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Life cycle assessment of a point-absorber wave energy array

Shona Pennock[a,*], Maria Vanegas Cantarero[a], Tianna Bloise Thomaz[a], Henry Jeffrey[a], Matthew J. Dickson[b]

[a]Institute for Energy Systems, School of Engineering, The University of Edinburgh, Edinburgh, United Kingdom, EH9 3DW

[b]CorPower Ocean, Västberga Allé 60, 126 30 Hägersten, Sweden

*Corresponding author.
E-mail address: shona.pennock@ed.ac.uk (S. Pennock).

Highlights

- Evaluation of the environmental impacts for a 10MW array of wave energy converters
- Inclusion of three scenarios to investigate impacts of use phase marine operations
- Monte Carlo uncertainty analysis presents results over 95% confidence intervals
- Environmental hotspots are identified to inform future design considerations

Abstract

Wave energy has a large global resource and thus a great potential to contribute to low-carbon energy systems. This study quantifies the environmental impacts of a 10MW array of 28 point-absorber wave energy converters, by means of a process-based life cycle assessment (LCA). Midpoint and Cumulative Energy Demand LCA results are presented over 19 impact categories, representing impacts encompassing human health, ecosystems and resource availability. Three scenarios are undertaken to represent the use phase of the array, identified as a particularly uncertain input, with very little long-term operation of wave energy arrays available to validate assumptions. The resultant global warming potential of the array ranges from 25.1- 46.0 gCO2e/kWh over a 95% confidence interval, 23-43 times lower than conventional fossil fuel electricity generation. The Energy Payback Time of the array ranges between 2.6-5.2 years. LCA results are found to be particularly sensitive to annual energy production across all impact categories, and to assumptions associated with the frequency of marine operations over a number of categories quantifying the production of greenhouse gases. This LCA has been undertaken at an early stage in the WEC product development and will inform innovative research focused on further reducing the environmental impacts of electricity generation.

Keywords: life cycle assessment, wave energy, environmental impact, carbon footprint, operations and maintenance

1. Introduction

Increasingly ambitious carbon reduction targets have been passed into legislation in many countries around the world [1], creating the requirement for increasing renewable electricity generation capacity. Ocean energy is so far a relatively under-exploited renewable resource, but could form an important part of low carbon energy mixes in the future. Wave energy, in particular, has a large global resource, with 29,500TWh/yr theoretical resource estimated worldwide [2].

Wave energy technologies are at a relatively nascent stage in development, with a considerable amount of progress seen in recent years. In Europe, a number of wave energy developers have deployed both part- and full-scale prototypes, funded by European agencies such as the European Commission and regional funding programmes such as Wave Energy Scotland. The European Commission have funded developers such as Wello-Oy and AW-Energy to deploy at full scale for technology demonstration in 2017 and 2019 respectively [3,4]. Wave energy Scotland has funded two half-scale devices to be deployed at the European Marine Energy Centre (EMEC) in Orkney in 2021 [5]. CorPower Ocean AB, a Swedish wave energy developer, deployed their half-scale 125kW C3 device at EMEC in 2018 and plan to deploy several devices at full scale in Aguçadora, Portugal between 2022-2024 [6].

Offshore renewable energy projects such as offshore wind, wave and tidal stream arrays can have high requirements for consumption of diesel and fuel oil during marine operations, compared with onshore renewable technologies such as wind and solar photovoltaics. As these technologies develop, Life Cycle Assessment (LCA) is an effective tool in measuring and minimising the environmental impacts resulting from offshore electricity generation projects.

1.1. Life cycle assessment of offshore renewables

A small number of LCA studies have been undertaken for Wave Energy Converters (WECs) [7–17]. However, many of the existing studies feature outdated devices which are no longer being developed or deployed for electricity generation. As such, very few LCA studies have been published based on current wave energy technologies to reflect the environmental impacts of more recent technology developments. This study contributes to the literature with the production of a process-based LCA of a current wave energy technology, conducted during the development and manufacturing of the first full-scale prototype.

Electricity generation LCAs often focus on the carbon intensity of the project as the key metric. The global warming potential (GWP) of WECs has been found to range from 23 gCO_2e/kWh [7] to 105 gCO_2e/kWh [11], as shown in Table 1. Many of these studies focus on lifecycle impacts only in terms of carbon and energy audits [7–10], but more recent publications have explored a wider range of metrics [11–17], accounting for additional ecosystem impacts such as eutrophication and ecotoxicity.

Table 1 – Device, number of impact categories considered and global warming potential from wave energy LCAs

Study	Device name	Number of impact categories considered	Global Warming Potential (gCO_2e/kWh)
Parker et al (2007) [7]	Pelamis	2 – embodied energy and carbon intensity	23
Walker et al (2011) [8]	Oyster 1	2 – embodied energy and carbon intensity	25
Dalton et al (2014) [10]	Wavestar	2 – embodied energy and carbon intensity	47
Uihlein (2016) [11]	Point absorber/ rotating mass	13 - various	105

Douziech et al (2016) [15]	Oyster 800	5 – Climate Change, Human Toxicity, Marine Ecotoxicity, Mineral Depletion, Particulate Matter Formation	65.5
Curto et al (2018) [16]	DEIM point absorber	6 – Resource Depletion, Global Warming, Human Toxicity, Freshwater Ecotoxicity, Marine Ecotoxicity, Terrestrial Ecotoxicity	49.1 – 86.5
Zhai et al (2018) [17]	Buoy-Rope-Drum (BRD)	19 - various	89
Patrizi et al (2019) [9]	OBREC	1 – carbon intensity	Not specified
Thomson et al (2019) [12]	Pelamis	19 – various	35
Karan et al (2020) [13]	Oyster 1	20 - various	79
	Oyster 800		57
Apolonia & Simas (2021) [14]	Waveroller	19 - various	33.8

The literature also highlights the impact of assumptions and scope of LCA studies, as some examples can be found where results differ for the same or similar input data. A number of LCA studies have been undertaken of the Pelamis and Oyster devices, with carbon intensity results found to range between 23-35 gCO$_2$e/kWh for the Pelamis device [7,12] and 25-79 gCO$_2$e/kWh for the Oyster 1 WEC [8,13]. The discrepancy in the Oyster results has been discussed in detail in the supplementary material produced by Karan et al. [13], and is a result of a range of factors including the definition of system boundary, the detail involved in the inventory analysis and the consideration of recycling within the waste and disposal scenarios. LCA standards specify that LCA studies should not be compared unless the scope, system boundary and assumptions are comparable [18,19].

A further study of particular interest is a comparative lifecycle assessment of a number of ocean energy technologies by Uihlein [11]. In this study, Uihlein uses input data from the ocean energy database compiled by the European Commission Joint Research Council (JRC) to conduct LCA analyses on 186 wave and tidal devices in total over thirteen impact categories. The study finds the average global warming potential to be 53 +/- 29 gCO$_2$e/kWh, which is broadly consistent with the publications shown in Table 1. However, there are of course many assumptions and estimations required to produce LCA results for such a large number of devices, as not all device manufacturers within the JRC database allowed detailed information to be shared. Uihlein finds the global warming potential of a point absorber device type to be approximately 105 gCO$_2$e/kWh, the highest GWP value of all the device categories modelled in the study.

Furthermore, the wave LCA studies in the literature all model single devices, designed and built specifically for short-term technology demonstration. It is very difficult to quantify the full lifecycle impacts of a single WEC deployed for testing over a short period, and such lifecycle impacts cannot be compared fairly with large-scale arrays of other generation technologies with optimised array layouts and marine operations, and shared components within the array balance of plant. Uihlein suggests that arrays of ocean energy devices should be a focus of future LCA studies [11]. As such, this analysis models an array comprised of multiple WECs so that components and operations which would normally be shared over the whole array (such as cables, substations, and installation, maintenance and decommissioning activities) can be considered for the full lifecycle of the array.

While existing wave energy LCAs are of course particularly relevant, LCAs of other offshore renewables such as tidal stream and offshore wind are also of interest, with considerable similarities in terms of scope and assumptions when modelling project infrastructure and marine operations. In terms of other marine energy LCA studies, very few publications have been produced conducting LCAs of tidal stream projects [11,15,20–23]. A particular study of note is Walker et al. [20], who compare LCA results for four different tidal stream devices which have been tested at EMEC, finding the GWP of these devices to range between 18-35 gCO_2e/kWh.

Although there is only limited recent work on LCAs of marine renewables, there is a good range of LCAs published investigating the lifecycle impacts of offshore wind generators. Kaldellis and Apostolou review and summarise carbon intensity results from twenty-six wind energy studies, finding values to range between 4.6 – 16.0 gCO_2e/kWh and 5.2 – 32.0 gCO_2e/kWh for onshore and fixed offshore wind respectively [24]. A review of LCA analyses for floating offshore wind technologies found the carbon intensity results to vary between 11.5 – 38.1 gCO_2e/kWh [25]. The comparatively higher ranges of carbon intensity figures produced by LCA studies on marine energy may reflect the early stage of the technologies involved.

1.2. Representation of marine operations

A key limitation of modelling early stage marine energy technologies is that there is very little long term real sea deployment experience to provide data on marine energy operations, and as such marine energy O&M models have yet to be thoroughly validated. Initial work using real sea data to validate O&M models for wave energy has indicated that this validation will be an important step in accurately quantifying the fuel consumption associated with the O&M life cycle phase [26]. LCA databases also include the impacts of marine and freshwater vessels primarily to account for the transportation of materials and products, and thus only represent large scale freight transport vessels rather than those typically used for marine operations. As such, LCA practitioners conducting offshore renewable energy LCA studies often have to either assume that large freight vessels can be used as a proxy for marine operations vessels or attempt to scale the LCA input assumptions to account for the difference in fuel consumption between the freight vessel and the marine operations vessel which would actually be used.

A wide range of assumptions for representing marine operations within marine energy LCA studies can be found in the literature. The number of annual operations ranges from 8 times per year for the Pelamis studies [7,12] to less than once a year in one of the tidal stream studies [20], with many studies including planned inspections with smaller vessels [7,12,13,20,23] and some studies representing all marine operations with larger vessels [11,22]. All of the studies only consider planned operations except for two tidal stream LCA studies [22,23], which include a representation of unplanned maintenance within the operating strategies.

The impact of using differing methodologies for representing O&M strategies is reflected by a considerable range of impact of the O&M phase within the overall LCA results. Most of the wave and tidal LCA studies in the literature have a proportional impact of less than 1% of the GWP from the O&M phase [8,11,13,15,17,20,21]. Of the remaining studies, O&M has an impact of less than 10% in one study [20], an impact of approximately 20-30% in five studies [7,9,10,12,23] and nearly 50% for one study [22]. This wide range of results, with a large proportion of the studies showing negligible impacts from the O&M phase and others showing significant impacts, suggests that it is not uncommon for marine operations to be misrepresented within LCA studies.

This study presents a cradle to grave LCA of the CorPower Ocean AB point absorber WEC as part of a 10MW array. It has the novelty of providing an initial LCA based on data from the first full-scale prototype from an active wave energy developer as part of a multi-device array. A number of scenarios are explored to represent the frequency of unplanned maintenance operations, based on published reliability studies for point absorber WECs. The sensitivity of the final LCA results to the assumptions involved with the transportation of components, representation of marine operations and annual energy production are also explored in detail. Finally, this study also discusses the limitations and risks associated with the comparison of LCA results between offshore renewable LCA studies, particularly concerning the heterogeneous approaches to representing marine operations such as installation, operation and maintenance.

2. Methods

This study comprises a conventional process-type LCA of an array of 28 WEC prototypes developed by CorPower Ocean AB (CPO), conducted using SimaPro v9.1.0 software. Foreground material and process data was collected and estimated from CPO, and background data sourced from the Ecoinvent database v3.6. SimaPro and Ecoinvent have been selected for this work as state-of-the art commercial products for environmental impact assessments, which are also commonly used in the LCA literature [27,28]. The software and study methods are aligned with the ISO 14040 [18] and ISO 14044 [19] standards. The following sections detail the study methodology with regards to the four phases outlined in these standards: goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1. Goal and Scope Definition

The goal of this study is to undertake a life cycle assessment of the full scale CPO point-absorber WEC within a 10MW array, with cabling and marine operations assumptions at array scale. CorPower Ocean AB is an independent wave energy developer based in Stockholm, Sweden [29]. Their WEC is a heaving buoy point-absorber device with novel phase control technology, which oscillates in resonance with the incoming waves to amplify the motion and power capture. The key WEC components are illustrated in Figure 1. The heaving buoy WEC system is connected to the seabed using a novel pile anchor and tensioned mooring system, and includes a pneumatic pre-tension system between the mooring and the buoy. The linear vertical motion of the buoy is amplified and converted to electrical output by means of a cascade gearbox and pneu-mechanical drivetrain.

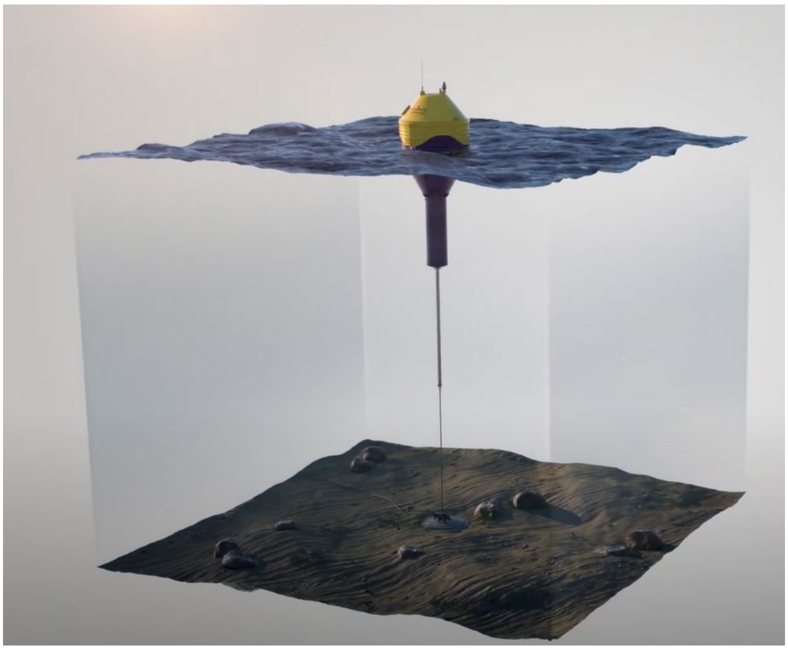

Figure 1 – Illustration of CorPower Ocean WEC, from [29]

The scope of this study is a cradle to grave LCA of a 10MW array, comprising 28 WECs. The LCA thus comprises of a number of life cycle stages, from raw material extraction to component manufacturing, transportation to site, installation, operation and maintenance and finally decommissioning and waste disposal, illustrated in Figure 2. The system boundary includes the electrical infrastructure up to and including the array export cable and does not include grid connection at an onshore substation. The cut-off allocation method has been used, meaning that the input data from Ecoinvent includes assumptions about recycled content. Therefore, no credit is provided for recycling within the project disposal scenario to avoid double-counting the impacts of recycling within both the study inputs and outputs [12].

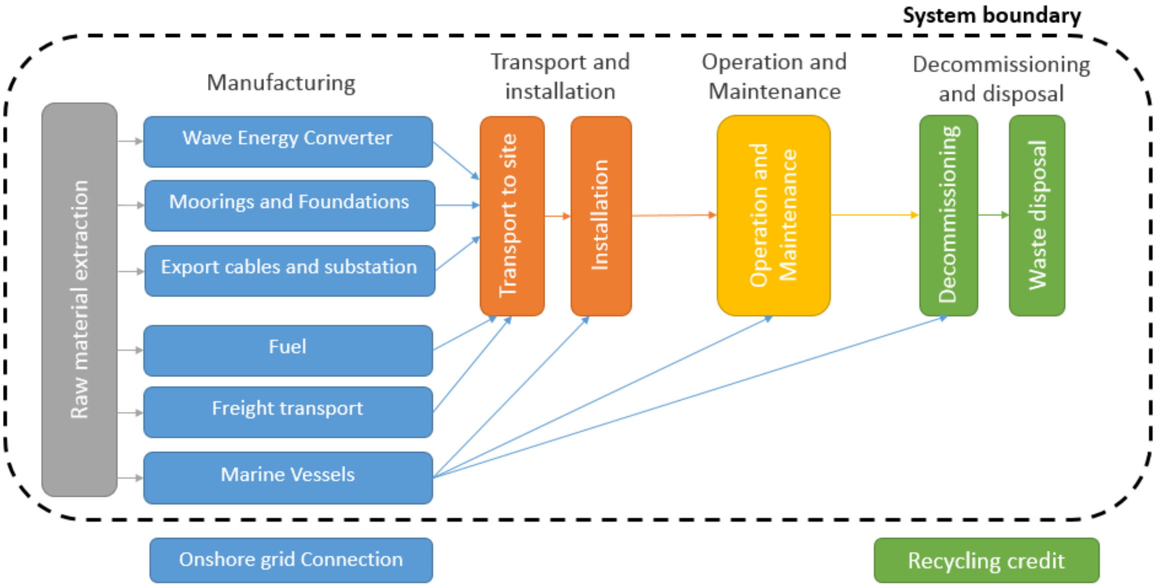

Figure 2 – Scope of LCA study, black dashed line represents system boundary

The functional unit is defined as 1 kWh of electricity generated by the wave energy array and delivered by the array export cable. WEC availability and electrical losses as far as the onshore network connection are thus included. The average annual energy production has been calculated for the hypothetical array location at Aguçadora, Portugal, with factors applied to represent availability, electrical losses, array interaction losses and auxiliary consumption. The final annual energy production of 33GWh/year for the array corresponds to a 38% capacity factor, which is consistent with other wave energy LCAs [12,15,17]. The study parameters are summarised in Table 2.

Table 2 – Study parameters

Parameter	Value
Array rating	10MW
Device rating	350kW
Number of WECS	28
Capacity factor	38%
Availability	90%
Lifetime	20 years
Array location	Aguçadora, Portugal
Distance from shore	10km
Water depth (mean sea level)	45.28m

2.2. **Inventory analysis**

2.2.1. Materials and Manufacturing

A full inventory of component parts, manufacturing processes and structural elements of the array has been built in collaboration with the WEC developer, CPO. Due to non-disclosure agreements with CPO and their suppliers, a comprehensive dataset cannot be released publicly. The WEC, mooring and anchoring system are broken down across eighteen modules, each comprising of a number of sub-components with associated materials, masses and manufacturing processes. CPO were able to provide this data in detail during 2021 as they completed the design, procurement and assembly process for their first full scale prototype WEC. Materials data for the array electrical cables, export cables and the array feeder hub for a 10MW array have also been provided by CPO. The length and rating of electrical cables have been provided and the materials breakdown for the specific cables derived from a submarine cables datasheet [30]. The materials included in each of the array components are shown in Table 3. The array is mostly comprised of steel (83% of total mass), with the WEC fibreglass hulls also making up a smaller but significant proportion (12%) of the final mass. Copper and aluminium each make up ~1% of the array, and plastics make up almost 3% of the array.

For components which have been machined, but the amount of removed material is unknown, it has been assumed that 23% of the mass of the finished product has been removed through machining. This assumption is from the Ecoinvent database entry for steel milling [31].

Table 3 – Components and materials used in the WEC array

Component	Materials
WEC Hull	Glass fibre, vinylester resin, reinforcing steel
Power take off	Steel, aluminium, copper, epoxy resin, tin, rubber, plastics, magnets
Moorings and anchor	Steel, glass-reinforced plastic
Electrical cables	Steel, copper, polyethylene, polypropylene
Feeder hub	Steel, polyethylene

2.2.2. Transport and Installation

Manufacturing locations for each of the array components have been provided by CPO and have been defined as either coming from Scandinavia, other European countries or locally produced. The percentage of the total array mass transported from each of these regions is shown in Table 4. Components are assumed to be transported by road to Portugal. It is also possible that for future arrays, a greater proportion of these components will be locally manufactured and so an additional sensitivity analysis has been undertaken on the distance travelled.

Table 4 – Proportion of total array mass and manufacturing locations

Manufacturing location	Transport distance assumed	Proportion of mass
Scandinavia (Sweden, Finland, Norway)	3500km	38.1%
Other Europe (UK, Netherlands, Germany)	2000km	33.5%
Local (Portugal, Spain)	0km	28.4%

Installation procedures have been modelled in detail using analytical calculations based on expert knowledge and experience at CPO, with separate marine operations included to install the anchoring system, collector point, WEC, WEC mooring system, inter-array cables and array export cable. The number of hours of operation required from specific vessels and their respective fuel consumption has been used to calculate the litres of fuel required for installation procedures, shown in Table 5. The fuel consumption of the exact vessels is not able to be shared due to confidentiality agreements. WEC installation activities can be seen to involve considerably lower fuel consumption, as much of the time is spent anchored at port or on site whilst preparations and electrical testing takes place. The 'Ferry' vessel within Ecoinvent v3.6 was found to have the closest fuel consumption to the marine vessels required for installation operations, and the tonne-kilometre input in SimaPro was scaled to ensure the total fuel consumption was consistent with the fuel consumptions required for the installation procedures modelled.

Table 5 – Installation operations and associated fuel burn for full 10MW WEC array

Operation	Length of operation	Fuel consumption
Cables Installation	15.7 days	13,000 litres/day
Anchor Installation	15.0 days	11,600 litres/day
WEC Installation	13.7 days	3,500 litres/day

2.2.3. Operations and Maintenance

The annual instances of Operations and Maintenance (O&M) activities required for future wave arrays are still relatively uncertain, with assumptions and models unable to be verified until sufficient deployment experience has been achieved. As such, three O&M scenarios were considered, each assuming bimonthly array inspections and 5-yearly planned maintenance activities. Instances of unplanned failures are varied from scenario to scenario, based on the commonly used assumption of two maintenance operations per year [12] (Scenario 1) and failure rate analysis of point absorber WECs in the literature [32,33] (Scenarios 2 & 3). The rate of annual instances of each of these operations per WEC are shown in Table 6. The 'Ferry' vessel within Ecoinvent was also used to model these marine operations, with the tkm input scaled to match the fuel consumption calculated for each scenario.

Table 6 – O&M strategy assumptions for three scenarios modelled, in annual instances per WEC

Scenario	Inspection	Planned maintenance	Unplanned maintenance	Source (unplanned maintenance)	Lifetime fuel consumption
O&M Scenario 1	6	0.2	1.80	Assumptions [12]	2.6 Mlitres
O&M Scenario 2	6	0.2	0.81	Failure rates [32]	1.4 Mlitres
O&M Scenario 3	6	0.2	3.56	Failure rates [33]	4.6 Mlitres

Due to the uncertainty associated with replacement of specific components, the impact from replacement parts during the operations and maintenance phase have not been included, this is consistent with the wave energy LCAs from the literature [7,10–12].

2.2.4. Decommissioning and disposal

Decommissioning activities are assumed to reflect the fuel burn associated with decoupling each of the wave energy converters and towing them to the nearest port, as the reverse of the WEC installation shown in Table 5. The site is assumed to be re-energised and so no impacts are considered from decommissioning the electrical cables, anchors and substation. WEC disposal is assumed to be primarily to landfill. As discussed in section 2.1, recycling credit is assumed to be outside of the system boundary, and not included in the results shown for this study, beyond excluding 90% of the total steel and aluminium from the material disposed to landfill. This is consistent with other wave energy LCAs from the literature [12,13].

2.3. Impact Assessment

As discussed in Section 1, conducting LCA over a range of impact categories beyond carbon intensity is necessary to fully understand and compare the lifecycle impacts of power generation technologies. The impact assessment methods used for this study are ReCiPe v1.31 Midpoint (H), hierarchist version, with European normalisation [34] and Cumulative Energy Demand (CED). As such, emissions and resource extractions are translated into 19 impact categories, shown in Table 7. The life cycle impacts are assessed over a 95% confidence interval using the Monte Carlo function within SimaPro, which runs 1000 combinations of the LCA calculations based on the uncertainty distributions assigned to the Ecoinvent data entries. This allows for a range of results to be presented, accounting for the implicit uncertainties within the Ecoinvent data. Finally, the Energy Pay-Back Time (EPBT) metric is used to quantify the ratio between the CED and the annual energy production of the array.

2.4. Interpretation

In the interpretation stage, LCA impacts are compared with existing figures for conventional electricity generation technologies across all 19 impact categories. The sensitivity of these results to input assumptions on transport, O&M strategy and annual energy production are also assessed. Results are not directly compared with individual LCA studies for renewable electricity generation due to inconsistencies between the scope and methods used to identify lifecycle impacts between studies. However, ranges of global warming potential outputs from this study are discussed in terms of the ranges found in the literature. Finally, the interpretation of lifecycle impacts also allows for the identification of hotspots, that is materials and processes with a high share of lifecycle impacts over the 19 categories assessed, and recommendations are provided on strategies to mitigate these impacts.

3. Results

3.1. Life cycle impact assessment

The life cycle impacts of the array are shown in Table 7, assessed over a 95% confidence interval for 19 impact categories and three O&M scenarios outlined in Table 6. The mean GWP ranges between 27.4-42.9 gCO_2e/kWh and the 95% confidence interval GWP results range from 25.1 to 46.0 gCO_2e/kWh. The mean CED ranges between 0.38-0.60 MJ/kWh and the 95% confidence interval CED results range from 0.34 to 0.68 MJ/kWh. Using these figures, the EPBT of the array ranges between 2.9-4.6 years based on the scenario mean values and 2.6-5.2 years for the 95% confidence intervals.

The results in Table 7 are particularly sensitive to the O&M scenario for the impact categories associated with greenhouse gas production (GW, SOD, OF HH, FPMF, OF TE, TA), fuel use (FRS) and energy demand (CED). The highest impact between the O&M scenarios is seen for the two impact categories associated with ozone formation (OF HH, OF TE), in which the mean results output for scenarios 2 and 3 are 32% lower and 54% greater, respectively, of the mean ozone formation results for scenario 1. It can also be seen in Table 7 that the water consumption (WC) values are negative in some instances, as the formation of water in the process of hydrocarbon combustion can result in a net negative water consumption [35].

Figure 3 shows the mean LCIA results for the array using O&M scenario 1 in terms of the proportional split between each of the life cycle stages. It can be seen that the Materials and Manufacturing (M&M) life cycle stage (comprising of the WECs, moorings, anchors and array cables) has the highest proportional impact for 12 of the impact categories and O&M has the highest impact for 6 of the impact categories. Transport also has the most significant impact on the Land Use (LU) impact category. For the O&M scenario 2 results, M&M has the highest proportional impact for 14 categories, transport for one category (LU) and O&M for 4 categories, shown in Figure A.1 in Appendix A. For O&M scenario 3, M&M has the highest proportional impact for 9 categories and O&M has the highest proportional impact for 10 categories, shown in Figure A.2 in Appendix A.

Table 7 – Lifecycle impact assessment results for the CorPower Ocean WEC for a functional unit of 1 kWh, for three O&M scenarios

Impact category and Acronym	Units (/kWh)	O&M Scenario 1			O&M Scenario 2			O&M Scenario 3		
		2.5%	**Mean**	**97.5%**	**2.5%**	**Mean**	**97.5%**	**2.5%**	**Mean**	**97.5%**
Fine particulate matter formation (FPMF)	g PM2.5 eq	0.13	0.15	0.17	0.10	0.11	0.13	0.19	0.21	0.24
Fossil resource scarcity (FRS)	g oil eq	8.31	9.21	10.24	6.78	7.54	8.44	10.84	12.15	13.65
Freshwater ecotoxicity (F Ec)	g 1,4-DCB	6.29	8.16	11.03	6.27	8.12	10.77	6.30	8.21	11.01
Freshwater eutrophication (F Eu)	g P eq	9.97E-3	1.53E-2	2.54E-2	9.90E-3	1.50E-2	2.38E-2	1.01E-2	1.56E-2	2.61E-2
Global warming (GW)	g CO2 eq	30.61	32.96	35.82	25.08	27.36	30.21	40.32	42.92	46.03
Human carcinogenic toxicity (HCT)	g 1,4-DCB	4.55	9.55	19.10	4.50	9.10	18.71	4.68	9.50	17.98
Human non-carcinogenic toxicity (HNCT)	g 1,4-DCB	80.45	106.88	144.76	80.35	105.24	145.63	81.07	107.82	146.73
Ionizing radiation (IR)	Bq Co-60 eq	0.19	0.97	4.36	0.18	0.90	4.44	0.25	1.11	3.73
Land use (LU)	m2a crop eq	4.19E-4	5.37E-4	7.27E-4	4.03E-4	5.17E-4	6.94E-4	4.55E-4	5.83E-4	7.95E-4
Marine ecotoxicity (M Ec)	g 1,4-DCB	8.08	10.41	13.89	8.06	10.35	13.70	8.11	10.49	13.90
Marine eutrophication (M Eu)	g N eq	1.65E-3	1.98E-3	2.50E-3	1.61E-3	1.95E-3	2.49E-3	1.65E-3	2.00E-3	2.48E-3
Mineral resource scarcity (MRS)	g Cu eq	0.55	0.74	1.01	0.55	0.72	1.00	0.57	0.76	1.04
Ozone formation, Human health (OF HH)	g NOx eq	0.26	0.37	0.52	0.18	0.25	0.34	0.40	0.57	0.80
Ozone formation, Terrestrial ecosystems (OF TE)	g NOx eq	0.27	0.37	0.52	0.19	0.25	0.34	0.41	0.58	0.80
Stratospheric ozone depletion (SOD)	g CFC11 eq	1.54E-5	1.89E-5	2.35E-5	1.23E-5	1.50E-5	1.88E-5	2.06E-5	2.58E-5	3.40E-5
Terrestrial acidification (TA)	g SO2 eq	0.36	0.40	0.46	0.26	0.28	0.32	0.54	0.60	0.69
Terrestrial ecotoxicity (T Ec)	g 1,4-DCB	260.30	441.84	818.96	251.59	426.38	887.12	275.88	469.26	924.13
Water consumption (WC)	m3	-3.28E-2	2.92E-4	2.58E-2	-3.61E-2	-2.15E-4	2.70E-2	-3.58E-2	7.05E-4	2.98E-2
Cumulative energy demand (CED)	MJ	0.41	0.46	0.52	0.34	0.38	0.44	0.52	0.60	0.68

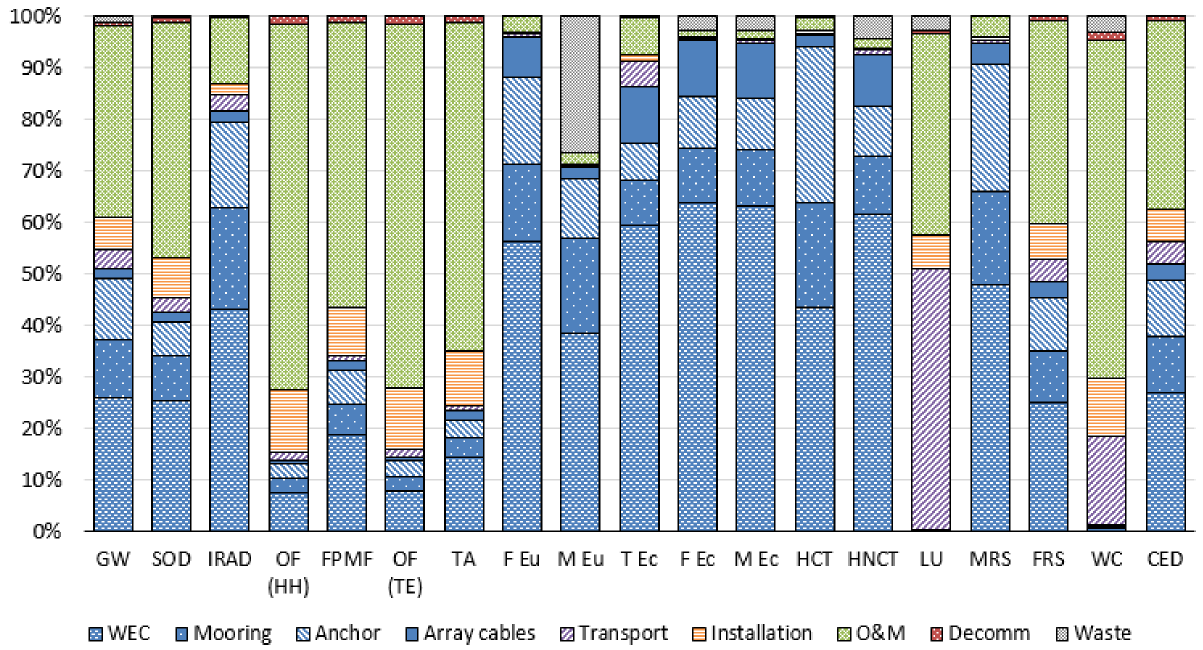

Figure 3 – Life cycle impact assessment results proportion by life cycle stage, O&M scenario 1

3.2. Uncertainty and sensitivity analyses

Figure 4 shows the statistical results from the Monte Carlo analysis of the array model using O&M scenario 1 as percentage change from the mean for each impact category. This allows for the comparison of the range of the relative 95% confidence intervals between impact categories. It can be seen that the lowest ranges in confidence intervals occur for the GW, FPMP, FRS, TA and CED impact categories. The WC and IR entries have the largest 95% confidence intervals relative to the mean. The relative confidence interval for WC has not been shown in Figure 4 as the values range from -11317% to 8729% of the mean value. This suggests that the uncertainties associated with WC are too high for the results to be statistically meaningful, a conclusion which has also been reached in several studies in the literature [25,36]. The Monte Carlo analyses undertaken using O&M scenarios 2 and 3 are included in Table 7 and produce very similar ranges relative to the mean as those shown in Figure 4.

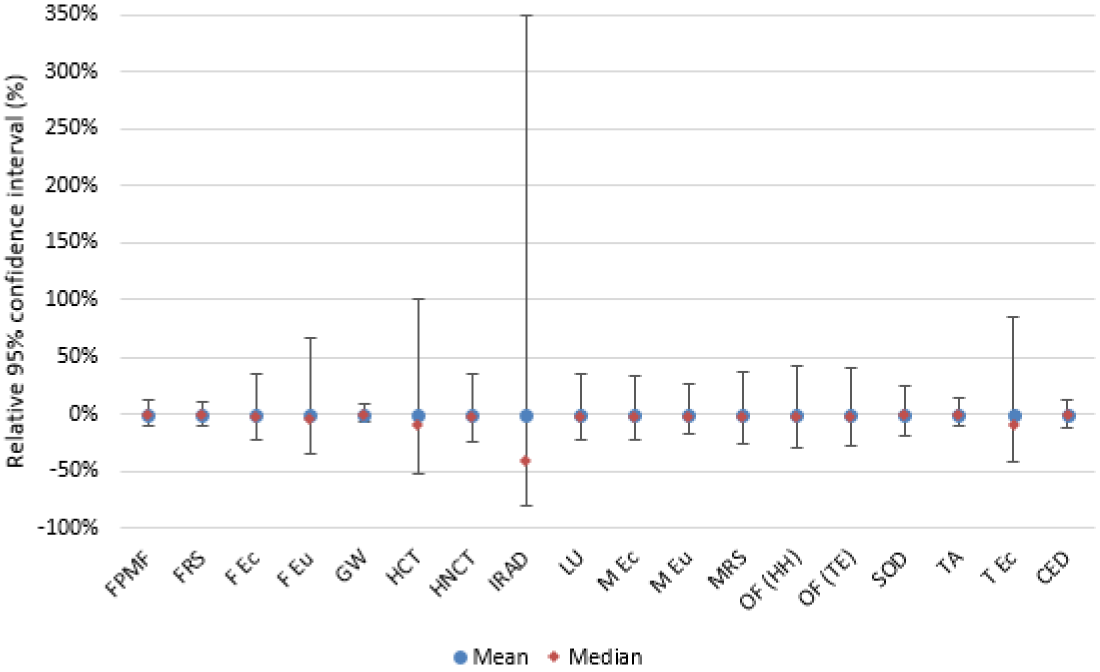

Figure 4 –Monte Carlo results with O&M scenario 1 - mean, median and 95% confidence interval relative to mean for each impact category

The highest uncertainties within the foreground data have been identified as the assumptions made on transport distances, annual energy production and fuel burn associated with O&M activities, as these inputs cannot be validated until an array has been deployed. For this reason, the impact of these inputs are further investigated through sensitivity analysis. Figure 5 shows the sensitivity of GWP results to AEP (GWh), O&M (fuel burn) and transport (tonne-kilometre) inputs. The impact categories with the highest and lowest percentage change are also shown to demonstrate the range of results produced by the sensitivity analyses. It can be seen that the results are most sensitive to changes in the AEP. All impact categories produce the same percentage change when altering the input annual energy production, as the functional unit of the study is 1kWh.

As noted from the O&M scenario analysis explored in detail in Section 3.1, the life cycle impacts have been shown to be very sensitive to the assumptions associated with the number of unplanned maintenance operations required. Figure 5 confirms that the results are sensitive to the O&M fuel burn assumptions, with a change in fuel burn input of +/-20% resulting in a percentage change in GWP of +/-8%. OF HH is found to be the most sensitive impact category to fuel burn, with a percentage change of +/-15% and F Ec is found to be the least sensitive with a percentage change of less than 1%. The results are shown to be considerably less sensitive to transport distance assumptions, with only a 1% change in the most impacted categories of GWP and T Ec.

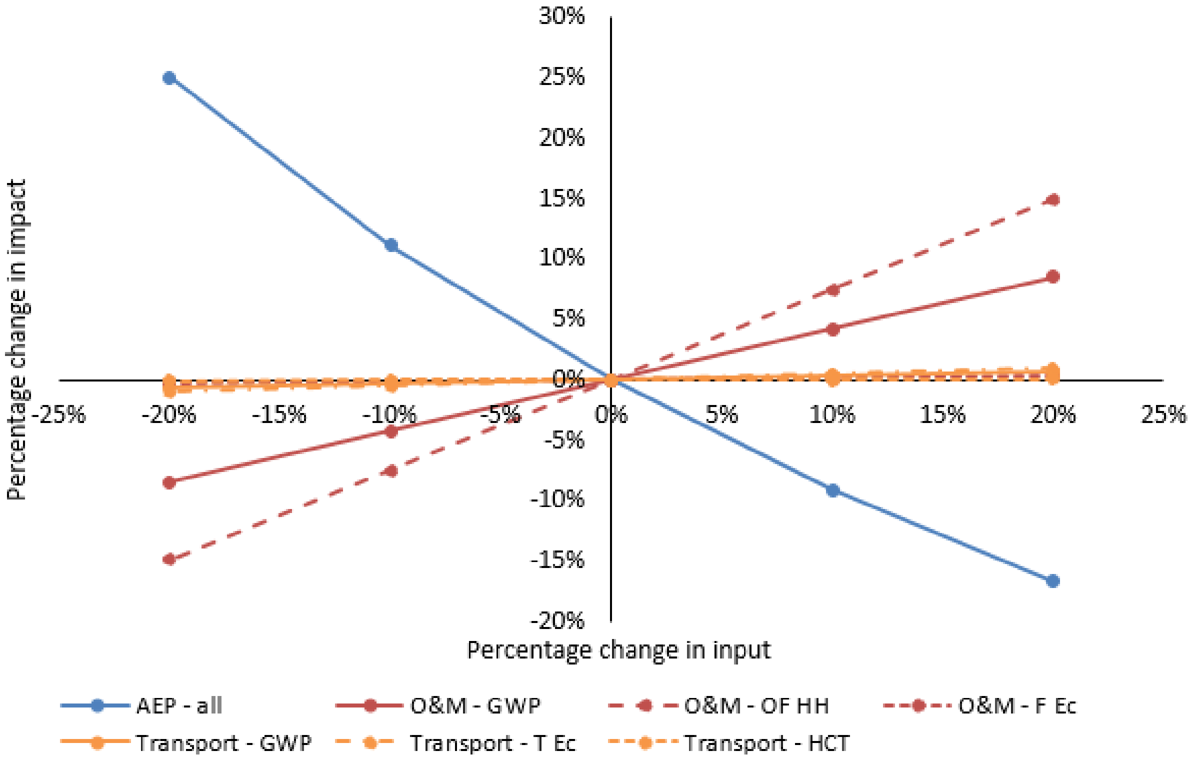

Figure 5 – Sensitivity to annual energy production, O&M fuel burn and transportation distance inputs over selected impact categories

4. Discussion

The following sections compare the results presented in this study with electricity generation technology LCAs from the literature, and offshore renewables in particular to consider the impacts of offshore operations and maintenance. It is also important to discuss the environmental impact hotspots and the study limitations and data quality when presenting these results.

4.1. Comparison with literature – electricity generation

4.1.1. Offshore renewable generation

The results presented in this study can be compared with LCA studies for other forms of electricity generation from the literature to provide context. Comparing the most commonly used LCA indicator of Global Warming Potential (GWP), the literature discussed in Section 1 provided a range of results between 23-105 gCO_2e/kWh for wave energy LCAs, 18-35 gCO_2e/kWh for tidal stream LCAs and 5-32 gCO2/kWh for offshore wind LCAs. The carbon intensity results for the CPO WEC presented in Section 3.1 are 27.4-42.9 gCO_2e/kWh and fall within the ranges produced for offshore renewables.

While comparison can be useful for context, it is also important to note that comparing LCA figures directly with the literature is not recommended unless the studies have directly comparable scopes. Offshore renewable LCA study scopes often vary in terms of the definition of system boundary, inventory analysis and the inclusion of recycling credit within the waste and disposal scenarios [13]. It should also be noted that this study presents an LCA for an array of 28 WECs, while all wave energy LCAs in the literature represent the installation and demonstration of single devices.

4.1.2. Conventional generation

Another useful comparison is with the Ecoinvent v3.6 data for electricity production, which allows the LCA results to be compared with a number of conventional electricity generation technologies over the full range of impact categories. This method of comparison was highlighted in Thomson et al. [12]

as a more complete analysis of the results than the more commonly published method focusing only on embodied energy and embodied carbon. Conventional electricity production technologies in Portugal are listed in the Ecoinvent database as ‘hard coal’, ‘natural gas, conventional power plant’ and ‘natural gas, combined cycle power plant’. Electricity production from the CPO WEC was found to outperform all of these forms of fossil fuel generation in six impact categories (GW, SOD, LU, FRS, WC, CED). The WEC array also outperforms electricity production from hard coal in all but one category (T Ec) across all three O&M scenarios. Focusing on carbon intensity, the CPO WEC GW results from this study are up to 18 times lower than for combined cycle gas, 29 times lower than conventional gas and 43 times lower than hard coal.

Only conventional generation has been used for this comparison, as the use phase associated with renewable generation is not well represented in the Ecoinvent database. Offshore wind, for example, only includes an annual change of lubrication oil within the use phase, with no transport processes to access, inspect and maintain the turbine. The Solar PV Ecoinvent entry only includes the water used to clean the panels, and also no transport associated with the operation and maintenance of the devices. As the O&M phase makes up a considerable amount of the environmental impacts within this analysis, the scope of the renewable electricity production data from Ecoinvent is deemed incomparable.

4.2. Comparison with literature – O&M modelling

A key focus of this study is to ensure that the lifecycle impacts of marine operations are sufficiently represented within the LCA calculations. Marine operations are undertaken at various stages of the WEC lifecycle, such as installation, operations and maintenance (O&M) and decommissioning. These lifecycle stages have been shown to incur a significant proportion of lifetime costs for wave energy converters [26,37–39] and are thus also expected to have a significant impact on LCA impact categories.

Section 1 discussed the percentage carbon intensity of the operational phase of marine energy lifecycles, which varies considerably depending on the chosen methodology, from less than 1% to ~50%. This would suggest that some methodologies may be under- or over-representing the lifecycle impacts of marine operations. The results for this study find the operational phase of the CPO WEC array to be 25%-52% of the total GWP.

The limitations associated with modelling O&M within existing offshore renewable LCA studies is twofold. Firstly, the representation of O&M strategies for offshore renewables involves a number of assumptions with respect to the number of annual operations required, the vessel requirements and the vessel fuel consumption. It is not yet possible to validate O&M strategy assumptions for wave energy as there is very little data associated with real sea experience, since no commercial scale projects have yet been deployed. Secondly, the representation of O&M activities is challenging within the confines of the LCA databases. The lifecycle impact from marine vessels is currently included within LCA databases to account for transportation of products rather than for long-term operation of offshore renewables. As such, large container ships, barges and ferries are the only vessels available within the Ecoinvent database v3.6. Some adjustment is required to the input tonne-kilometres to adjust for fuel consumption of specific vessels, but this likely does not properly scale the impacts associated with the materials breakdown of the vessel or use of port infrastructure.

4.3. Potential for life cycle impact reduction

One of the goals of applying life cycle assessment to nascent renewable technologies is to identify hotspots, or points of high environmental impact, that may be able to be ‘designed out’ of developing technologies. This study has been undertaken very early in the design stage, during the commissioning of the first full scale prototype WEC, which enables the use of LCA as a complementary design tool for future innovative developments. This study has been undertaken for a 10MW array deployment, and it should be noted that for larger scale arrays it could be possible to see further reduction in lifecycle impacts due to sharing infrastructure such as export cables, and optimising marine operations to service multiple devices per trip.

Steel has the highest impact within the materials and manufacturing life cycle stage as the array is comprised of 83% steel. Reducing the amount of steel within the WEC and WEC infrastructure would reduce this impact. The use of alternative materials could be a solution to this, such as composites, which can provide similar strength properties for lower density and mass. However, recycling techniques are still under development for composite materials [40], and are well established for metals like steel and aluminium, so caution should be taken to ensure that the use of alternative materials to steel does not result in higher volumes of waste going to landfill.

Marine operations such as installation, O&M and decommissioning make up to 57% of the total GWP and CED, and up to 90% of the total OF HH and OF TE. O&M consistently makes up the greatest proportion of this impact. The scenario analysis and sensitivity analysis undertaken also highlight how sensitive the LCA results are to the use phase of the array. This impact could be reduced by optimising O&M strategies in terms of the number of corrective/preventative marine operations, ensuring high reliability of components and systems and using greener marine vessels with lower fuel consumptions.

Finally, the impacts associated with the transport of components could be reduced further by maximising utilisation of local supply chains, and the impacts associated with the waste cycle can be reduced by maximising the number of components composed of recyclable or reusable materials.

4.4. Limitations and data quality

It is important to present these LCA results alongside a discussion of the limitations and assumptions involved in this study. In terms of the WEC materials and manufacturing inputs, data collection was undertaken during the construction of the first full scale WEC prototype and as such very few assumptions had to be made. The only major assumption was the amount of steel removed during machining processes, which was set to 23% based on Ecoinvent recommendations [31]. Inputs for array electrical infrastructure, O&M and energy production are based on assumptions on future commercial arrays and so will be less certain than the WEC inputs. The sensitivity analysis presented in Section 3.2 quantifies the potential impact of some of these assumptions. It was found when ranging inputs for each lifecycle stage by up to +/-20% resulted in a variation in output impact categories ranging from -17% to +25%.

It should be noted that many inputs to this LCA study are very sensitive to site characteristics such as wave resource, distance from shore, distance from port and water depth. Such site-specific inputs include energy production, cabling, transport, installation, O&M and decommissioning. This analysis has been completed based on assumptions relating to a specific site at Aguçadora, Portugal, and results could change considerably if the technology was deployed at a different location.

It should also be highlighted that this analysis represents the WEC at an early point in the design phase of the first prototype WEC. CorPower Ocean have planned a range of innovative projects to develop their technology in the coming years, whilst installing additional WECs to form an array. Some examples are the UMACK project [41], which involves the design and testing of a novel anchor and mooring system, the SeaSnake project [42], which is developing solutions for dynamic cables within ocean energy projects and the COMPACT project, which is investigating and testing the use of novel composite materials for internal WEC components such as cylinder barrels. This LCA study has been conducted on the first full scale WEC prototype and, in the future, there will be scope for refining all aspects of this analysis and further reducing lifecycle impacts.

5. Conclusions

This study has presented a full lifecycle assessment of a 10MW array of CorPower Ocean Wave Energy Converters, deployed in Aguçadora, Portugal, over 19 impact categories. The outputs of this LCA show the CPO WEC to perform similarly to other offshore renewable energy technologies, and to consistently outperform fossil-fuelled thermal generation over six impact categories, including those representing embodied carbon and energy. It should be noted that the results shown in this study may not be directly comparable for other WEC types, even when deployed in the same location, as wave energy technologies can differ greatly in terms of material composition, marine operation requirements, and generation and failure modes. It is highlighted that comparison between technologies is useful for context, but care should be taken to ensure a consistent scope of analysis when directly comparing LCA studies.

A Monte Carlo uncertainty analysis has allowed these results to be presented in ranges covering a 95% confidence interval, accounting for uncertainties implicit within the Ecoinvent database. Further sensitivity analysis indicates that the results are most sensitive to the annual energy production and O&M fuel burn.

The range of different methods for representing marine operations within LCA studies in the literature has been discussed. Further work needs to be done to be able to comprehensively represent offshore renewable energy components and operations within LCA software and databases. As more wave energy devices are deployed and the technology is successfully demonstrated, LCA input assumptions representing array infrastructure, marine operations and energy production will be able to be validated and refined.

LCA results are particularly meaningful at this early stage in technology development for wave energy, as they can inform design considerations and identify hotspots of particular impacts to be designed out of future iterations of the technology.

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Appendix A. Additional figures

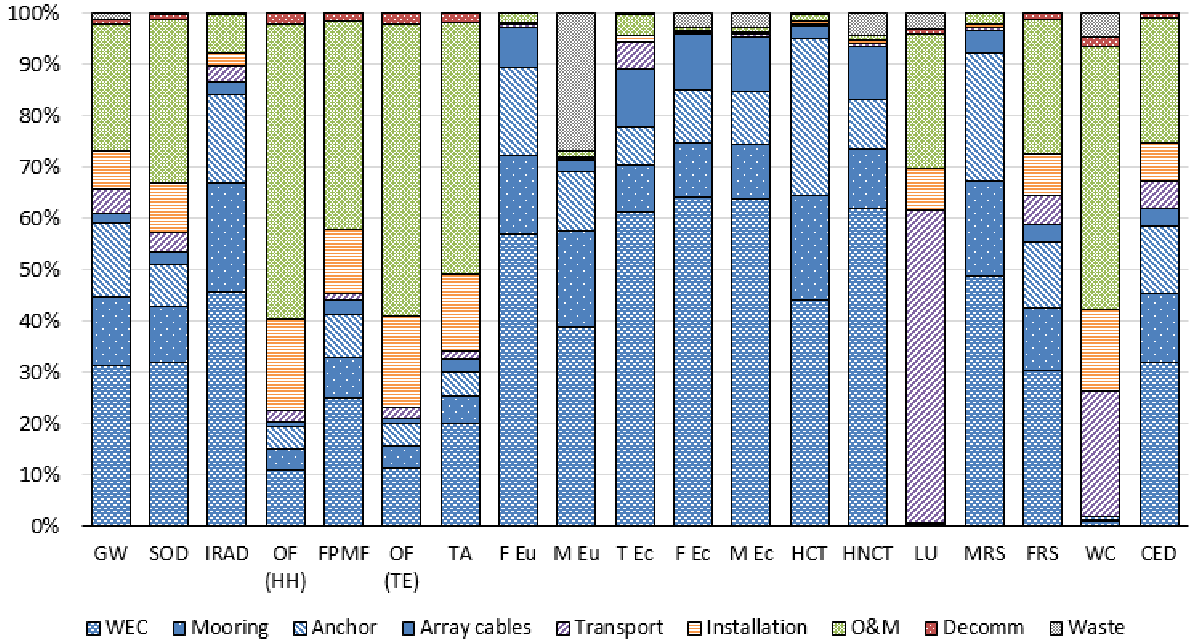

Figure A.1 – Life cycle impact assessment results proportion by life cycle stage, O&M scenario 2

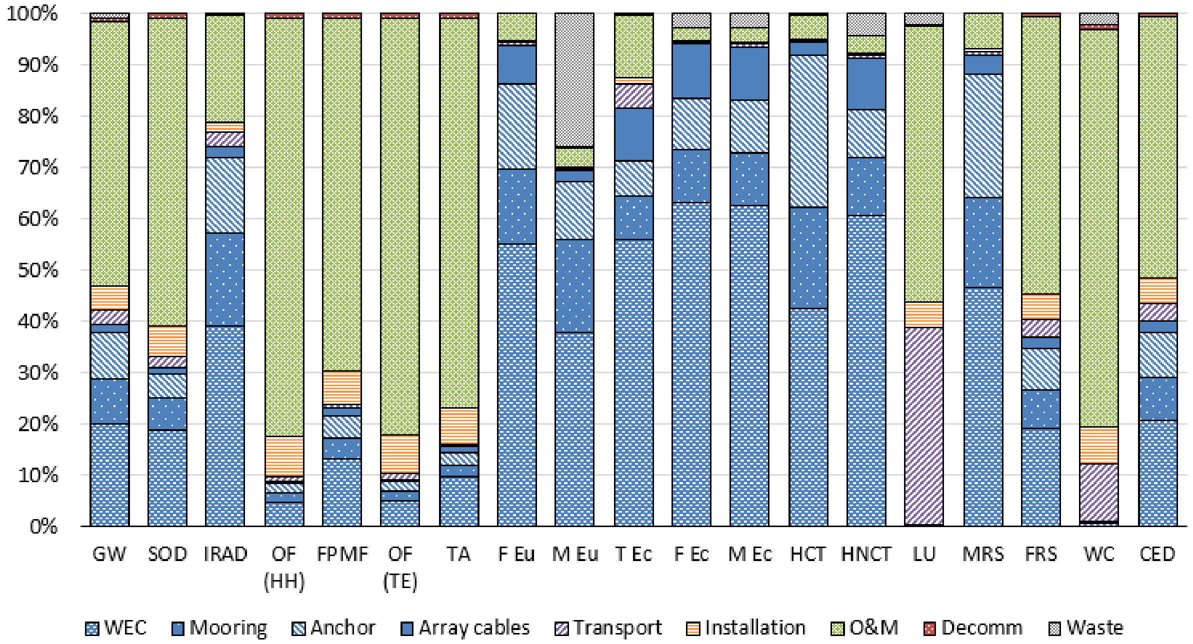

Figure A.2 – Life cycle impact assessment results proportion by life cycle stage, O&M scenario 3

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