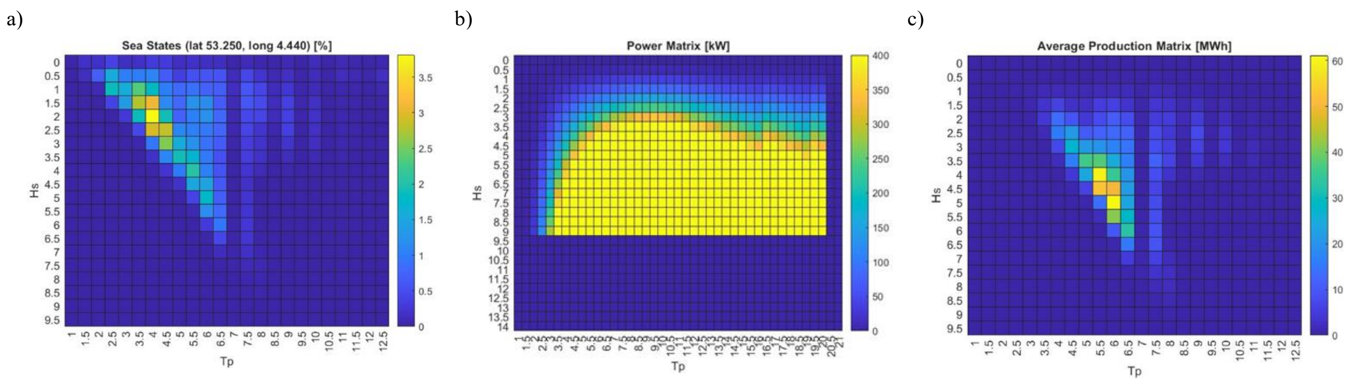


Figure 5 Occurring sea states at the assessed deployment location (a), a representative PAs power matrix (b) and the resulting production matrix (c)

A WEC as described in Table 3 at the chosen location contains the following materials:

Table 4: Bill of materials (BOM) of the representative PA

Floater, Mooring, Cable, Foundation	**t in Steel WEC**	**%**	**t in Concrete WEC**	**%**
Steel*	402,2	27,41	112,5	5,01
Steel galvanized	432,8	29,52	432,8	21,28
Fibre reinforced concrete	-	-	66,7	3,28
Concrete	-	-	490,0	24,10
Copper	240,2	16,39	240,2	11,81
Magnetite	-	-	312,0	15,34
Lead	276,8	18,88	276,8	13,61
PP	44,4	3,03	44,4	2,18
PE	65,2	4,45	65,2	3,21
NdFeB magnets	0,9	0,06	0,9	0,04
Others**	4,8	0,33	3,5	0,17
Total	**1467,3**	**t**	**2045,03**	**t**

*without steel fibre in concrete
** electronics, paint, iron, epoxy, aluminium, porcelain, paper, transformer oil

only Floater	**t in Steel WEC**	**%**	**t in Concrete WEC**	**%**
steel*	296,6	97,94	46,9	39,81
Fibre reinforced concrete	-	-	66,7	56,64
Copper	1,4	0,48	1,4	1,22
iron	1,5	0,50	1,5	1,27
aluminium	0,2	0,07	0,2	0,17
NdFeB magnets	0,9	0,30	0,9	0,76
electronics	0,4	0,15	0,4	0,37
transformer oil	0,3	0,11	0,3	0,29
Others***	1,4	0,47	0,2	0,13
Total	302,8	t	118,50	t

***paper, porcelain, epoxy, paint

3.3.2. Manufacturing

In the manufacturing stage the floater is assembled from its hull materials, structural material 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 at the assembly site. The concrete floater is casted from fibre reinforced concrete (see chapter 3.3.1.) 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.

The pre-manufactured components are produced at an unknown site in Europe and transported as one piece to the port site where they are coupled with the floater. Pre-manufactured components of the floater are the transformer and the linear generator modules as well as an anti-corrosive glass-flake paint (applicable for steel hull). For these components only major material processing steps (e.g. sheet rolling, milling and such) are represented in the model. Other manufacturing processes are left out of analysis. A brief description of the modelling of the mentioned components as well as the data sources used for the LCI is given in Table 5:

Table 5: Description of modelled pre-manufactured components

Component	Description	Data Source for LCI
Transformer	Low to medium voltage transformer to process 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 & Marquart et al., 2018
PTO	Modular direct drive linear generator based on an iron core, copper coils and Neodymium permanent magnets (NdFeB) as proposed for the AWS waveswing device. The generator for the AWS waveswing has a 2MW capacity and is built of two 8m high modules. For this study a 100kW module is modelled that can be scaled to the rated power of the assessed WEC. Direct drive linear generators have low mechanical system complexity, high efficiencies and are therefore expected to be more widely used in WECs in the future (Guo et al., 2022, Lopez et al., 2013, Yang et al.,2024).	Hodgins et al., 2012 Prado & Polinder, 2011

Further a fixed amount of steel (35t) is added to the floater to represent a generic internal structure of the device e.g. end-stop springs, rods, bolts and nuts. A connection of the floater to the later foundation is modelled in a representative way by a hollow steel pipe. Depending on the water depth and draft of the floater ~10t of steel are used. The electrical control system in the floater is resembled by a fixed amount of generic electronics common for generator control, as proposed in ecoinvent datasets for wind turbines.

For modelling transport and choosing the applicable geography of background processes a two-level hierarchy is applied. Inputs to the pre-manufactured components are represented by global market processes (transport included in the datasets). The full weight of the pre-manufactured component is then transported from the unknown production location to the port site. Direct inputs to the floater are modelled by ecoinvent market processes of the closest available geography. Transport is modelled according to the general European modal split (Eurostat, 2024), average transport distance for road transport (Eurostat, 2023) and assumed average distance of 1000km for rail and inland waterways (Uihlein, 2016). For steel and ferrous metals, a product specific modal split with increased shares of rail and barge transport is used (eurofer, 2003).

As for the direct steel input to the floater no European market process exists in ecoinvent, the global steel market process has been adapted to match the European ratio of domestically produced (76%) and imported steel (24%) according to eurofer, 2023. All other steel that is input to subcomponents is from unknown origin, therefore the ecoinvent global market is used (ecoinvent, n.d.).

3.3.3. Installation

Once the floater is assembled at the port, it is ready to be brought to the deployment site via towing and coupled with its foundation and periphery. The required periphery as well as different steps of the installation are described in the following.

3.3.3.1 Periphery

To allow the floater to fulfil its function it needs to be referenced to the seabed, connected to the grid and depending on the specific design kept in position. For these purposes a foundation, an electrical transmission system and a mooring system is required (Table 6). These are added during the installation phase. The export cable, mooring chains and anchors as well as the steel foundation are pre-manufactured components where the same modelling rules (transport, assembly) apply as described in chapter 3.3.2.

The foundation chosen differs between the two modelled product systems (see chapter 3.3.1.). Further it does officially not belong to the periphery as it takes part in the actual energy extraction, but it is an external part to the floater that does not get added at the port but is only coupled with the floater during installation. Therefore, it is nevertheless being covered in this section.

Table 6: Modelling of external floater components and periphery

Component	Description	Data Source for LCI
Foundation (steel product system)	**40t steel vertical anchor resembling the UMACK anchor** used by CorPower Ocean. The anchor is installed in one piece and is fully retrievable.	CorPower Ocean, 2022
Foundation (concrete product system)	**800t gravity-based concrete-magnetite foundation with 10m diameter and 3m height**. Magnetite is a highly dense iron oxide that is used in gravity foundations to reduce the overall volume of required material. The foundation is assumed to be partially poured in place.	MREL expert knowledge LKAB Minerals, 2015
Transmission	**33kV medium voltage AC cable to shore.** This type of system is a suitable choice for short distances to shore (<70km) and small plant sizes <1MW due to lower losses and lower cost than e.g. HVDC transmission that would require an offshore substation. Losses for the modelled system lie around 6% of the produced electricity. The cable is a ~15cm diameter XLPE (polymer) insulated copper conductor cable with galvanized steel mantel, and lead (total cable weight of 26,4t/km). Its LCI is derived from Li et al. 2022 that aggregated it from different cables of that specification on the market. For the specific location in this analysis (see chapter 3.3.1.) the shortest distance to shore is 40km to the island Vlieland where grid connection is unlikely to be possible, though for the representative nature of the assessment it is assumed that a WEC is deployed in a location where a connection point lies at the point of shortest distance to shore (see appendix A). A cable length of 40km is therefore modelled.	Lopez et al., 2010 Li et al. 2022 Birkeland, 2011 Arvesen et al., 2013 Elginoz & Bas, 2017 Taormina et al., 2017
Mooring	**Catenary 3-line spread chain mooring with drag embedment anchors**. A chain of 48mm diameter and a weight of 50kg/m is derived from several proposed mooring systems for PA WECs. Anchors have a weight of 15t each. The catenary mooring lines require a length of ~5,5 times the water depth so that sufficient chain rests on the seabed in non-exited conditions. The mooring is modelled as optional as not all PAs require mooring in addition to the connection to the seabed (reactor).	Cerveira et al., 2013 Depalo et al., 2021 Pecher et al., 2014 Harris et al., 2004

For all the components in touch with the seabed, land use in the form of transformation (habitat loss) and occupation (land competition) (Guinée, 2002) is taken into account.

3.3.3.2 Activities

The floater and periphery need to be installed at sea by offshore vessels, this happens in several different steps: Cable laying, pre-lay of moorings, installation of the foundation, tow out of the device, hook up to the moorings as well as cable and foundation (Pennock et al., 2022; Thomson et al., 2019; Garcia-Teruel et al., 2022). All of these steps are executed by specialized sea vessels like tugboats, cable layers (CLV), anchor handlers (AHTS) and offshore support vessels (OSV). The modelling of these actions requires data on vessels and their fuel consumption (Table 7) as well as the duration of actions (Table 8). Due to the lack of operational experience of WECs this information is not publicly available in good quality.

For this study data on fuel consumption and duration has been extracted from literature on WECs as well as floating- and bottom fixed offshore wind parks. Some of the information in these references is of unclear source or might not represent the actions for PA installation accurately though is seen as good enough representation for purpose of this study. Further uncertainty in the data is induced through the variety of operating modes of the used vessels: Offshore vessels are built for a wide range of purposes all leading to different engine loads. An OSV or AHTS might have up to 15 use cases with different fuel consumptions (Adland et al., 2019). Also, during the actions for the WEC installation different phases (transit, towing, station keeping) might occur. This level of detail cannot be represented without actual data from WEC deployment which is not available.

Table 7: Used vessels, 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*	Li et al., 2022	Transport, freight, sea ferry
Tug	Tugboat	HFO	600	Garcia-Teruel et al., 2022 Brussa et al., 2013	Transport, freight, sea ferry
CTV	Crew Transfer Vessel	Diesel	300	Garcia-Teruel et al., 2022 Brussa et al., 2013	Transport, freight, inland waterways, barge**

HFO=Heavy Fuel Oil
* value was translated from l/h with a HFO density of 983kg/m3 (Arvesen et al., 2013)
** adapted to not include canal infrastructure

Table 8: Installation steps, duration and vessels 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 under the sea floor	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 & cable	10h	1xOSV 1xTug	Pennock et al., 2022
Deinstallation Floater	1x towing, 1x unlatching	See above	See above	-

Actions that are not included due to large variations between projects and deployment locations as well as lack of publicly available data are: Scour protection of the cable and foundation, surveying and site preparation, distance to port dependant transit of the OSV and AHTS at pre-lay and foundation installation as well as the travel of the offshore vessels to the project area (start points unknown).

The specific offshore vessels required are so far not sufficiently represented in ecoinvent (Arvesen et al., 2013). Therefore, existing shipping processes in the databased are scaled in a way that it matches the fuel consumption of the information provided in Table 7. This is similar practice to other LCA studies on offshore renewables (Thomson et al., 2019, Arvesen et al., 2013, Pennock et al., 2022). The ecoinvent dataset for "transport, freight, sea ferry" (Notten, 2018) is seen as most applicable for the larger HFO-propelled vessels due to the comparable deadweight tonnage of the ferry (10.000t) and the used sea vessels (~4000t) (van Oord, n.d.; Boskalis, 2024; Maersk Supply Service, 2024). The CTV (small fast vessel) is modelled as a smaller diesel-powered barge "transport, freight, inland waterway, barge" (Spielmann, 2007).

Using these datasets allows for including the whole supply chain of a ship including manufacturing, maintenance and port facilities as well as the combustion emissions and supply chain of the used fuel into the analysis. The use of the ferry and barge for one activity is modelled as shown in the following formula:

$$transport, freight, ferry/barge\ [t * km] = \frac{\left(\sum fuel\ consumption\ vessel(s)\ \left[\frac{kg}{h}\right] \times duration\ of\ activity\ [h]\right)}{fuel\ consumption\ ferry/barge\ [\frac{kg}{t * km}]}$$

3.3.4. Use Phase

Once installed, the device produces electricity from the sea waves without any direct emissions related to the power conversion. To ensure continuous operation over the lifetime maintenance is required as input.

Due to the lack of operational experience, specific maintenance strategies have not yet been established for the wave energy sector. A few studies present possible O&M Strategies for WECs based on component failure rates from data bases related to other industries and applications (Rinaldi et al., 2018; Mueller et al., 2016). Although this induces uncertainty as the actual failure of a component is heavily dependent on specific load characteristics and the environmental conditions, these estimations can provide a basis for pre-commercial estimation of the maintenance needs of a WEC and are currently the only available quantified estimations on that topic (Rinaldi et al., 2018; Mueller et al., 2016).

Maintenance strategies can differ widely in how and when interventions are executed. To determine when maintenance is required preventive scheduled maintenance, conditional maintenance based on inspections or corrective maintenance philosophies can be applied. When applying preventive maintenance strategies, the number of replaced components during a lifetime is higher while corrective maintenance is the simplest strategy but may lead to larger costs due to cascaded failure effects and potential higher downtime (Ambühl et al., 2015). How maintenance actions on floating structures such as PAs are performed also differs per case and depends on the accessibility of the deployment location and WEC as well as the failed component inside the device (Ambühl et al., 2015). Repairs can be either performed on-site or at port site, where the floater needs to be disconnected, towed to a harbour and returned afterwards.

In previous WEC-LCAs, if any, various device specific assumptions have been made ranging from maintenance scenarios with 6 inspections per year and different corrective maintenance scenarios (Pennock et al., 2022 - CorPower Ocean Point absorber), 2 hours of maintenance per year (Dahlsten, 2009 - Seabased PA), 2 tow backs a year and remote controlled inspections (Thomson et al., 2019 - Pelamis attenuator), yearly inspection of several days as well as repair and maintenance on site every 5 years (Karan et al., 2019 - Oyster wave surge).

For this study a mix of scheduled preventive inspections on site and anticipated corrective maintenance at the port site is modelled. Influences of downtime because of failures and maintenance periods on availability as well as annual energy production cannot be considered in this representative model. 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). 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). To resemble the variety of WEC maintenance approaches for this representative analysis three different scenarios are assessed. These are presented in Table 9, with a description of the activities given in Table 10.

Table 9: Maintenance scenarios

	Inspection [x/year]	Corrective maintenance [once x years]	Description
Baseline	1	4	Corrective Maintenace 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

Table 10: Modelling of maintenance activities

	Description	Duration	Vessel	Source
Maintenance (Inspection)	Inspection of the device from the outside with manual underwater equipment from a crew transfer vessel with station keeping system	6h stationary 0,036h/km travel	1xCTV	Garcia-Teurel et al., 2022 Bossa et al., 2013
Maintenance (Towing)	2x towing (to and from port); 2x hook up (latching & unlatching from mooring and foundation)	See Table 8	See Table 8	Thomson et al., 2019

During the use phase the reference flow of 1 kWh of electricity is delivered to the grid. This functional unit requires only a small part of the device and inputs from the use phase. Therefore, all the in- and outputs to the use phase are divide by the total electricity production of the device over its Lifetime (L). This depends on the annual energy production (AEP) as well as the transmission efficiency (effE).

The AEP is defined by the capacity factor (CF), the rated power of the device (RP) as well as the number of operating hours in a year. The mentioned values are all parameters adaptable in the model. The transmission losses are assumed to be constant within the applicable range of the model (distance to shore <70km and <1MW plant – see chapter 3.3.3.1.) and do not scale with distance to shore although there is a physical relationship (Lopez et al., 2010).

$$AEP = RP \times CF \times 8760 \,, \qquad Inventory\ of\ 1kWh = \frac{Inventory\ of\ Inputs}{AEP \times L \times effE} + \frac{Inventory\ of\ Outputs}{AEP \times L \times effE}$$

Modelling wise next to the maintenance also the decommissioning activities (sea vessel operations) are inputs to the use phase to be able to provide a decommissioned WEC to the last phase of the life cycle. These required activities are specified in the following chapter.

3.3.5. End of Life

After the lifetime of the WEC (20 years) it is removed from the deployment site and is towed to shore for dismantling. The moorings and steel foundation are removed as well, and the materials are recovered for EOL treatment or recycling. The gravity foundation is assumed to stay in place as lift operations are difficult due to the weight and little negative effects, even more positive effects of leaving it (artificial reef) are expected (Topham & MacMillan, 2017). For the sea cables similar applies: Despite cable removal being technically feasible, it is currently common practice to leave cables in the seabed as long as they are buried in a way that it doesn't show up on the surface. The cables are embedded in compacted soil and removal would require costly and invasive techniques like jetting or ploughing that disrupt the seabed once more (Al-Sallami, 2021).

No emissions from the cable left in the seabed are considered as no leaching is expected and other influences like heat emissions and electromagnetic fields are neither applicable when abandoned nor representable in LCA impact assessment models (Taormina et al., 2018). Only the long-lasting occupation of the seabed is represented in the LCA by a 1000-year occupation period. The materials of the components left in the seabed are lost and therefore cannot be treated or recycled. They 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 (see chapter 3.3.3.2). 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 same as for the assembly stage (building hall and lift operations with a diesel-powered crane). The regained materials are partially modelled to be recycled and partially to be disposed of in the form of incineration or landfilling. The following table gives an overview over the modelled EOL treatments for all the recovered materials of the WEC, including PTO, steel foundation, mooring, control and transformer.

Table 11: EOL treatment of recovered materials

Values in t	Steel WEC	Concrete WEC	EOL Treatment
Steel*	402,18	112,49	10% steel scrap (partial Incineration and Landfilling). 90% recycling[1]
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[1]
Plastics	0,08	0,08	inert waste (landfilling)
Others	0,07	0,07	inert waste (landfilling)
Magnets	0,90	0,90	inert waste (landfilling) [2]
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	

*does not include steel fibres in hull-concrete
1 EuRIC, 2020
2 Kumari et al., 2018

In this study the cut-off allocation method is applied. End-of-life recycling processes are therefore considered to be outside the system boundary, and no recycling credits are given to avoid double counting. The recycled material contents as shown in Table 11 only reduce the amount of material that is e.g. incinerated or landfilled otherwise.

4. Results

4.1. Impact Assessment

To obtain the environmental impacts of 1kWh of electricity produced in a WEC, the flows from and to the environment inventorised in the LCI (supplementary material 1) are translated to environmental impacts in certain categories by means of characterization factors (Guinée, 2002). The impact assessment method (determining used characterization factors and assessed impact categories) used in this study is EF 3.1. that is provided by the JRC and is in line with the European environmental footprint measurement and reporting regulations specified in EN 15804. Impacts are assessed on a midpoint level. With the LCI of the baseline scenario described in the previous section the following impact assessment results are obtained:

Table 12: Impact assessment results of the baseline scenario with description of impact categories and characterization factors in EF 3.1

			Steel WEC	Concrete WEC
AC	acidification - accumulated exceedance (AE)	mol H+-Eq	1,1E-02	1,1E-02
GW	climate change - global warming potential (GWP100)	g CO2-Eq	325,4	299,9
FET	ecotoxicity: freshwater - comparative toxic unit for ecosystems (CTUe)	CTUe	11,9	11,8
FD	energy resources: non-renewable - abiotic depletion potential (ADP): fossil fuels	MJ, net calorific value	4,2	3,9
FE	eutrophication: freshwater - fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq	5,9E-04	5,8E-04
ME	eutrophication: marine - fraction of nutrients reaching marine end compartment (N)	kg N-Eq	1,3E-03	1,3E-03
TE	eutrophication: terrestrial - accumulated exceedance (AE)	mol N-Eq	1,7E-02	1,7E-02
HTc	human toxicity: carcinogenic - comparative toxic unit for human (CTUh)	CTUh	2,0E-09	1,7E-09
HTnc	human toxicity: non-carcinogenic - comparative toxic unit for human (CTUh)	CTUh	1,0E-07	1,0E-07
IR	ionising radiation: human health - human exposure efficiency relative to u235	kBq U235-Eq	2,0E-02	1,7E-02
LU	land use - soil quality index	dimensionless	2,8	2,7
MD	material resources: metals/minerals - abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq	1,0E-04	1,0E-04
OD	ozone depletion - ozone depletion potential (ODP)	kg CFC-11-Eq	6,6E-09	6,0E-09
PM	particulate matter formation - impact on human health	disease incidence	3,3E-08	3,1E-08
POF	photochemical oxidant formation: human health - tropospheric ozone concentration increase	kg NMVOC-Eq	4,3E-03	4,2E-03
WU	water use - user deprivation potential (deprivation-weighted water consumption)	m3 world eq. deprived	0,1	0,1

A contribution to global warming of 300-325gCO2eq./kWh is found. This is roughly double than what previous WEC-LCA literature suggests (23-152gCO2eq./kWh). The concrete WEC performs better across all impact categories, although the difference between the two systems is low (see Figure 6a). As it can be seen from the contribution analysis of the baseline scenario aggregated on a component level (Figure 6b), the large impacts stem mainly from the electrical transmission cable ranging from ~40% in ME up 99% in MD. The cable is very material intensive and a relatively long distance to shore is modelled in comparison with other studies. Within the cable the main contributor across most impact categories is the copper conductor.

a) b)

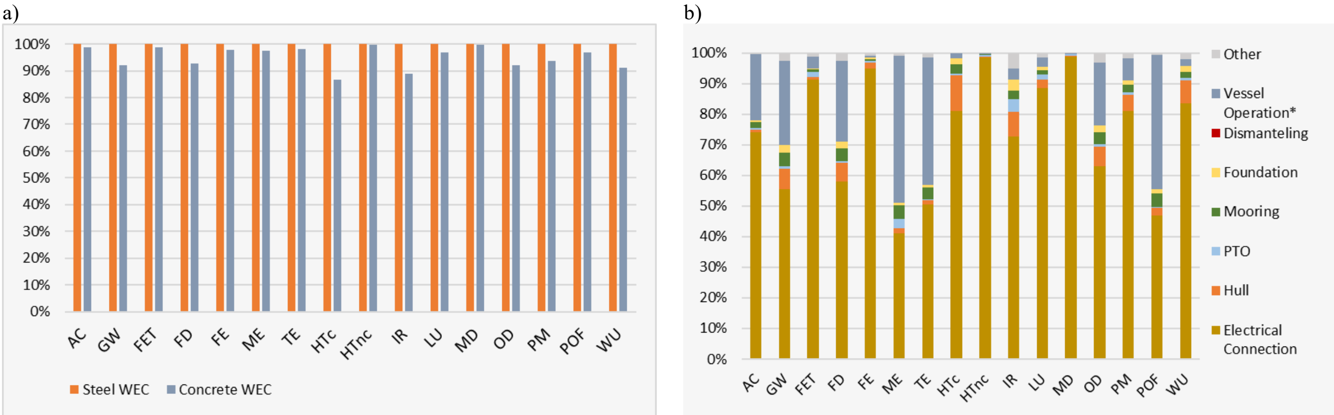


Figure 6 Relative impact assessment results for the steel and concrete floater (a) and contribution analysis of the baseline scenario for the steel floater(b)

*Installation, Maintenance and decommissioning. Component related activities included with the components (e.g. cable laying, pre-lay)

As the cabling potentially overshadows impacts within the actual device (floater) a scenario without periphery (mooring & cabling) is assessed for the purpose of an in-depth analysis of the floater components. The following much lower impact assessments results are obtained:

a)

		Steel WEC	Concrete WEC
AC	mol H+-Eq	1,1E-03	9,1E-04
GW	g CO2-Eq	77,7	52,2
FET	CTUe	0,6	0,5
FD	MJ, net calorific value	0,9	0,6
FE	kg P-Eq	2,4E-05	1,0E-05
ME	kg N-Eq	3,2E-04	2,9E-04
TE	mol N-Eq	3,1E-03	2,8E-03
HTc	CTUh	3,4E-10	7,8E-11
HTnc	CTUh	1,4E-09	9,0E-10
IR	kBq U235-Eq	4,5E-03	2,3E-03
LU	dimensionless	0,2	0,2
MD	kg Sb-Eq	1,1E-06	8,8E-07
OD	kg CFC-11-Eq	1,4E-09	8,5E-10
PM	disease incidence	3,9E-09	1,9E-09
POF	kg NMVOC-Eq	9,1E-04	7,7E-04
WU	m3 world eq. deprived	0,0	0,0

b)

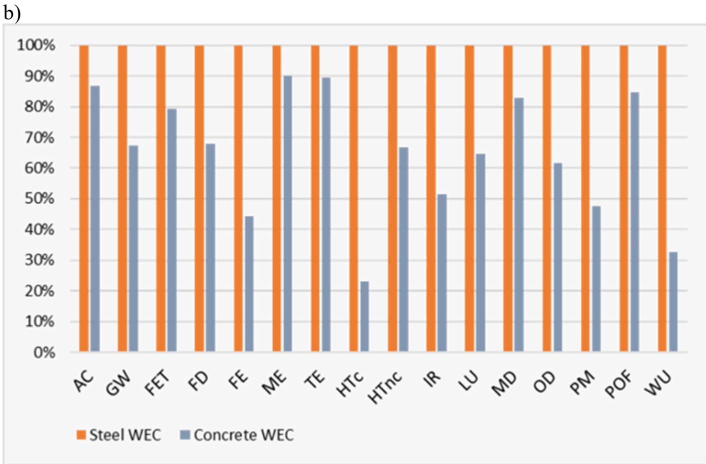


Figure 7 Impact assessment results for the baseline scenario a) absolute and b) relative

A kWh of electricity from a representative WEC without cable and mooring contributes with 52,2 – 77,7gCO2eq./kWh to GW. This lies in the middle of the range found for WECs in previous studies suggesting that cabling has been omitted in these as well.

As shown in Figure 7, 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. Contribution to GW can be reduced by 35% (25,5gCO2eq./kWh). The concrete has a very low material impact on a weight basis compared to structural steel (see Figure 9), reducing the impact of the hull to a minimum (Figure 8b). Nevertheless, the overall impact reduction potential of the hull for the WEC varies between impact categories (Figure 7b): 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.

a) b)

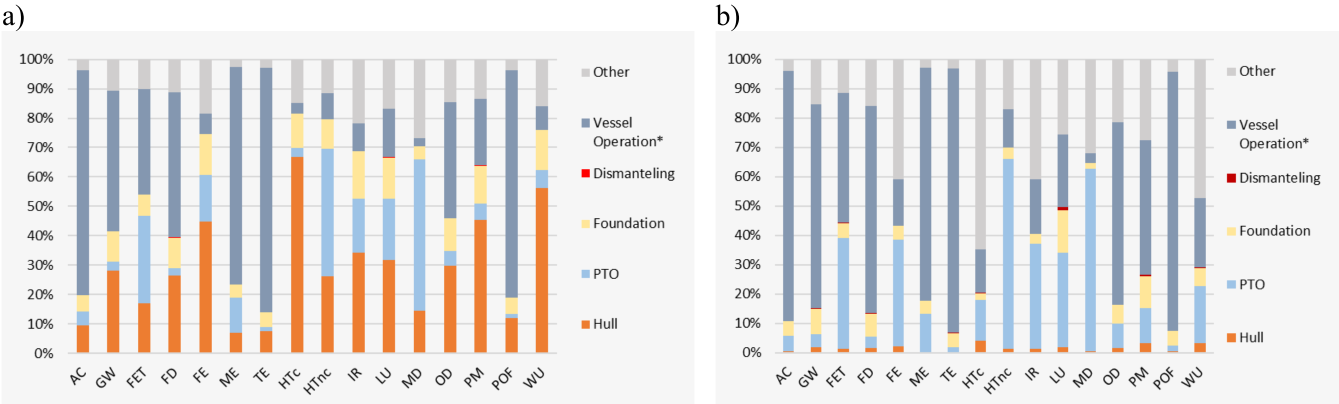


Figure 8 Contribution analysis of the baseline scenario without periphery a) for the steel-. b) for the concrete floater

*Installation, Maintenance and decommissioning. Component related activities included with the components (e.g. cable laying, pre-lay)

The impacts of sea vessel operations represent another significant contributor to the results, accounting for up to 83% of TE (see Figure 8). Most influential vessel activities are related to maintenance, due to the time-consuming and vessel-intensive un- and relatching actions that are required for towing when corrective maintenance is needed (see Figure 10). Transport and processing requirements are not shown specifically in Figure 8 but are included within the different components. The contribution of these activities to the different impact categories is overall low, with a percentage contribution of less than 10% for processing and less than 2% for transport.

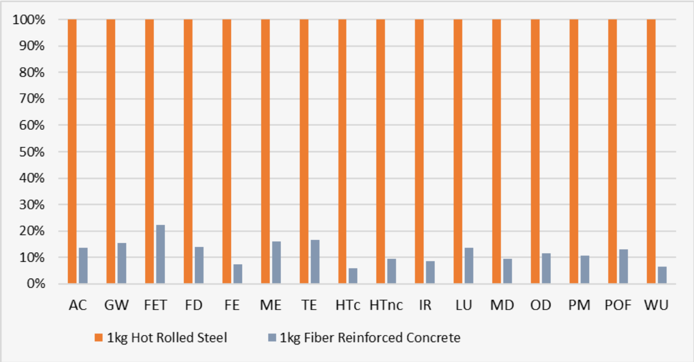


Figure 9 Impact comparison of two possible hull materials on a weight basis

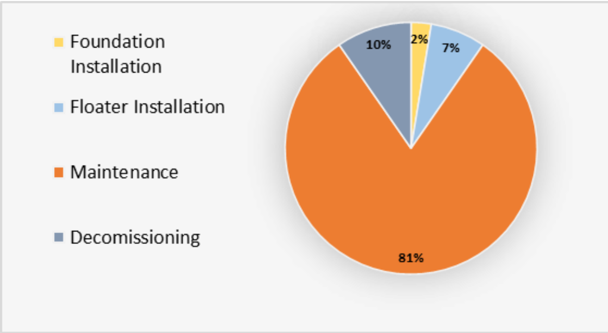
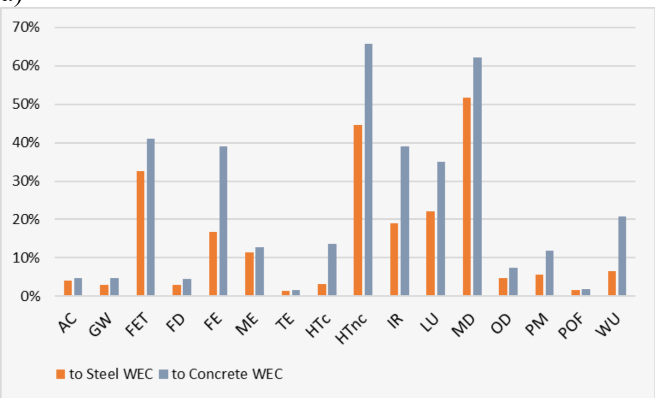


Figure 10 Composition of sea vessel impacts by activity

The results of the WEC without periphery may not be seen as final results as a WEC without cable cannot fulfil the function of delivering electricity of the grid. The scenario rather resembles a WEC that is theoretically located very close to shore (cable length <10km) as assessed in other WEC studies (Uihlein, 2016; Pennock et al., 2022). For further understanding of the impacts of single components like the cable, impacts of major components have been extracted in a stepwise modelling approach and are provided in the supplementary material 1.

A component especially necessary for the electricity generation in the WEC is the PTO. In this study a direct drive linear generator was assessed. This type of PTO contributes to the impacts of the steel WEC without periphery between 1% in TE and 52% in MD. Contribution to GW is minor (3%). The categories with higher domination are not directly in line with the metal dominated categories pointed out earlier. This is due to the specific impact profile of the NdFeB magnets used in the PTO. Figure 11 shows the PTOs contribution per impact category and the components within the PTO responsible for them. The magnets have significant high shares of impacts in the categories of IR, FET, MD, ME and OD.

a)



b)

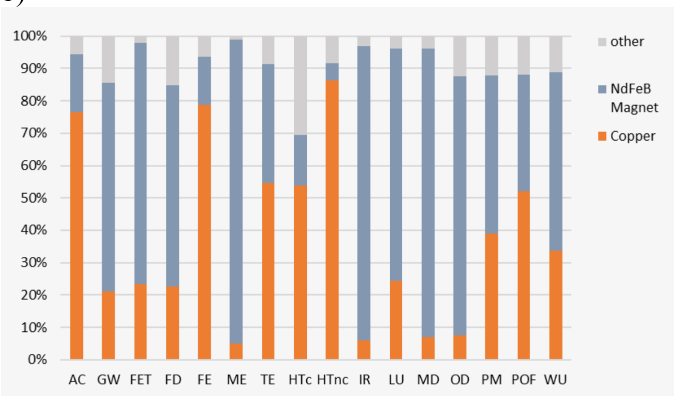


Figure 11 Contribution of the PTO to each impact category (a) as well as the distribution of contribution of PTO components to these impacts (b)

4.2. Sensitivity Analysis

Prior results have shown high contribution of structural material and vessel operations, especially for maintenance activities. Therefore, a sensitivity analysis on different maintenance scenarios and, later in this chapter, on different performance, location and geometry related parameters is performed.

The previously specified alternative maintenance scenarios (see chapter 3.3.4.) lead to nearly quadrupled impacts in the vessel dominated impact categories for the pessimistic scenario (yearly towing and several inspections a year) and a potential decrease of up to 44% in the optimistic scenario (only yearly inspections) – see Figure 12.

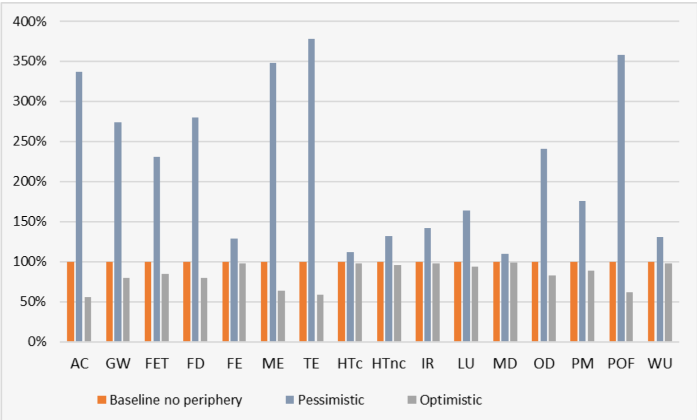


Figure 12 Changes in impact assessment results with different maintenance scenarios

The possible decrease in impacts with alterations of certain geometry, performance of location related parameters is shown in Figure 13. 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. These relations are not considered in this sensitivity analysis.

a) b)

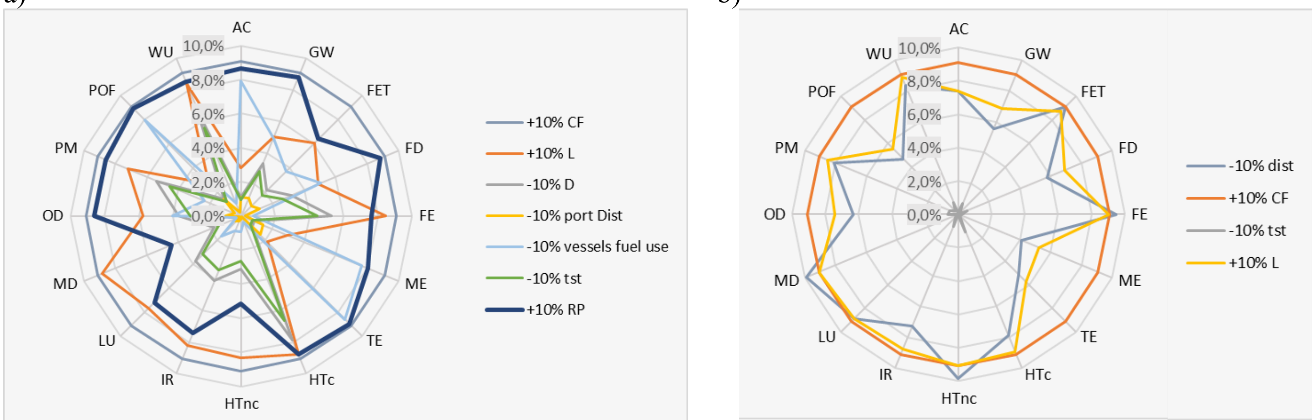


Figure 13 Sensitivity analysis on a selection of parameters, showing the decrease in impacts per category for a) the WEC without periphery and b) with periphery (baseline)

Increasing the CF has the highest potential influence in all impact categories as it influences all parts of the inventory equally in a linear manner (chapter 3.3.4.). 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).

Generally, 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 similar 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.

Next to the gradual sensitivity analysis specific cases have been assessed: An extended lifetime of the concrete WEC to 25 years as proposed by Wave Energy Scotland Limited, 2021 can lead to an additional impact reduction of 2,5% (TE) to 16% (MD) of the concrete option over the steel WEC. A thinner steel hull (20mm instead of 50mm as reported for the Pelamis; Anderson, 2003) can also reduce impacts from 4% (ME) to 40% (HTc) but can't reach the performance of the alternative material. Full impact results of the assessed cases can be found in the supplementary material 1.

Further an alternative possible European WEC deployment location at the coast of Aguçadoura and close to the port of Viana do Castelo has been assessed, with 20-year wave data provided by MREL. At this location a device could be installed at ~45m water depth, 10km from shore and 25km away from a feasible port. As done earlier for the North Sea, the CF for the representative PA at this location has been obtained based on the scatter plot of the occurring sea states at that location paired with the representative power matrix. An increased CF of 47% can be achieved at this stronger resource site. The results of the analysis of a steel WEC with periphery at the described site are presented in Figure 14.

a)

		Portugal	North Sea
AC	mol H+-Eq	3.31E-03	1.11E-02
GW	g CO2-Eq	129.22	325.42
FET	CTUe	2.55	11.92
FD	MJ, net calorific value	1.61	4.20
FE	kg P-Eq	1.18E-04	5.95E-04
ME	kg N-Eq	6.07E-04	1.32E-03
TE	mol N-Eq	6.88E-03	1.69E-02
HTc	CTUh	5.68E-10	1.96E-09
HTnc	CTUh	1.87E-08	1.05E-07
IR	kBq U235-Eq	6.39E-03	1.96E-02
LU	dimensionless	0.65	2.81
MD	kg Sb-Eq	1.85E-05	1.05E-04
OD	kg CFC-11-Eq	2.37E-09	6.55E-09
PM	disease incidence	8.91E-09	3.27E-08
POF	kg NMVOC-Eq	1.86E-03	4.31E-03
WU	m3 world eq. deprived	0.04	0.14

b)

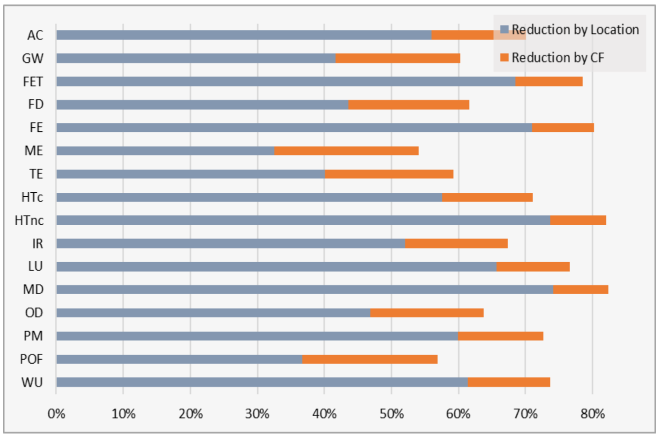


Figure 14 Impact assessment results of a representative steel PA with periphery deployed at the coast of Portugal in comparison to the Dutch North Sea (a) and the achieved, split into the reduction by the changed location parameters (distance to shore and port) and the increased CF (b).

As visible in Figure 14b the reduced cable length due to the reduced distance to shore combined with shorter travel distances for vessels creates the largest share of the decrease in impacts. The higher water depth coming with additional material demand for the moorings is also outweighed by the closer distance to shore. An additional impact reduction of 10 to 20% is achieved by the increased capacity factor.

5. Discussion

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

5.1. Context with WEC LCAs

The results for the full functional WEC including the electrical transmission cable have shown to be much higher than what previous WEC LCAs have proposed (see chapter 4.1). The very 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 13 therefore key assumptions of other relevant studies in that field are compared.

Table 13: Comparison between key assumptions in this study and other relevant LCAs on WECs

	Pennock et al., 2022	**Uihlein, 2016**	**Thomson et al., 2019**
Description of the study	Assessment of the CorPower Ocean C4 PA deployed in an array in Portugal, non-disclosed data, modelling not documented in detail	Collective assessment of 103 WEC prototypes of different working principles based on a JRC database, non-disclosed data, modelling assumptions partially documented	Assessment of a Pelamis P1 device at the coast of Scotland, partly disclosed data, transparent documentation of modelling assumptions and the LCI
Differences in key assumptions on….			
… Electrical transmission	10km export cable Shared between 28 WECs	Average of 3km export cable length	unknown
… Others	Array Composite hull Mechanical, geared PTO	Data from prototype database Lower CF Generic assumptions on vessel operations	Higher CF More vessel operation hours for installation and maintenance
GW Results	23-47gCO2.eq	105gCO2eq. (for PAs)	35 gCO2 eq.

Table 13 clearly 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 periphery assessed in this study than the one with the 40km transmission cable for a single device. Using the no-periphery scenario as a basis for comparison, the range of results 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 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 operation. More detailed assumptions were made in this 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 10km export cable) to the overall results is less then what was 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; Perez-Collazo & Iglesias, 2015).

More transparent and broader LCAs are suggested to quantify overall changes in impacts induced by potential reduction of impacts due infrastructure sharing and increase because of additional required transmission infrastructure (inter array cables, substations, higher voltage/ more cables and potential DC conversion). Other effects of arranging wave energy converters in arrays are potentially positive hydrodynamic interactions between the single devices and increased capacity factors depending on the location and layout of an array. These could further intensify impact reductions of WEC arrays. Quantification of such effects is still being researched and depends highly on the wave climate, devices characteristics and array layouts (Raghavan 2024, Lavidas & Blok, 2017).

5.2. Model Applicability & Limitations

The model of the representative PA and the analysis of environmental impacts in this study is consistent with its intended use defined in the goal and scope definition. As an envisioned deployment of 40GW ocean energy in Europe serves as motivation for this assessment, two possible European deployment locations – the Dutch North Sea and the Atlantic at the coast of Portugal - have been assessed. Further this context is resembled in the chosen impact assessment methodology in line with European policy as well as considerations of the modelling of supply chains (see chapter 3.1.2.).

As LCA assessments for WECs are not largely abundant yet this study serves the purpose of providing a representative, transparent and adaptable baseline analysis for understanding environmental impacts of a WEC device. This is building a basis for potential further assessment of specific devices or prospective LCA assessment of the scaled-up technology. To be able to serve that purpose, the representative LCA model can be reproduced and altered freely to fit a specific case by adjusting the parameters defined. However, the following limits of applicability have to be considered: First, the modelled transmission system as well as its efficiency are only representative for distances shorter then 70km to shore and small plants (single devices). Although the distance to shore is parameterized the physical relationship between losses in the electrical cable and the cable length is not represented in the model. Furthermore, larger plants 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, in reality these parameters are physically dependant on each other and 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 first. For this assessment the CF has been obtained based on a representative power matrix of a 400kW device and real long term wave data at the described locations (see chapter 3.3.1.).

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, with the exception of the submarine cables and gravity foundation, where the common practice to leave them in the seabed is modelled. This is represented in the model as long-term seabed occupation. Other potential emissions are ignored, partly because the fate of sea cables in the ground is not well understood due to a lack of experience with decommissioned sea cables (Smith & Lamont, 2017; Topham & McMillan, 2017), and partly because current mature LCA impact assessment methodologies are not suitable for representing direct interactions of the technosphere with the marine environment.

Potential impacts of WECs and submarine cables on the surrounding marine environment, such as electromagnetic fields, changes in currents, noise and vibrations, do not have assessment models within mature impact assessment models such as EF, Recipe and others and have therefore not yet been considered in marine energy studies (Paredes et al., 2019; Guo & Ringwood et al., 2021; Uihlein & Magagna, 2016). Seafloor land use is modelled as an environmental flow (see LCI – Supplementary material 1) but does not have a characterisation factor in EF. Therefore, also this is not included in the calculation of environmental impact presented in the Results section.

The absence of assessment models for direct marine impacts implies that the potential consequences of marine activities like removing or leaving structures on the seabed may be misrepresented. If e.g. cable removal for recycling was to be assessed in the LCA this would require additional vessel impacts and energy inputs for dismantling and recycling, consequently yielding higher impact assessment results then when the cable is left buried. This could be a motivation to leave structures at sea, although from a circularity perspective it is unacceptable (Jensen et al., 2020) to lose such large amounts of valuable materials in the ground. Furthermore, potential trade-offs between e.g. greenhouse gas emissions and effects of the cable to the seabed are not becoming obvious. As the utilisation of the sea for the generation of renewable energy continues to expand, it becomes increasingly evident that the current LCA impact assessment models and future studies must be expanded in order to allow for a quantitative assessment of the marine impacts and a holistic evaluation of the environmental sustainability of the technologies in question.

Wave energy technology is pre-commercial and operational experience is lacking. This leads to particular big uncertainty in the used data for modelling of maintenance strategies, installation procedures and associated sea vessel operations. The results proved to be highly sensitive to the assumptions made on maintenance intervals and techniques. The combination of high uncertainty with large impact on the results highlights the need for further research or trials to adequality quantify required sea vessel operations and gain experience on lifetime WEC survivability to determine the environmental impacts of this technology – especially when scaled up. To be able to represent sea vessel operations more accurately in future studies, activity specific data on fuel consumption in the particular case of WEC installation should be gathered. A potential future specific assessment should then also consider all actions including site preparation, surveying and site-specific requirements due to the seabed composition, and wave climate at the location. This was not possible in this representative study.

5.3. Context with other Electricity Generation Technologies

To create context between WECs and other renewable energy technologies in this section the GW impact of conventional and renewable energy technology are compared. Further the use of critical raw materials is discussed.

When looking at the life cycle environmental impacts of different electricity generation techniques in the global warming category, the following picture results:

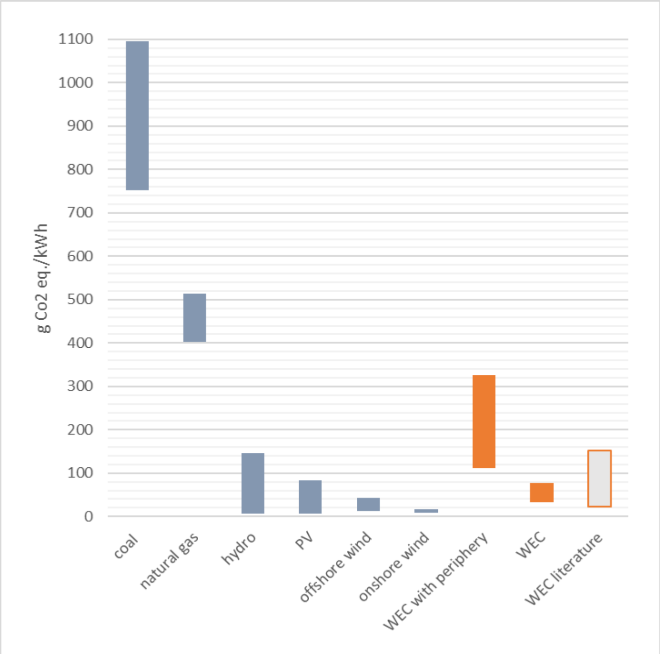


Figure 15 Comparison of GW impact assessment results of WECs and other energy technologies based on United Nations, 2021 extended with the values for floating offshore wind from Garcia-Teruel et al., 2022 in the offshore wind category

Electricity from WECs performs significantly better than conventional fossil-based technologies but has higher impacts compared to other renewables (see Figure 15). A single concrete WEC without cable and mooring can reach the upper bound of the range given for offshore wind. The ranges found in this study are composed of the concrete WEC at the Portugal deployment location without periphery (best case) and the steel WEC with periphery deployed in the North Sea (worst case).

As materials account for a significant share of the environmental impacts associated with renewable electricity generation, the weight-to-power ratio can be a valuable indicator for comparison. For the modelled steel and concrete WEC the ratio lies between 295-755kg/kW rated power without the cable and moorings. This is within the upper range of what is reported for other more mature renewable electricity technologies like 330-360 kg/kW for solar photovoltaic (PV) and about 340-770kg/kW for wind turbines (Uihlein, 2016).

Especially for materials, environmental impacts are not the only aspects that have to be considered as criteria of choice. Scarcity and strategic availability are also important. The EU defined a list of critical and strategic raw materials based on their scarcity and supply risk because of geopolitics (European Union, 2023). The lifecycle requirements of some crucial critical materials for electricity from WECs and other renewables are presented in Figure 16.

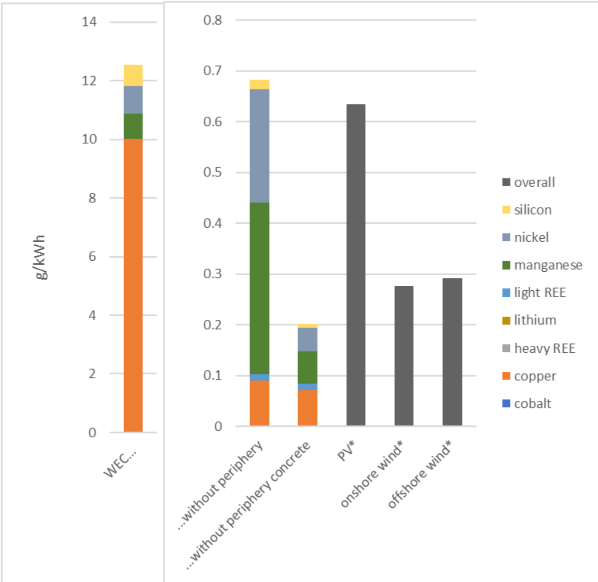


Figure 16 Comparison of life cycle critical material requirements between electricity from WECs and other renewable technologies

* Cumulative values from United Nations, 2021 values for particular materials have not been published

The life cycle critical material intensity for electricity from a steel WEC is found to be higher than for commercial renewables. Once more the large contribution of copper, mostly in the cable is striking. Manganese and nickel make up high shares of the used critical materials as well and can be associated with the steel used in the device itself as well as in the background. A concrete WEC can decrease critical material intensities below the level of solar PV, on- and offshore wind. This makes additionally clear that a transition away from steel hulls can have significant positive outcomes beyond environmental impact reduction.

To the device itself the only direct input of strategic or critical materials according to EU classification are the rare earth element (REE) Neodymium in the Magnets, the copper for the PTO, copper in the export cable and aluminium in the transformer (see BOM chapter 3.3.1.). Material intensities per kW rated power of a WEC with 40km cable derived from the BOM are 0,67kg/kW (Neodymium), 600kg/kW (Copper) and 0,5kg/kW (Aluminium). For the copper less than 1% is used in the floater.

Copper is not critical as it is not scarce and its supply is very well diversified, however, it is it is challenging to substitute due to its superior performance in electrical applications (European Union, 2023). Paired with a foreseen strong increase in demand among others for the growth and replacement of transmission infrastructure because of growing and replacing of old transmission infrastructure it is seen as strategic raw material (Gielen, 2021). Furthermore, the quality of copper ore in resources is decreasing, requiring higher efforts for extraction and increasing the quantity of tailings created (Gielen, 2021). As a significant portion of the environmental impacts from copper stem from the inefficient extraction as well as tailings and their treatment (Tao et al., 2022), it is possible that environmental impacts of copper and therefore cables might increase in the long-term. Technically existing but currently less efficient transmission cables with aluminium conductors may need to be considered and their development accelerated in order to expand the transmission and renewable based energy system in the ways it is required (Gielen, 2021).

The direct drive linear generator of the modelled WEC requires NdFeB magnets for its stator. These are composed of ~30% REEs (Omerod et al., 2023) in this case mostly Neodymium. The key challenge associated with REEs is that mining and processing of these materials is dominated by one country – in the case of Neodymium China (European Union, 2023). The modelled WEC has a magnet requirement of 2250kg/MW. This is much higher than magnet requirements for wind turbines reported to lie in a range of 250-650kg/MW (Kumari et al., 2018). Direct drive linear generators are particularly material intensive as the low speeds and low frequency working range requires more mass (Lopez et al. 2013) and the magnets must cover the whole length of the stroke while rotary generators only have to cover a single rotation.

5.4. Future Outlook

Given the difficulties of current WEC development to reach the impact levels and critical material intensities of other mature renewable energy technologies, from a sustainability perspective one might question whether it is worth investigating this technology further. And while this may be an easy conclusion to draw from this baseline analysis of the environmental impacts of WECs, a future perspective will show why this is unjustified.

The role of WECs is not to replace mature renewables like wind and solar but rather to function as an additional and diversifying component in the energy system. Integrating wave energy in a multi-source energy system with e.g. wind can lead to a smoothed-out power output and better predictable base load. This is because most waves are wind generated, leading to a time delay of several hours between peaks in the winds and waves resource availability. By this, the waves act as energy storage for the wind, ensuring that the combined renewable generation of wind turbines and WECs is more stable than the output of either of the two technologies (Friedrich & Lavidas, 2017). WEC integration can therefore provide a baseline power output and reduce storage needs up to 30% (Gao et al., 2021; Friedrich & Lavidas, 2017; Kluger, 2023).

The importance of such diversified electricity generation systems will continue to grow as the future challenge of Europe's evolving energy system is not the overall availability of renewable electricity, but rather its timed accessibility and high storage requirements to ensure power security and quality with an increasing demand and supply mismatch (IEA, 2024; Child et al., 2019). A challenge that cannot yet be met by a cost-effective and feasible storage technology in its entirety (Luo et al., 2015; Deguenon et al., 2023). The reduction of storage needs has the potential to benefit not only a more robust energy system, but also to reduce the impact of 1 kWh of electricity at the end consumer. This could be achieved by avoiding the high environmental impacts and the vast use of critical raw materials like lithium, cobalt and nickel currently associated with electrochemical batteries (Arshad et al., 2022; IEA, 2021). It is therefore recommended that the possible environmental benefits resulting from the reduction in storage demand through the integration of WECs be quantified in a LCA study in order to provide further motivation. In addition to the aforementioned benefits from storage reduction, integration of WECs in larger renewable electricity plants can reduce environmental impacts further by higher energy yields on the same marine space with reduced overall grid infrastructure, logistics, O&M efforts and material for substructures (Perez-Collazo & Iglesias, 2015).

Instead of discouraging WEC development, this comparison between mature renewables and a single precommercial device with no economies of scale considered whatsoever, rather highlights that there is still significant potential for impact reduction in wave energy. This study contributes to understanding and unravelling these potentials towards a future sustainable integration of wave energy into the European energy system.

6. Conclusion

This study assessed the environmental impacts of a single representative point absorber wave energy converter deployed in the Dutch North Sea by means of LCA. It was found that GW impacts of 1kWh electricity from a WEC lie between 55 and 77gCO2eq. without its periphery and 300 to 325gCO2eq. with cable and mooring (RQ i). The lower end 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.

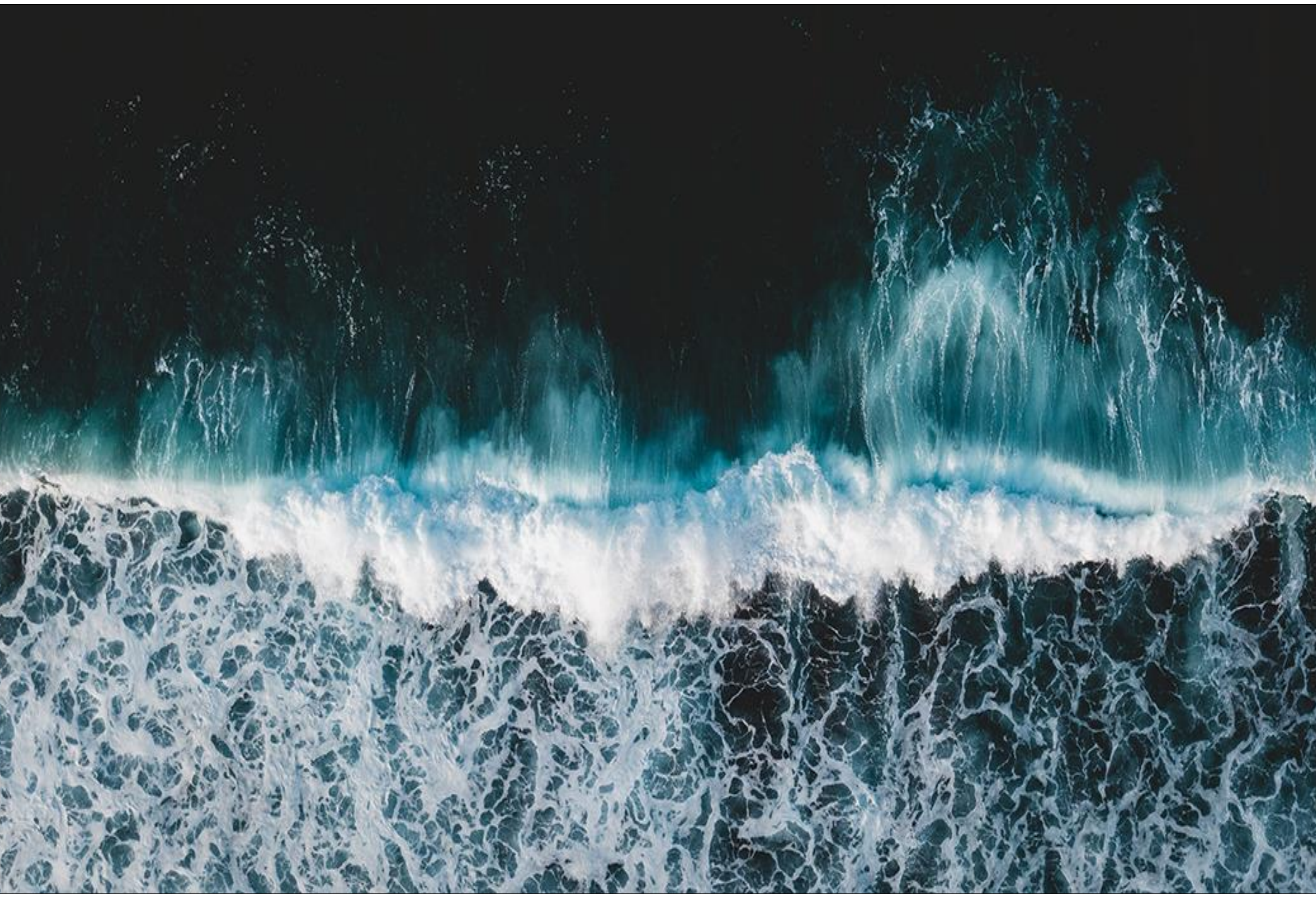
This alternative material can reduce environmental impacts significantly (10-78%) across all impact categories and decrease pressure on the supply chain by relying less on critical raw materials like manganese and nickel (RQ ii). Assessing the WEC on a component level the electrical transmission cable (4-99%) and the steel hull (5-65%, without periphery) have a large share of the total environmental impacts in the material dominated impact categories (GW, FET, FE, HTnc, HTc, IR, LU, MD, PM, WU). In terms of critical raw materials, the PTO and the cable are most impactful as the direct drive linear generator is material intensive and contains high shares of REEs (Neodymium). The cable includes large amounts of copper (RQ iii). Next to the structural materials, vessel operations were found to contribute between 4 and 85% to the impacts of a WEC, mostly in categories dominated by fuel combustion (AC, FD, ME, TE, POF, OD). Of all offshore activities towing the floater back to shore for maintenance has been found to have the highest influence on the results.

As shown by the assessment of an alternative WEC deployment scenario in the Atlantic at the coast of Portugal, the location has significant influences on the environmental performance of a WEC. A GHG-intensity of 33-129gCO2eq./kWh was found for a concrete and steel WEC at this location depending on whether the cable is considered. Generally, a stronger wave resource paired with an adapted WEC can lever 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 (RQ iv).

A comparison of the impacts of the electricity from WECs with those of other renewable generation technologies showed that impacts need to be reduced in order to achieve the GHG intensity of, for example, solar PV, onshore and offshore wind. However, this study also reveals where a potential pathway to improvement could lie: First it is recommended to shift the development of WECs from steel towards innovative concrete compositions. Second as much emphasis should be placed on the development of efficient installation & maintenance procedures that minimise tow backs and less critical 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. Thirdly, choosing a less material and permanent-magnet intensive PTO, such as a mechanical geared generator could further reduce impacts and the reliance on critical materials, although trade-offs with potentially lower efficiency and reliability of alternatives still need to be assessed quantitatively.

At present, direct marine interactions of ocean energy devices cannot be quantified in LCA, creating a space of potentially significant unknown impacts of marine renewables. As the use of our oceans increases, LCA methodology should also develop assessment models capable of representing these actions.

As wave energy is still on its road to commercialization pulling levers to decrease environmental impacts can on the one hand improve the motivation to use these low-impact devices in European waters but can on the other hand also go hand in hand with making a device more cost effective. Vessel operations for installation and maintenance are also known to contribute largely to the high costs of WECs, currently hampering the deployment. Targeting innovation in that field (efficient maintenance strategies, quick installation, infrastructure sharing) could have a major impact on both commercial viability and environmental sustainability.



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Supplementary Materials

SupplementaryMaterials 1.xlsx

Additonal information on the inventory model, documentation of assumptions and obtained results.

SupplementaryMaterials 2.xlsx

Cross-Consistency check within the morphological analysis

Appendix A – System Analysis

Prior to the LCA assessment a socio-technical system analysis has been performed with the goal to gather an understanding of the context of the technology and determine important parameters that define a WEC for the LCA model.

For this analysis the SIMPL method presented by Langkau et al., 2022 was used. It proposes a step wise approach to analyse possible scenarios for the ex-ante LCA assessment of emerging technologies. Although this study does not consider scenarios for technology development in a temporal manner, parts of the method are applied here to assess possible technology configurations for a representative WEC in the current state.

SIMPL describes a three-level built up of the LCI model.

1. Factors that influence the inventory.
2. Inventory parameters that are directly influenced by the factors and systematically determine the inventory flows.
3. Inventory flows that underly changes through the parameters.

To obtain the factors a PESTEL analysis is proposed. Further the method proposes the use of causal loop diagrams (CLD) to establish a relationship between the factors and the inventory parameters (Langkau et al., 2022). In this study the CLD analysis is omitted, but further understanding of possible technology configurations is created by a general morphological analysis (GMA) of a WEC. This approach is proposed by Delpierre et al. 2021 to "develop exploratory scenarios in a systematic and transparent way, while bringing in diversity and addressing complexity and uncertainties" (Delpierre et al., 2021, p.4). According to Ritchey (2011) the GMA consists of the following steps: defining variables, identifying possible values (qualitative) for the variables, resulting in the morphological field, consistency analysis, and generating and assessing scenarios.

In the end the outcomes of this approach are the basis for the LCI model with a chosen technical configuration of the representative PA as well as an understanding of parameters necessary to depict the possible variations of a PA in different deployment scenarios and made from different structural materials. The parameters used in the LCA Model will be extracted from the Inventory parameters. The outcomes of the system analysis executed via a PESTEL analysis and literature research are described in the following. The outcomes and procedures for the morphological analysis are described in Appendix B.

Socio technical dynamics influence technology design through factors. The resulting configuration of a device requires certain materials and processes to be able to deliver a certain power output to the socio-technical sphere. The power output creates benefits when used in the energy system. The required materials, energy and acquired waste during the lifecycle of the device then have impacts on the environment. A summary of this WEC-System is given in Figure 17.

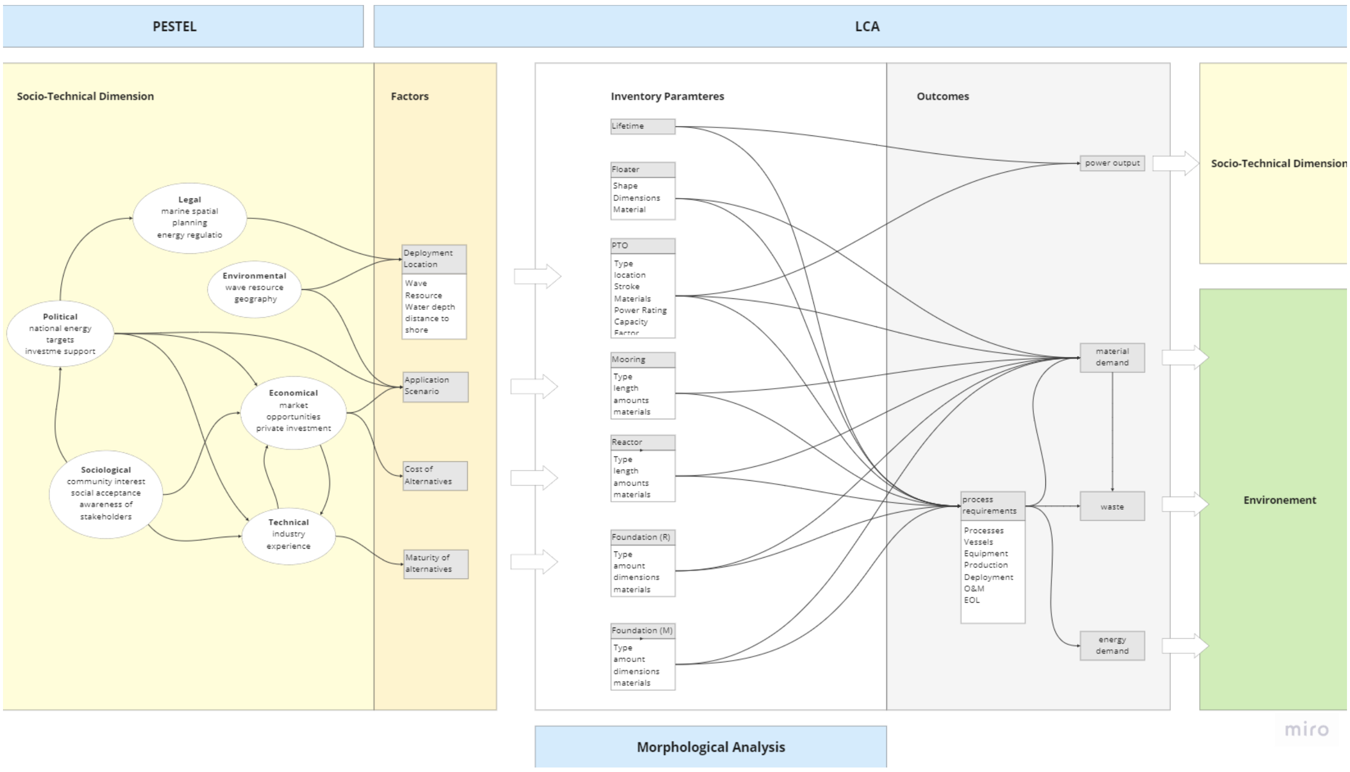

Figure 17 High level system overview and assessment methods

The PESTEL analysis on the question "What is the technical configuration of a representative point absorber WEC for the Dutch North Sea?" revealed influences on the technical system from the socio-technical sphere. Main sources for gaining an understanding of the system, also when not directly cited were: IRENA, 2021, Guo & Ringwood 2021, Lavidas & Blok, 2021 and Uihlein & Magagna, 2016.

Factors that can influence the configuration as well as their socio-technical drivers are identified as the following:

Deployment location: The choice of deployment location is influenced by legal issues like permits for marine space use that have to be given by state authorities. Until now ocean energy is not mature and therefore does not have specific sets of regulations applied to it. Using the sea for electricity generation in most countries depends on a complex structure of energy and electricity laws, environmental laws as well as laws for the use of oceans (Uihlein & Magagna, 2016). Whether permits are given also depends on the environmental characteristics determining potential benefits of utilizing the resource given by either the estimated power output or system integration benefits. Whether a good power resource is identified and integrated into the planning is dependent on the availability of clear sustainability roadmaps and already existing offshore infrastructure e.g. through wind parks. More regions establish marine spatial plans to deal with the complex relationships between various sea users (fishing, shipping, aquaculture, fossil fuel extraction) and the marine environment (nature conservation) in specific sea areas (Hammar et al., 2017), though these kinds of plans are not in place everywhere yet.

The characteristics of the wave resource at a location (wave heights, spectrum, temporal variations, extreme weather conditions) are the main driver for device design as only this allows optimal extraction of energy from the waves (Lavidas & Blok, 2021). The present wave resource requires WEC design to be optimized to the resource to be able to reach required capacity factors and in the end economic feasibility. The relations between the wave resource and device design are complex and refer back to hydrodynamic interactions and resonating behaviour with the waves (Guillou et al. 2020). In this work the physical concepts of this interaction are not further discussed, and the baselines of floater design, control and PTO types is based on literature and expertise at MREL.

Next to the wave resource itself, characteristics of a location like water depth and distance to shore directly drive material demands (moorings, cabling), cost for operational actions (vessel kilometres, specialized installation equipment) and risks due to reachability of the device in case of failure.

Targeted application: Weather a WEC is being deployed as a single device, in an array, a hybrid energy system or in a specialized niche application determines the required performance of the WEC and therefore its design. WEC installations can target delivering electricity to the local utility market. This implies a systems electricity output has to compete with the prices of electricity achieved by mature conventional and renewable technologies. In the immature state of WECs this creates challenges for economic viability as the required price level can't be reached yet (Guo & Ringwood, 2021; Curto, 2021). Another viewpoint on possible utility market integration comes from a system integration perspective. Wave energy is known to be more predictable than other energy sources (Reikard, 2013), and has a different intermittency pattern then wind and solar. Therefore, it is a renewable energy source that can smooth out renewable power output and reduce storage needs (Kluger, 2023). For this purpose, WECs can be deployed stand-alone (single-devices or arrays) or as integrated offshore energy systems in the renewables market to achieve a diversification of energy sources. Integrated energy systems can either follow a co-location principal where devices share only a grid connection or a hybrid principal where devices also share their foundation. Motivation for these kinds of systems is to yield more and more consistent energy with less infrastructure and less space demand as well as to share of costs O&M and infrastructure to reduce the overall levelized cost of electricity (LCOE) (Clemente et al., 2021). Especially hybrid systems require specific WEC designs and combined technologies. As of today, these systems are not as far developed as stand-alone WECs. Therefore, the morphological analysis following this analysis will only take into account single PAs. Next to the utility market there are other more niche application scenarios that could support the development of WECs through accumulating field experience, demonstrating success and thereby building confidence for stakeholders (Renzi et al., 2021; Guo & Ringwood, 2012). Wave energy development can play a role in the following niche markets: micro-grids for remote and coastal areas, combined coastal protection systems, electrification of offshore platforms, offshore navigation equipment, aquaculture and more of the so-called blue economy applications (Clemente et al., 2021, Renzi et al., 2021). Although here other performance measures then for utility market devices are applicable, the devices are primarily comparable to stand-alone grid devices and the same life cycle assessment model is expected to be applicable.

Which application is targeted is highly influenced by the present energy markets and the cost of competition (mainly LCOE) which is again underlying political support schemes for renewables and the energy strategy in the particular region of deployment. Geographical parameters play a role here as well: Islands or remote areas may face difficulties or high costs of conventional energy systems. Here emerging renewables energies like WECs can fill in a niche. Also, the intensity of already existing offshore electricity structures or other activities such as fossil fuel extraction and other offshore industries can influence on the attractiveness of a certain application.

Cost and maturity of alternatives are influencing the choice of the developer in an indirect way and are difficult to quantify as development choices are never purely made on cost but also on feasibility. This factor exceeds influence both on the micro- and macro-level: The micro level overarches which alternatives for WEC device design are available, how far developed and at which price certain components are available. The macro level considers competing renewable energy alternatives: The cost of electricity (driven by cost of installation and power output) of already more established renewables like wind and sun determines the prices that needs to be achieved by the WEC development. This sets a range for realistic investment costs for a device and that again can constrain the design choices during WEC design and the performance that need to be achieved.

Social factors are seen as less influential factors for WEC design. WECs are small devices compared to e.g. wind turbines and are deployed either several kilometres from shore, submerged or in already artificial shorelines (breakwater systems). Therefore, direct effects like e.g. visual impacts to humans are of less importance for WEC design. Though indirect influence of social effects may not be disregarded: Social acceptance and community interest shapes the political sphere by possible public opposition due to the novelty of the technology that could interfere with the site selection but also with the general political agenda towards a renewable energy system (IRENA, 2021). Further technology awareness of relevant stakeholders is an important factor that reaches to the political and economic sphere. Given the novelty of offshore renewable energy technologies, and especially ocean energy technologies it is not uncommon that policy makers, possible investors and regulators are lacking the necessary technological awareness to advance these technologies (IRENA, 2021).

Appendix B – Morphological Analysis

A general morphological analysis is performed to obtain a representative technical configuration of a point absorber WEC to be modelled in the LCI. For further context to why this method is selected the reader is referred to Appendix A.

The first step is to create the morphological field by determining the variables and possible values (qualitative) (Delpierre et al., 2021). In this assessment the variables are determined by the different general components (and sub-components) of a PA WEC for the morphological field to resemble the technical configuration of the device. Possible values are obtained based on a review of various point absorber WECs in development and technical reviews in literature (Pecher & Kofoed, 2017; Guo et al., 2022; Lopez et al., 2013). The resulting morphological field is presented in Figure 18.

The electrical connection is not included in the morphological field as its design is not dependant on the shape and design of the device and more on the grid, deployment location and the power rating of the device as well as whether a device is installed alone or in an array.

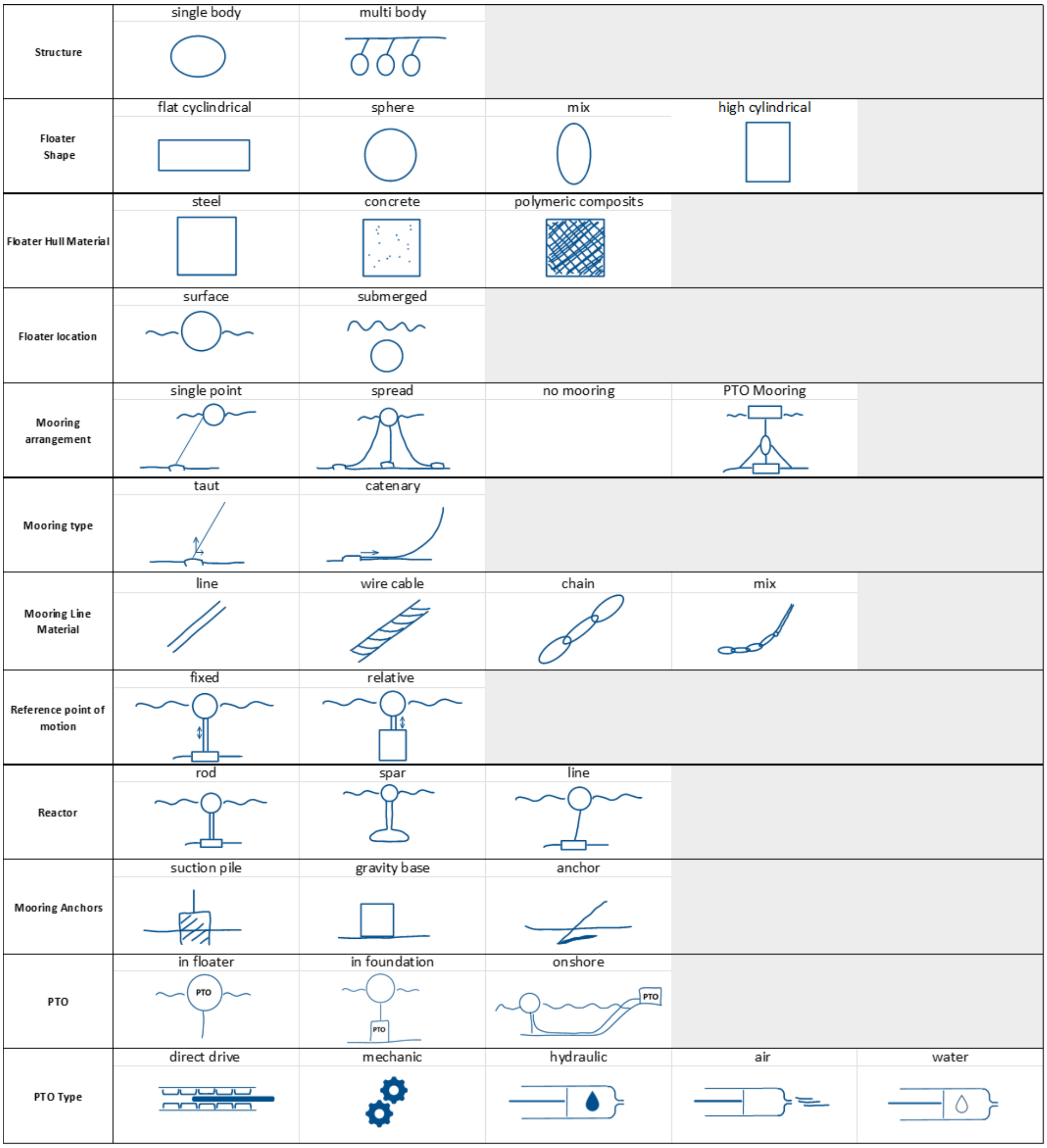

Figure 18 Morphological field of a point absorber WEC

The next step of the GMA is a cross-consistency assessment (CCA) to rule out combinations that do not exist together. The CCA is not further discussed in this chapter, but the reader is referred to the supplementary material 2. Generally, most variables that interfere with each other are the foundations with moorings and the reactor as well as possible PTOs in multi- and single-bodies with different floater designs. Therefore, the floater, the mooring and reactor are assessed separately.

Floater

After the CCA there are initially 155 combinations left for the floater.

This study will focus on single body systems which eliminates a large number of combinations as they can be applied in more wide environmental conditions and locations. Further submerged floaters are eliminated as they officially belong to a different category and are not what is initially thought of as point absorber in the EMEC categorisation (see chapter 2.1. - heaving buoy that uses elevation of waves and not pressure differential). Also, onshore PTOs are disregarded as this is very site specific and also not common for PAs as this highly restricts possible deployment locations. This leaves 75 configuration left. Mainly driven by the various PTO types. The assessed PTOs are narrowed down to exclude air, water and hydraulics as these are not common for PAs. Air is most used in OWC devices, water typically only in overtopping applications. Hydraulic systems are possible for PAs but uncommon. Most point absorbers use either mechanic drives (ballscrew, rack-pinion) or direct drive linear drive generators (Yang et al., 2024).

For this study linear drive PTOs will be assessed. Direct drive linear generators have lower mechanical system complexity, high efficiencies and are therefore expected to be more widely used in WECs in the future (Guo et al., 2022, Lopez et al., 2013, Yang et al., 2024). Apart from that, linear generators are typically very mass intensive due to high forces require to extract Power at low speeds (Lopez et al. 2013). This, as well as the impacts of the permanent magnets makes the assessment interesting from an environmental perspective.

With this general set up of a fixed reference single body point absorber with linear generator PTO two major shapes are still possible: Cylindrical, spherical and mixed-spherical. A flat cylindrical floater has its PTO located in the foundation and has a floater wider then high. A sphere is an unrealistic shape due to its bad manufacturability from steel or concrete – the two materials of interest for this study. A mixed-spherical floater is in this definition seen as higher then wide and having a curved surface, such a high device would inherit the PTO in the floater. Both the cylindrical and mix-spherical configurations are common (see CorPower Ocean and Infinity WEC, Seabased). To be able to create a representative floater shape a high cylinder is chosen. This gives the possibility to assess both shapes, as a high cylinder can also roughly represent a mixed-spherical shape which exact curvatures and forms would otherwise be impossible to resemble in a representative manner.

The baseline model in this study will consider the PTO in the device and therefore a high cylinder but by adjusting the dimension parameters of the cylinders the model can facilitate the assessment of the flat cylindrical floater type. This rough shape resemblance can cause uncertainties and possible overestimations of used materials. Overestimations of the hull materials due to misjudgement of the actual shape can account for the inner structure of the device and additional non-representable parts in the device. Overall, the level of accuracy using a cylindrical device shape with the resource specific dimensions to resemble a generic PA is sufficient for the purpose of this study.

The control mechanism is also an important performance factor for the WEC and interacts closely with the choice of the PTO. As point absorbers work through being in resonance with the incoming wave, the control mechanism can increase the PAs hydrodynamic efficiency by adjusting e.g. the damping or the reaction of the PTO to the wave characteristics changing with location but also with sea states and between each wave (Aderinto & Li, 2019). With a suitable control mechanism PAs are (with little investment and mechanical effort) more adaptable to different locations and tuneable to extract more power in different sea states without changing other major components (Aderinto & Li, 2019; Guo & Ringwood, 2021). Linear generators can be controlled by a fully electric control via the modification of generator power or current (only based on electronic control components). There are other control mechanisms even with accumulators and hydraulics. These differ widely in working principle and dimensions between different WECs from different developers (Yang et al., 2024) and therefore cannot be represented accurately in a representative manner. This study will use the electronic control as baseline scenario.

Reactor

There are 5 overall possible configurations for the reactor composed of different options for the reactor type, connection to floater and the foundation. The relative two-body system with a spar is eliminated as it has little relevance for the deployment in the North Sea (to shallow waters). Four possible structures remain depending on the combination of the connection of the floater via a stiff rod/pile or a line with a foundation that can either be a concrete gravity-based foundation or a steel suction pile. PAs with a fixed reference and the PTO in the floater mostly require a stiff reactor and therefore are connected to the seabed with a rod/ stiff hollow pipe. For the foundation depending on the hull-material scenario both a steel suction pile/vertical anchor (CorPower Ocean, 2022) and a gravity based concrete foundation proposed by MREL are assessed.

Moorings

Several Studies assessed and reviewed possible mooring configurations for WECs and come to the conclusion that performance highly depends on wished characteristics, wave climate and the device and that there is no one fits all mooring (Meyer et al., 2023; Cerveira et al., 2013; Moura Paredes et al., 2016; Pecher et al., 2014).

The discussion on which mooring design is best for a PA WEC is still ongoing (Meyer et al., 2023). Generally, there is a variety of systems composed by either several (spread) or single mooring lines in a tensioned or slack manner. The design interferes with the possible choices of anchors and materials for the "lines" themselves. Moorings are important for design cost, potentially material intensive, important for survivability and risk minimization but should also interfere minimally with the power extraction and furthermore highly depend on the environmental forces at the location and device chosen (Paredes et al., 2016). Different studies assessed whether different mooring influences the device heaving motion (and therefore the Power take off) significantly but suggest that interference is insignificant in most designs (1-3% power extraction) (Paredes et al., 2016; Cerveira et al., 2013, Meyer er al., 2023).

After this brief review for the representative PA and the CCA initially 14 mooring configurations can be found (see supplementary material 2). For large WECs mostly single point structures where the WEC is moored to either a catenary spread or tension moored buoy are proposed (Harris et al., 2004; Pecher et al., 2014). For small WECs – as which a single heaving point absorber can be classified – the use of spread moorings without additional buoys is proposed (Xu et al., 2019). Further a device can move around the buoy in a single-point configuration which is neither required for a PA (that doesn't need to align itself to the direction of the incoming waves) nor beneficial as this can create difficulties for the fixed reference on the seabed. Therefore, the single point mooring is excluded for this model.

For the spread mooring a catenary or taut system is possible though for heaving WECs a taut system does not allow enough motion and is therefore not applicable for the representative PA. Taut moorings are more complex to dimension for the system and pose challenges with tidal differences (Harris et al., 2004). Although for Bottom fixed foundations not in the floater, a taut mooring on the PTO to keep it well positioned is another possibility (Ocean harvesting n.d.). Catenary moorings are material intensive due to their immense slack. Also, these systems become less feasible for shallow water as line lengths then increases significantly (Meyer et al., 2023).

Due to a lack on data and generalizability of synthetic taut moorings, for this study a catenary system is considered. For small WECs installed at depths around ~50m +-20 it appears to be the most feasible and widely used mooring system (Cerveira et al., 2013; Depalo et al. 2021). In general, in offshore engineering there are spread moorings with 2, 3, 4 or even more lines. Though, all regarded reviews and assessments on moorings for WECs consider 3-line arrangements (Paredes et al., 2016, Cerveira et al. 2013; Meyer et al.2023; Pecher et al.2014; Depalo et al., 2021, Zhai et al., 2019). Therefore, for this analysis a spread, 3-line catenary mooring system is chosen for the PA. The PA is further directly referenced to the seabed via the reactor, comparable to the system presented by Zhai et al. 2019.

A catenary line could be composed of different strength chains and fibre ropes to decrease material footprint, nevertheless for this analysis the assumed base case is full-chain. This option might present higher material impacts due to the sheer mass of the chain compared to a light polymer fibre but is the only case generalizable for this representative assessment. A mixed design depends on depth, device and case specific parameters. Further fibre rope dimensioning is less straight forward under dynamic loads, has abrasive issues so possible replacements might be needed. From an LCA perspective it makes sense to assess the "worst case" and to be able to allow how much reduction potential such a system could bring with it. As there are PAs that do not require additional mooring (Pennock et al., 2022; Dahlsten, 2009) a scenario without mooring can be assessed by just eliminating the mooring from the analysis.

Appendix C – Modelling parameters

As described in Appendix A, as system analysis was performed to determine suitable parameters for the LCA model, to make it representative, adaptable and able to assess key scenarios.

The derived input parameters and dependant parameters are given in the following table.

Table 14: Model parameters

	Unit	Var name	Type	Formula	Baseline
Device Performance Specifications					
Rated Power	kW	RP	GP		400
Capacity Factor	%	CF	GP		0,32
Annual Energy Production	kWh	AEP	C	=RP*CF*24*365	C
Lifetime	years	L	GP		20
Environment					
Distance to Shore	km	dist	GP		40
Water depth	m	depth	GP		25
Distance to nearest Port	km	portDist	GP		50
Geometry					
Diameter	m	D	GP		9
radius	m	R	C	=1/2*D	C
height	m	H	GP		18
Surface Area	m2	A	C	=2*PI*R^2+2*Pi*R*H	C
Hull thickness concrete	m	tc	GP		0,04
Hull thickness steel	m	tst	GP		0,05
required amount of material	m	Vmat_FloaterSt	C	=A*tSt	C
required amount of material	m3	Vmat_FloaterC	C	=A*tc	C
density steel	kg/m3	rho_steel	GP		7850
mass floater hull (steel)	kg	mSteel_Hull	C	=Vmat_Floater*rho_steel	C

Amoutn of PTO	units	PTO	C	=RP/100	C
weld seam length	m	lweld	C	=8*H+6*pI*R	C
Moorings (catenary spread mooring - chain only)					
Switch for Mooring	0/1	mooringIO	switch (GP)		
Amount of mooring lines	-	nMoorings	GP		3
Chain mass per m	kg/m	mCspecific	PP		50
Total mass of anchors	kg	mAnchors	C	=nMoorings*15000	C
Total Mass of Chain	kg	mChain	C	=mCspecific*5,5*depth*nMoorings	C
Reactor					
draft	m	draft	C	=2/3*H	C
rod weigt	kg	mRod	C	=0,1*(depth-draft)*rhoSteel	C
Electrical System					
Switch for the electrical cable	0/1	cableIO	switch (GP)		
efficiency	%	effE	GP		0.94
Vessels & Fuel Consumption					
fuel consumption AHTS	kg/h	fAHTS	GP		600
fuel consumption CLV	kg/h	fCLV	GP		563
fuel consumption CTV	kg/h	fCTV	GP		300
fuel consumption OSV	kg/h	fOSV	GP		400
fuel consumption Tug	kg/h	fTug	GP		600
duration towing	h/km	tTow	GP		0,1
duration cable laying	h/km	tCableLay	GP		3,5
duration maintenance inspection	h	tInspection	C (PP)	=300kg/h*(6h+0,036h/m*portDist)	C
duration Foundation Installation	h	tInstallFoundation	GP		13
duration connection to foundation	h	tLatchFoundation	GP		10
duration connection to mooring	h/ line	tLatchMooring	GP		8
duration prelay	h/ line	tPrelay	GP		12
fuel Foundation	kg	fuelFoundation	C (PP)	=fAHTS*tInstallFoundation	C

fuel Prelay	kg	fuelPrelay	C (PP)	=nMoorings*mooringIO*tPrelay*2*1460kg/h	C
fuel Cable Laying	kg	fuelCableLaying	C (PP)	=tCableLay*dist*fCLV	C
fuel Tow	kg	fuel Tow	C (PP)	=tTow*portDist*fTug	C
fuel Hook up to Foundation	kg	fuelHookFoundation	C (PP)	=tLatchFoundation*(fOSV+fTug)	C
fuel Hook up to Moorings	kg	fuelHookMooring	C (PP)	=mooringIO*nMoorings*tLatchMooring*(fOSV+fTug)	C
fuel towing for Maintenance	kg	fuelTowingM	C (PP)	=2*(tTow*portDist*fTug + tLatchMooring*nMoorings*mooringIO*(fOSV+fTug) + tLatchFoundation*(fOSV+fTug))	C
Maintenance					
Inspection Interval	tiems/year	InspectionInterval	PP		1
Inspection once every X years	times*year	TowIntervalY	PP		4
Amount of tow operations during the lifetime	times/lifetime	TowAmount	C (PP)	=L/TowIntervalY-1	C
Two Interval	times/year	TowInterval	C (PP)	=TowAmount/L	C
EOL					
Recycling rate steel	%	steelRrate	PP		0,9
Recycling rate copper	%	copperRrate	PP		0,6
Amount of steel retrieved (concrete WEC)	kg	mEOLsteel	C (PP)	=mSteel_Floater+35000+mRod+PTO*200+533+mooringIO*nMoorings*(15000+50*5.5+depth)+40000	C
Amount of steel retrieved (steel WEC)	kg	mEOLsteel	C (PP)	=35000+mRod+PTO*200+533+mooringIO*nMoorings*(15000+50*5.5+depth)	C
transport					
transport distances Road	km	tdistRoad	GP		140
transport distances Rail	km	tdistRail	GP		1000
transport distances Inland Water	km	tdistInlandwater	GP		1000

* GP (global parameters); C (dependant, calculated parameters); PP (process parameters)

The following figure depicts which parameters influence each other:

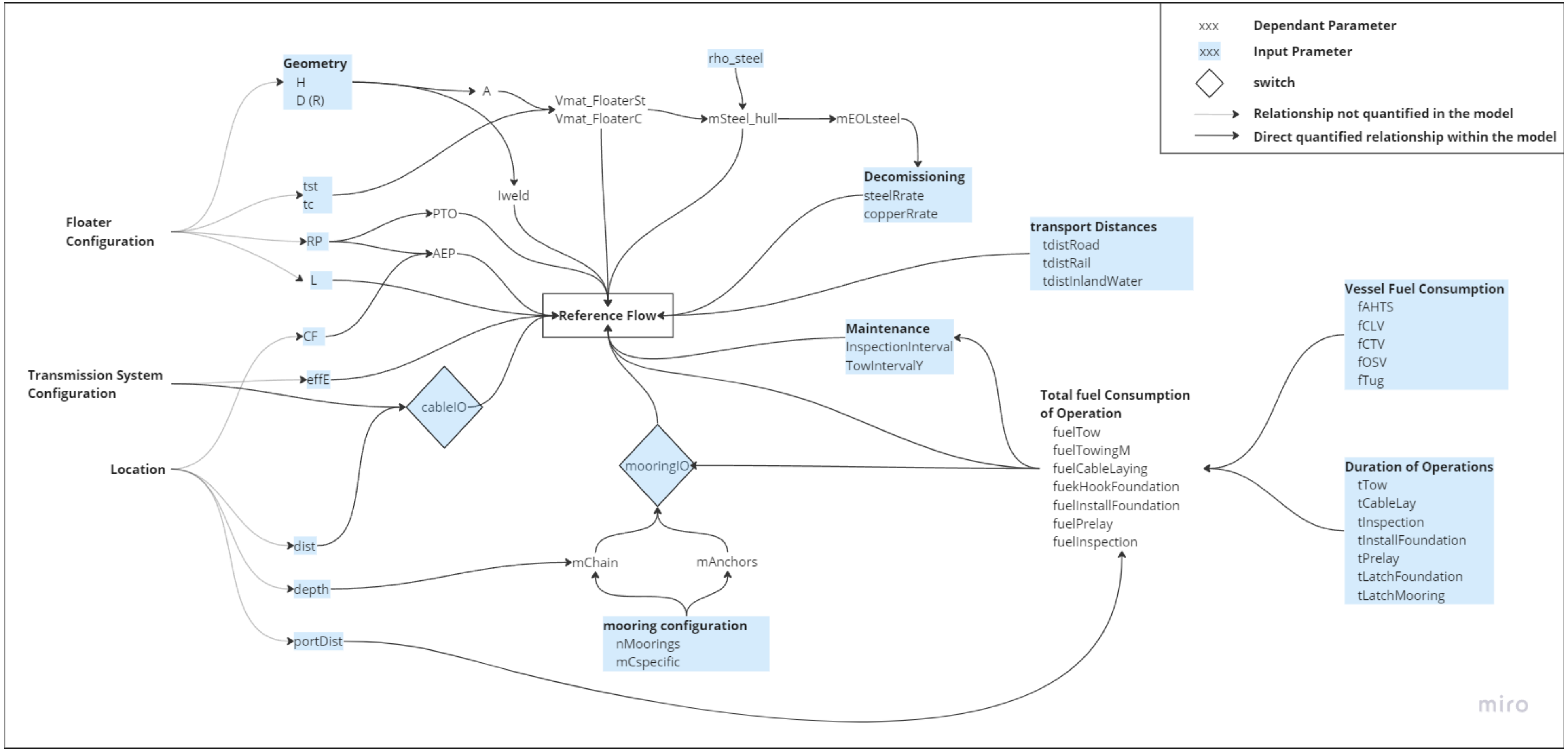

Figure 19 Interdependence of parameters used in the model

Appendix D - LCA Flow Diagram

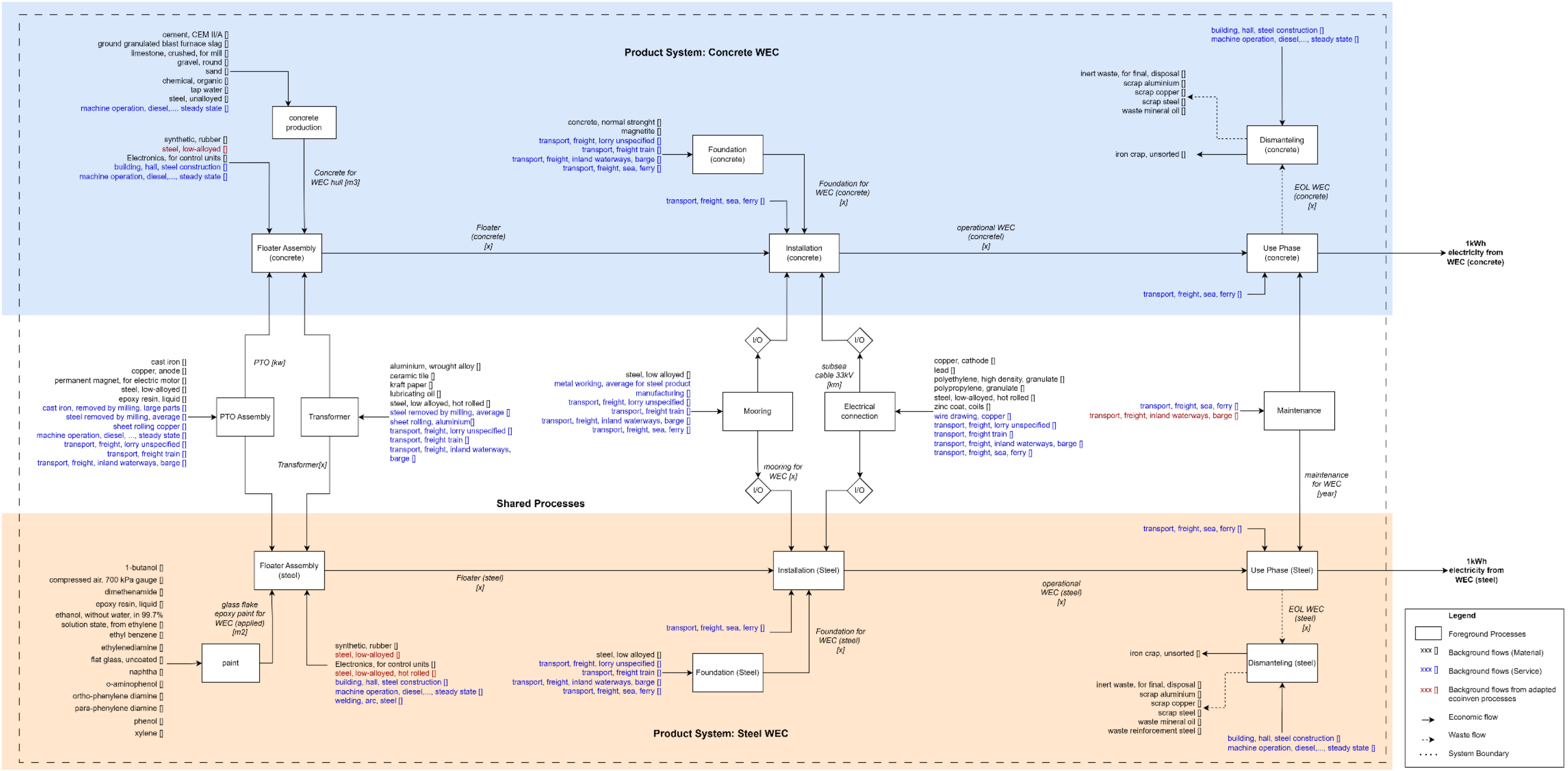

Figure 20 LCA Flow Diagram