Life cycle assessment of a lift-based wave energy converter

Paula Bastos, Fiona Devoy-McAuliffe, Abel Arredondo-Galeana, Julia Fernandez Chozas, Paul Lamont-Kane, and Pedro A. Vinagre

Abstract— **Evaluating the overall advantages of a new configuration of wave energy technologies goes beyond techno-economic performance and reliability. As the marine renewable energy sector expands, it is important to ensure that the technologies prove to be environmentally friendly alternatives. A cradle-to-grave life cycle assessment was conducted on a novel energy converter (LiftWEC) to evaluate its potential cumulative impacts. The global warming potential was characterized, indicating that the configuration could be a potential low-carbon alternative compared with many wave energy devices and conventional forms of energy production. The carbon and energy payback time were also analysed to estimate the time required to offset the carbon emission and demanded energy. This assessment highlighted the impact of the characteristic energy mix profile and energy production potential of the deployment region on the results obtained. The study also analysed alternative scenarios of materials, deployment locations, and end-of-life strategies to identify potential improvement opportunities to reduce the environmental impacts.**

Keywords — **life cycle assessment, carbon footprint, wave energy, marine energy.**

I. INTRODUCTION

THE transition to a low-carbon economy has fostered the development of various alternative means of energy production, including marine renewable energy (MRE). However, despite years of research and development, the industry still faces challenges in making wave energy commercially viable. Whilst it remains possible that successful wave energy technologies exist within the traditional research trend, it is also appropriate to explore alternative approaches. In this context the LiftWEC system has been proposed as a promising configuration of a lift-based wave energy converter (WEC) [1] [2] [3] [4] [5]. The LiftWEC device, which utilizes two hydrofoils that rotate in a single direction aligned orthogonally to the direction of wave propagation, offers a potential solution to overcome the techno-economic limitations of conventional wave energy technologies [6]. However, to fully comprehend the benefits of these emerging technologies, it is crucial to also investigate the carbon and energy footprint throughout the entire life cycle to ensure that these technologies are not only technically and economically viable but also an environmentally sustainable alternative to traditional energy sources.

In contrast to offshore wind energy, which is a more established technology of MRE, there are currently fewer studies into the environmental effects of deploying a WEC. Aiming to contribute to decision-making regarding the least carbon and energy-intensive design choices of the LiftWEC configuration, this study details the methodology used for implementing a life cycle assessment (LCA) and computing the energy and carbon flows from a theoretical large-scale development. LCA is a widely recognized methodology to evaluate environmental impacts by considering the technology's resource requirements and operational performance over its entire life cycle, covering all life cycle stages from cradle-to-grave.

A brief description of the LiftWEC system and its main characteristics are presented in Section II, followed by an outline of the methodology used for the life cycle assessment in Section III. Data collected for each stage from manufacture to disposal is presented in Section IV. This framework is subsequently used to analyse the carbon

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and energy footprint of the base scenario in Section V, as well as a range of alternative scenarios varying the selected materials and operations, which are presented in Section VI. Through comparison with other MRE technologies, it is possible to evaluate the potential of LiftWEC as an alternative for renewable energy generation and suggest potential improvements, as discussed in Section VII. Finally, in Section VII conclusions are drawn on the preliminary results of the proposed LiftWEC configuration.

II. System Description

The EU H2020 LiftWEC project developed a novel type of WEC which uses hydrodynamic lift forces to incite device motion and extract wave energy using rotating hydrofoils. An outline of the operational mechanisms employed by the device can be found in [7]. The system can be divided into 5 main sub-systems: rotor, stator, spar-buoy structure, mooring system, and electrical cables.

The rotor subsystem is composed mainly of two hydrofoils that terminate within bearing elements set within the circular endplates. The stator comprises two nacelle structures which support the rotor section and house two direct driver generators, along with other smaller components, such as ancillary power electronics and braking mechanisms. The spar structure consists of the structural station-keeping elements. In the lower portion of the structure, the tube connecting both nacelles is used as a ballast tube, and to react to the rotor torque generated during operation. The set rotor-stator-spar floater is indicated in Fig. 1 . The structure is held in place by single-point twin-line yoked mooring which sinks to a 3-point catenary line mooring system, anchored to the seabed using 2 drag anchors per line Fig. 2.

The proposed layout considers two rows of staggered devices. The electrical system consists of inter-array cables that connect devices to an offshore substation, and an export cable connecting the offshore substation to the grid.

The key parameters assumed for this study are summarized in Table I.

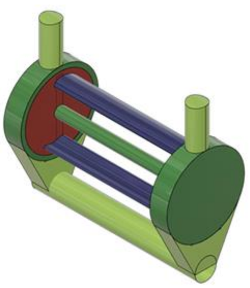

Fig. 1 Spar LiftWEC configuration: rotor-stator-spar floater set

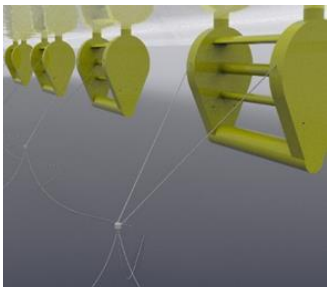

Fig. 2 Spar LiftWEC configuration: mooring system

III. Life Cycle Assessment

LCA is a method to assess the environmental aspects and potential cumulative impacts of a system over space and time throughout its life cycle, helping in the decision-making process regarding system design.

The methodology used in this work complies with the international standards ISO 14040 [8] and ISO 14044 [9], which specifies the general framework, principles, and requirements for conducting and reporting this type of assessment, comprising four main stages: goal and scope definition, inventory analysis, life cycle impact assessment (LCIA), and interpretation.

The main purpose of this analysis is to assess the environmental impacts of a potential 100MW array deployment in France. The functional unit (FU) is defined as 1 kWh of electricity delivered to the French electricity network from the array. According to the preliminary studies carried out by [10], one device is estimated to produce 2491 MWh/year, over the entire lifespan (Table I).

The system boundary encompasses all life cycle stages from cradle to grave comprising the production of components, their assembly and transportation to the installation site, operation and maintenance (O&M), and finally decommissioning and waste disposal strategies.

Regarding the physical boundaries the substation and all parts of the onshore electricity grid are outside the scope of this analysis. Additionally, no credit is provided for recycling within the project disposal scenario to allow comparison to other results obtained in the literature, although a sensitivity analysis is carried out to investigate the impact of this process on the established boundaries.

To allow comparison with other MRE technologies and traditional means of electricity generation, carbon dioxide equivalent emissions per produced electricity (g CO_2 eq/kWh) were defined as the main unit for the study.

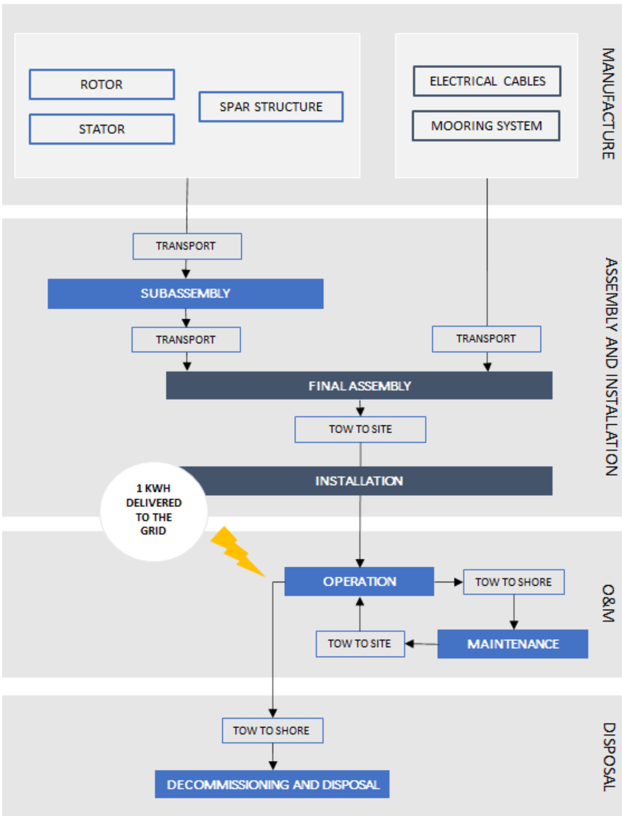

Fig. 3 Flowchart of the life cycle assessment

SimaPro 8 was the software used to model the system, with Life Cycle Inventory (LCI) data sourced from the Ecoinvent database (version 3.5). The impact assessment is achieved by translating the environmental loads from the inventory results into midpoint impact categories using ReCiPe 2016 Midpoint method [11]. To provide a simplified and understandable representation of the impacts, the midpoints were aggregated to endpoints, also known as damage factors, providing a summary of the overall environmental performance. Although this LCA focuses on climate change, an energy input assessment was carried out using the cumulative energy demand (CED) to calculate the total direct and indirect amount of energy consumed throughout the life cycle.

IV. DATA COLLECTION

Foreground or primary data were collected from the LiftWEC project design team, material experts and engineers. All background or secondary data were ultimately derived from the Ecoinvent database (v.3.5). Since the Ecoinvent database does not contain all inventory information, some materials and manufacturing processes were modelled according to data sourced from literature, suppliers' catalogues, and experts' knowledge.

Given the expected small contribution of some electronic and electrical systems to the overall embodied carbon and considering their complexity, it was more appropriate to simplify this stage to avoid time consumption. Thus, a cut-off criterion of 1% was applied throughout the life cycle to exclude minor impacts and help set boundaries for the total system inventory [12]. As the main product of WECs is only electricity, there is no need to assign impacts to co-products (e.g. heat), which simplifies the analysis.

TABLE I
KEY PARAMETERS OF LIFTWEC

Parameter	Quantity	Unit
Location	Bay of Audierne, FR	-
# WECs	80	-
# WECs per row	40	-
Distance between rows	400	m
Distance between WECs	360	m
Hydrofoil span	30	m
Wave power average	36	kW/m
Single WEC rated power	1250	kW
Total array capacity	100	MW
Energy loss row after row	2%	-
Inter-array cables voltage	10	kV
Export cables voltage	132	kV
Annual energy production	198	GWh/year
Capacity factor	22.51%	-
Lifetime	25	years
Distance from shore	10	km
Distance from assembly port	50	km
Distance from the service port	20	km
Water depth	80	m
Lifetime	25	years

A. *Materials and manufacturing*

The initial phase bounded by the system starts with the processing of raw materials, which is followed by the manufacturing phase where materials are moulded and shaped to produce sub-components of the device.

The rotor subsystem is composed mainly of composite material, such as fibre glass (hydrofoil), while offshore steel is the main material of other components. Steel alloy is the main material used for stator components and spar-buoy structural elements. Additionally, the ballast tube is partially filled with concrete.

The mooring lines are mainly fabricated by fibre ropes and the prefabricated anchors are made of steel. At this stage of the project, the expected station-keeping loads and consequently the specification of the anchors have not yet been defined. Thus, taking a reference WEC [13] and considering some margin due characteristics of LiftWEC, the drag embedment anchors 5te [14] were chosen to compose this system.

The substation and all parts of the onshore electricity network and grid integration are outside the scope of this analysis. Based on [15] copper cables were assumed with 22.2 kg/m and 65.2 kg/m for 10kV and 132 kV cables respectively. The material composition was taken as a reference from [16].

An estimate of the mass breakdown indicates that the spar structure composes the largest part of the total mass (82%), followed by the stator (12%), rotor (4%), mooring system (1%) and electrical cables (1%).

Concerning the type of material considered for the mentioned sub-systems, including the prefabricated components, the following distribution is estimated: concrete (72.94%); low-alloy steel (25.27%); fibre glass (0.92%); stainless steel (0.26%); other polymers (0.21%); lead (0.17%); copper (0.14%); other materials (0.09%).

It is assumed that steel passes through the processes of machining and welding before being painted to avoid biofouling and corrosion. The energy consumption for the heavy machining and painting processes was based on [17]. Calculations for the welding process were completed assuming the need for 4,35 kg of welded steel per meter [18] To estimate the volume of coating required for the main structures, 0.2 mm, 0.1 mm, and 0.1 mm thickness were assumed for the primary, intermediate, and anti-fouling treatment, respectively.

B. *Assembly and installation*

The assembly phase involves the road and sea transport of each subcomponent to a fabrication yard in France from the assumed manufacturing locations: steel panels and shafts (Germany), hydrofoils and anchors (UK), mooring lines (Belgium), generators and other main equipment (Finland), electrical cables (China), structural subcomponents and concrete ballast (France). After final assembly, specialized vessels are required to prepare the seabed, install moorings, tow and install the device. The processes to prepare the site installation were not considered in this analysis given their relatively small impacts on the results. The installation strategy of the devices defined in [19] served as input for this analysis, providing vessel types, fuel consumption and time spent for a certain baseline scenario of weather constraints and task duration.

The summary of the vessels considered for this stage is detailed in TABLE II. By scaling Ecoinvent data for a freight ship to match the fuel consumption of each type of vessel, as suggested by [20], it is possible to achieve the correspondent payload of each operation, where 1 end corresponds to 0,0028 litres of fuel. The payload (tkm), is a metric used to express the total work of transporting 1 tonne of cargo over 1 km.

TABLE II
SUMMARY OF VESSELS AT INSTALLATIONS TASKS

Vessel	Average consumption (t/h)	Sets	Tasks
2 tugs + 2 divers	1	3	Devices: tow to site and connection to mooring lines.
AHTV	0.7	3	Anchors and mooring lines: installation.
CLV	1.8	2	Electrical cables: installation.
AHTV + 2 tugs	2.8	1	Offshore substation: tow to site and connection to mooring lines.
AHTV	1.4	1	Offshore substation: anchors and mooring lines installation.

C. *Operation and maintenance*

The LiftWEC configuration enables the implementation of a return-to-base (RTB) strategy for maintenance campaigns, both preventive and corrective. This approach assumes that large repairs are carried out at the port, avoiding the use of large offshore vessels and minimizing risks, stoppages, expenditures and emissions.

The O&M analysis conducted by [19] considered failure rates and weather conditions to estimate the total offshore hours required during the 25-year lifetime of the project by the necessary resources, which include a set of two tugs and two support divers. By the failure rate evaluation, no significant requirement for component replacement was identified. An estimate of the lubricating oil change is considered as 15 t per MW of device capacity [21].

TABLE III
SUMMARY OF VESSELS AT MAINTENANCE TASKS

Vessel	Average consumption (t/h)	Sets	Tasks
2 tugs + 2 divers	1	1	Corrective and preventive maintenance.

D. *Decommissioning and disposal*

Decommissioning and disposal are crucial aspects of the life cycle assessment as they mark the end-of-life (EoL) phase of the project and determine its management approach. The chosen strategy can significantly reduce the overall environmental impact by offsetting the effects linked to earlier stages. In this analysis, decommissioning of LiftWEC mainly includes transport from the operation site to the yard, where disposal actions will follow. According to the assessment conducted by [10], the cost of the decommissioning phase represents about 77% of the installation expenditures. Assuming a contingency margin, the decommissioning phase was considered as 85% of the payload of the installation phase.

The disposal scenario considers three different EoL approaches: recycling, reusing, and landfilling. While reuse implies using the same product over again, recycling alludes to the transformation processes of disposal residues to a useful resource, both addressing the reduction of waste of potentially useful material. The assumed EoL scenarios are indicated in TABLE IV.

TABLE IV
ASSUMPTIONS FOR END-OF-LIFE SCENARIOS

Parameter	Quantity
Steel	Recycle 85% Landfill 15%
Copper	Recycle 100%
Other metals	Recycle 90% Landfill 10%
Plastic	Recycle 80% Landfill 20%
Concrete	Re-crush and reuse 90% Landfill 10%
Other materials	Landfill 100%

Although the recycling cut-off approach used in this study does not fully reflect the role of recycled materials beyond the system boundary, it was considered to allow a closer comparison with other studies. As a result, recycling in this study does not directly translate to impact reduction through the use of virgin materials. Instead, it focuses on minimizing net energy and carbon flows by reducing the quantity of waste sent to landfills. In terms of the concrete's EoL, it is assumed that the material can be reused, effectively avoiding the need for new production and providing a positive impact credit. The transportation of concrete to the final disposal site was considered to have minimal significance compared to other stages of the life cycle and, as a result, it was excluded from the analysis.

V. RESULTS

A. *Life cycle impact assessment*

The LCI produced a list of around 1700 substances consumed or emitted throughout the life cycle. TABLE V shows the total life cycle emissions of all six Kyoto greenhouse gas (GHG) emissions: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons and perfluorocarbons (HFCs and PFCs respectively) and sulphur hexafluoride (SF_6).

A cut-off criterion of 1% was applied aiming to visualize the most relevant contributors. Special attention was given to the global warming potential (GWP) since ocean energy systems are being broadly considered a contributor to mitigating climate change. Nevertheless, an overview of all 18 impacts from both ReCiPe and CED impact assessment methods is summarized in TABLE VI.

TABLE V
EMISSIONS OF THE KYOTO PROTOCOL GHGS

Gas	Emissions (g/kWh)	GWP (g CO_2 eq/kWh)
Carbon dioxide (CO_2)	32.17	32.17
Methane (CH_4)	7.31E-03	2.61
Nitrous oxide (N_2O)	1.39E-07	0.55
Sulphur hexafluoride (SF_6)	1.66E-06	3.90E-02
Hydrofluorocarbons (HFC)	7.90E-02	1.45E-02
Perfluorocarbons (PFC)	9.54E-07	1.10E-02

TABLE VI
RESULTS OF LCIA AND CED CALCULATION WITH ACRONYMS

Impact Category	Emissions	Unit/kWh
Global warming (GWP)	32.17	g CO_2 eq
Stratospheric ozone depletion (SOD)	2.57E-05	g CFC11 eq
Ionizing radiation (IR)	3.33E-01	Bq Co60 eq
Ozone formation human health (OF Hum)	1.32E-01	g NO_x eq
Fine particulate matter formation (FPMF)	9.37E-02	g PM2.5 eq
Ozone formation terrestrial ecosystems (OF Eco)	1.37E-01	g NO_x eq
Terrestrial acidification (TA)	1.83E-01	g SO_2 eq
Freshwater eutrophication (F Eut)	1.89E-03	g P eq
Marine eutrophication (M Eut)	1.13E-03	g N eq
Terrestrial ecotoxicity (T Etox)	524.19	g 1.4-DCB
Freshwater ecotoxicity (F Etox)	9.62E-02	g 1.4-DCB
Marine ecotoxicity (M Etox)	3.77E-01	g 1.4-DCB
Human carcinogenic toxicity (HTcar)	4.64	g 1.4-DCB
Human non-carcinogenic toxicity (HTnoncar)	26.47	g 1.4-DCB
Land use (LU)	8.11E-01	m^2a crop eq
Mineral resource scarcity (MRS)	1.34	g Cu eq
Fossil resource scarcity (FRS)	8.55	g oil eq
Water consumption (WC)	2.25E-01	m^3
Cumulative energy demand (CED)	515.45	kJ

The GWP per phase is indicated in Fig. 4 and reveals that impacts related to assembly and installation, and O&M hold a lower impact on the overall results, (3% and 6% respectively).

Manufacturing presents the biggest effect, contributing to approximately 31.18 g CO_2 eq/kWh to the overall GWP results, including transport across the fabrication site to the yard. The fabrication of the stator and spar structure accounts for 34% each of the total manufacturing impact (approx. 10.8 g CO_2 eq/kWh) being the most significant contributors. These impacts reflect the carbon and energy intensity from the production of heavier materials such as steel alloy and concrete.

The results of the impact assessment at the endpoint level are shown in Fig. 5 where emissions are related to their damage to the three areas of protection: Human Health, Ecosystems Quality, and Natural Resources. These three main areas represent the broader consequences of the midpoint indicators, as mentioned in Section III. The contribution of each life cycle stage is fairly even across the last two areas, while for Human Health, the phases of manufacturing and disposal indicate slight variation.

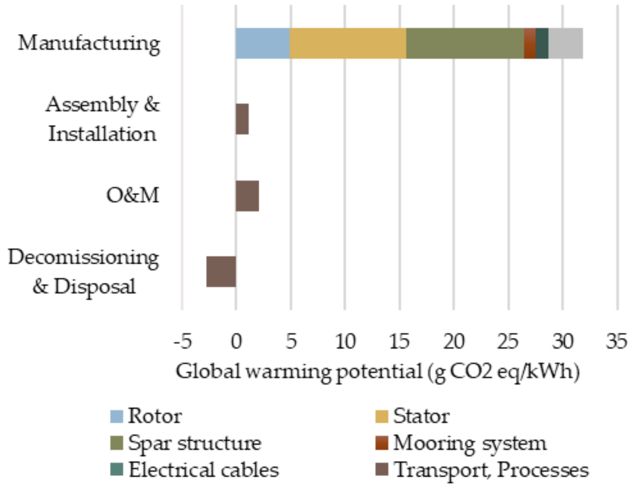

Fig. 4 Global warming potential results per phase

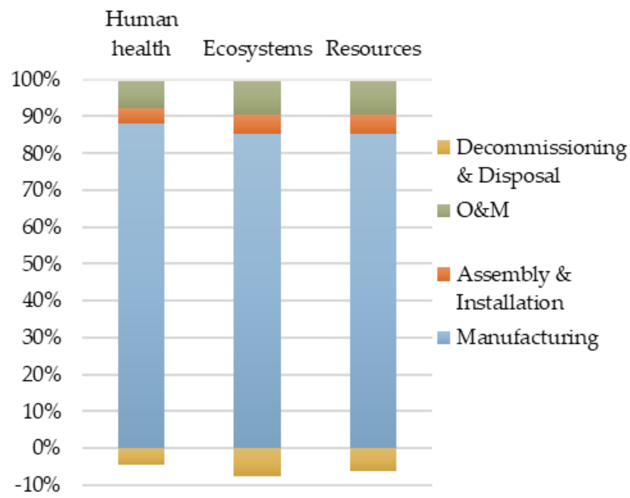

Fig. 5 Results of ReCiPe impact assessment method applied at the endpoint level

In Fig. 6 the CED of 515 kJ/kWh, computed in TABLE VI, is split according to five classes of primary energy carriers: fossil, nuclear, hydro, biomass, and others (wind, solar and geothermal), reflecting the final energy demand according to location-specific electricity mixes, based on the origin where each component was produced. The preponderance of non-renewable energies is notable, especially energy from fossil fuels which account for 73% of the total demand for each kWh of electricity generated.

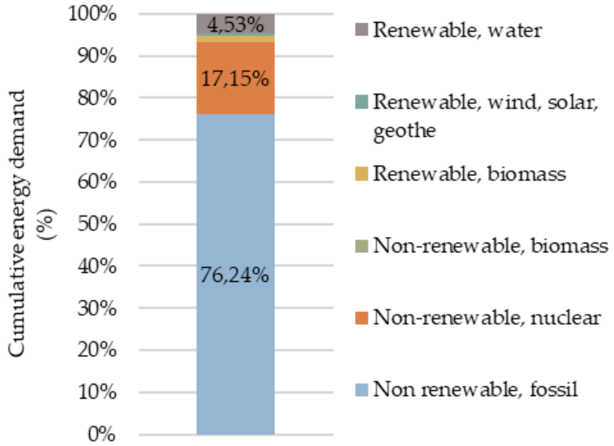

Fig. 6 Cumulative energy demand per energy source

B. *Carbon and energy payback time*

Energy and carbon payback time (EPT and CPT, respectively) are important indicators for renewable resources. While CPT measures the period required for LiftWEC to offset the carbon emissions generated along the lifetime (1), the EPT represents the amount of time that the system needs to run to produce the amount of energy equivalent to the primary energy consumed throughout its lifetime (2).

$$CPT = \frac{Total\ CO_2eq\ emissions}{Annual\ CO_2eq\ avoided} \quad (1)$$

$$EPT = \frac{Life\ cycle\ embodied\ energy}{Annual\ energy\ production} \quad (2)$$

The annual energy production (AEP) is estimated including a percentual energy loss and disturbance due to the placements of one row in front of the another [36]. Considering the energy loss indicated in TABLE I, the AEP. of the proposed wave energy farm is estimated at around 198 GWh.

It was assumed that the electricity offset by the device will be the average of the French grid, which holds 85% of nuclear contribution and a CO_2 intensity of 87.32 g eq CO_2/kWh (Ecoinvent database). Due to this lower emission characteristic of the French grid, when compared to the avoided emissions, the CPT was estimated about 14.5 years, indicating to be longer than what is usually found in the literature (around 1 to 2.5 years). Considering the energy intensity of 515 kJ/kWh, the estimated EPT corresponds to approximately 3.6 years.

VI. ALTERNATIVE SCENARIOS

A range of three alternative scenarios was considered to investigate the project's sensitivity to specific inputs and, consequently, to assess potential improvements in the life cycle environmental impact. Results presented in this section are indicative and interpretation needs further study regarding the sensitivity of each parameter variation, given uncertainties arising from some approximations made in this early stage of LiftWEC.

A. *Materials*

With manufacturing being the main driver of the overall impact, this section is addressed to evaluate the potential of reducing the required material quantities by replacing the steel used for the structure with different materials with lower density. It is worth mentioning that this analysis represents a rough estimate, not considering possible variations on design that may be required in terms of structural resistance or other technical aspects such as failure rates. The assumptions taken for this analysis were based on the materials assessment carried out by [22] and are detailed in TABLE VII. As transportation is expressed by the payload distance (tkm), it may also reflect a slight reduction in its impact due to mass reduction. All other considerations made for the baseline scenario remain unmodified.

TABLE VII
ASSUMPTIONS FOR ALTERNATIVE SCENARIO (MATERIAL)

Parameter	Baseline scenario	Alternative scenarios
Material	Steel (8050 kg/m3)	Aluminium alloy (2710 kg/m3); Carbon fibre (1750 kg/m3)

Despite the material reduction, the GWP suffers a significant increase compared to the baseline scenario, estimated as 58.18 and 259.27 g CO_2 eq/kWh for aluminium alloy and carbon fibre, respectively. Analysing further the results it was noticed that the fabrication of these two alternative materials is considerably more carbon- and energy-intensive than steel, therefore not compensated by the reduction in their amounts.

When considering composite materials, due to the nature of thermosetting resin, which is produced by an irreversible hardening process of a viscous fluid, the impact can be even greater, as separation and recycling processes are expensive and require many energy-intensive processes, being in many cases opted to be directed to landfill.

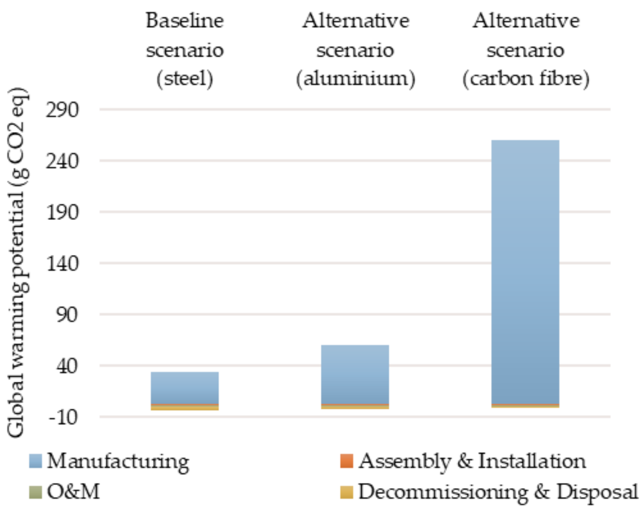

Fig. 7 GWP results for alternative scenarios (material)

B. *Recyclability and circularity*

The discussion on EoL is a critical issue to be addressed in the framework of value chain processes and the technical processes of MRE projects. To provide an overview of the disposal role of the LiftWEC, a scenario without recyclability and reusing actions was considered, as indicated in TABLE VIII.

TABLE VIII
ASSUMPTIONS FOR ALTERNATIVE SCENARIO (MATERIAL)

Parameter	Baseline scenario	Alternative scenarios
Recyclability	85% steel, 100% copper; 90% other metals; 80% plastic	100% landfill
Circularity	90% concrete	100% landfill

Assuming this alternative scenario, the estimated GWP is estimated as 64.34 g CO_2 eq/kWh. This value represents almost the double of the result obtained from the base case, highlighting the important role that the disposal strategy plays in the overall life cycle. It is important to mention that in this model the metals that will be recycled do not count as avoided material (reuse), but as avoided emissions in the process of waste treatment (landfill).

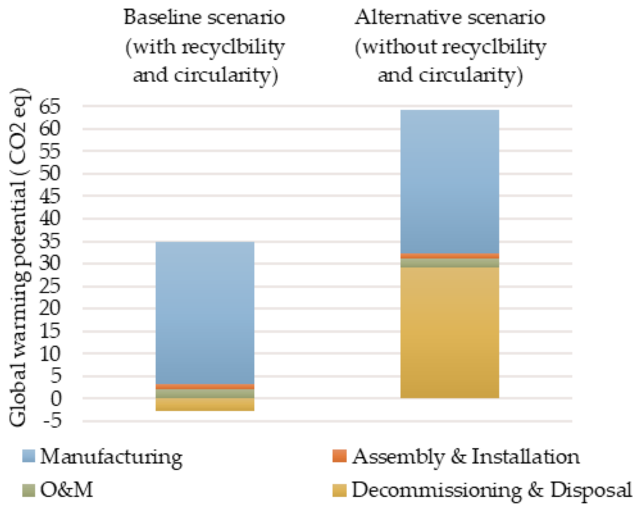

Fig. 8 GWP results for alternative scenarios (recyclability and circularity)

C. *Site deployment*

The analysis was performed for two different deployment locations: in the offshore area of Lisbon (Portugal) and the coastal area of Bellmulet (Ireland). For this approach, the same assumptions of manufacturing (material, process, and location), assembly site and O&M port are considered, varying just the distance between these and the installation site.

Despite the increased distance between the assembly yard in France to the installation site, the project indicates a lower GWP impact per energy unit. Since the contribution from the manufacturing phase is equally high, but the potential energy production rises due to higher local wave energy resources (estimated 6% higher for the Portuguese site and 102% higher for the Irish site), it is found a reduction to 30.48 and 16.11 g CO_2 eq/kWh for Portugal and Ireland, respectively.

It is worth highlighting that it reflects an early-stage evaluation and that impacts on the demand for materials due to varying structural requirements in the context of changing environmental loads were not assessed and therefore need to be covered in future studies. On the other hand, choosing a nearby supply chain as well as service ports could also minimise impacts.

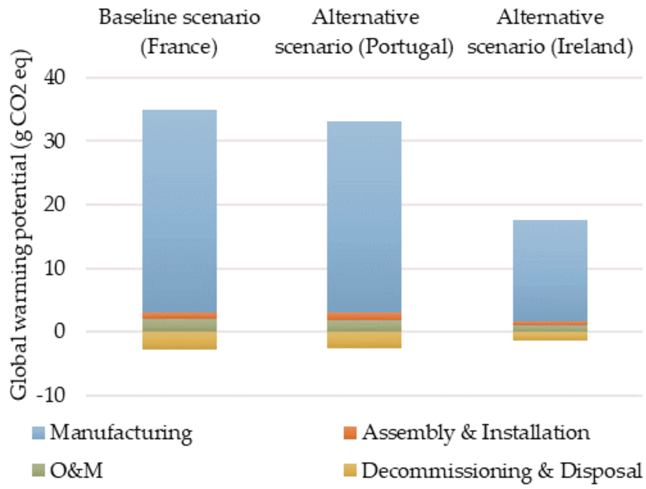

Fig. 9 GWP results for alternative scenarios (site deployment)

For this approach, the same assumptions of manufacturing are considered, as the assembly site. As the installation and O&M phases express a small share of total carbon intensity, the impact caused by the distances travelled during these actions is not substantial overall.

Furthermore, with manufacturing playing a substantial role in the final impact, in this case, the variation in energy production profiles is the driver of the g CO_2/kW ratios, i.e. the same amount of material is distributed per higher electricity delivered to the grid.

Considering the energy production profile in these two alternative sites with increased load from fossil sources (higher GHG emissions), the CPT reduces to values more aligned with previous studies, indicating 2.2 and 0.61 years for Portugal and Ireland respectively. These results illustrate the additional benefit of the device in avoiding emissions when allocated in scenarios with significant environmental burdens.

VII. DISCUSSION

The lack of more accurate data on LCAs conducted in the field of wave energy poses a challenge in determining definitive conclusions on the viability of wave energy based on the existing literature. Furthermore, for a valid comparison between resultant impacts, it is essential that the studies use the same characterization factors and methodology. Nevertheless, a comparative analysis of the results was conducted in light of the current literature on other ocean energy sources and conventional energy production methods.

A. *Comparison with other marine renewable energy devices*

A study conducted by [23], including fifteen tidal and wave energy technologies, concluded that the GWP may range from 15 g CO_2 eq/kWh for enclosed-tip devices to 105 g CO_2 eq/kWh for point absorber and rotating mass devices, with an average of 53±29 g CO_2 eq/kWh for all technologies. Despite being the same type of energy production, the indicated analyses cover different types of technologies and configurations and, considering the eventual variations in the methodology and premises assumed in these different assessments, it can be expected that this may justify the wide range presented by the results obtained presently.

Considering different types and configurations of WECs, the LCA results are consistent with the range found in the literature, as presented in TABLE IX (13 - 123 CO_2 eq/kWh). As indicated in Fig. 10, LiftWEC shows GWP impact below the threshold of 25% of the average results obtained across the ten different reference technologies [12] [20] [24] [25] [26] [27] [28] [29]. Additionally, most studies agree that the manufacturing phase accounts for the most substantial contribution to the net impact, pointing also to the critical role played by the decommissioning and disposal phase. In contrast to the offshore wind energy sector, a literature review [30] [31]and [32] indicates that the carbon footprint of wind energy devices can range from 11 to 23 g CO_2 eq/kWh, depending on their adopted configuration and technologies. Nevertheless, it is important to acknowledge the advanced level of maturity that this type of technology has achieved, which has allowed for its continuous enhancement over time.

TABLE IX
CARBON FOOTPRINT AND EMBODIED ENERGY ESTIMATES FOR DIFFERENT MRE DEVICES

Device #	Technology	Carbon intensity (g CO_2 eq/kWh)	Energy intensity (kJ/kWh)
#1 LiftWEC	Lift forces	32	515
#2 Wave Dragon	Overtopping	13	174
#3 Seabased Norway	Point absorber	37	720
#4 Seabased Sweden	Point absorber	123	1760
#5 Oyster	Oscillating wave surge	25	236
#6 Wave Star	Point absorber	47	536
#7 Buoy-Rope-Drum	Point absorber	89	387
#8 Pelamis	Attenuator	35	493
#9 Overtopping Breakwater	Overtopping	37	-
#10 MegaRoller	Oscillating wave surge	33	432

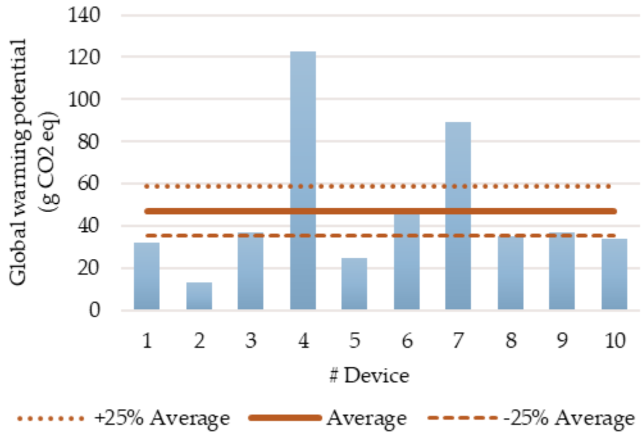

Fig. 10 Comparison with other WEC devices

B. Comparison with other types of energy generation

Regarding other sources of electricity generation, based on data provided by [33] and [34], the LiftWEC technology presents itself as a promising low-carbon alternative, particularly when compared to traditional power generation methods, and it also demonstrates comparable results to solar photovoltaic technologies. Fig. 11 provides a summary of the carbon footprint associated with producing 1 kWh of electricity through various other means of production.

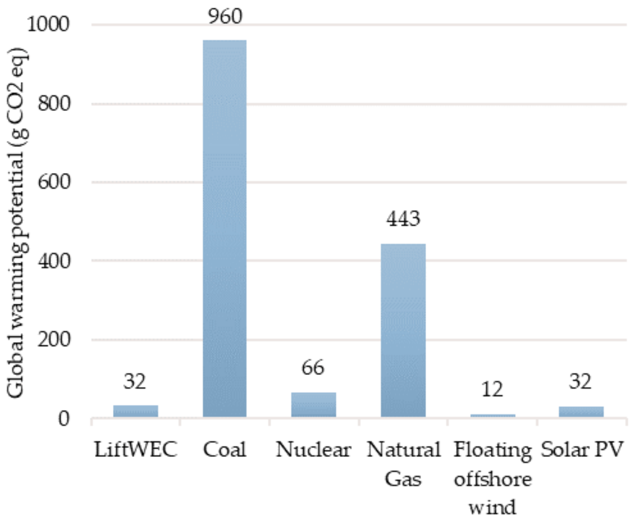

Fig. 11 Comparison with other forms of energy production

C. Potential for future improvement

The early phase of MRE development is crucial for the technology's market entry. During this phase, environmental risks, costs, and impacts, including those related to GHG emissions and biodiversity, are at their highest. Addressing concerns such as carbon footprint and energy intensity at the beginning of the development process is essential to identify critical points, tackle opportunities for improvement and generate market interest.

The identification of materials, processes and life cycle stages that contribute to global warming and energy consumption showed that manufacturing is responsible for over 80% of LiftWEC's estimated GWP impact.

The studies carried out within [35] introduce the potential for further optimization of the structure, by reducing the steel mass and increasing the amount of ballast concrete in counterpart. Through a rough estimate of 30% steel reduction and 30% concrete addition, a potential for around 19% GWP reduction is estimated. This meaningful variation stands for the assumption of a 90% reuse rate of concrete, implying credits towards the total impact. Additionally, a more recent study conducted by [36], considers the potential of LiftWEC to increase the annual energy production by up to 70%, based on more detailed numerical models. Considering the system efficiency and WECs availability, the GWP impact can be reduced roughly to 21g CO_2 eq.

Another example of a potential improvement opportunity to reduce these environmental impacts could lie in further research into the application of lighter and less impactful materials, such as thermoplastic or flax fibre composite. The thermoplastic resin combines thermal welding techniques and, since it offers a higher potential for recyclability, has been considered for application in wind blades [37]. On the other hand, studies related to bio-based materials, such as flax fibre, indicate the possibility of reduced use of the material compared to steel, with less impact at the manufacturing stage, enabling a better EoL strategy with the re-use of the fibre and similar or lower costs than conventional composite materials [33].

To understand the realistic impacts at a commercial scale, a future study could also consider LiftWEC's implementation at a site with increased energy production potential, which could reduce environmental impacts by about 50% per kWh of electricity produced, for example in Ireland, considering the same technical and operational assumptions taken in the base case.

VIII. Conclusion

This preliminary LCA was performed primarily to assess the embodied carbon and energy of the proposed LiftWEC farm and to comprehend the key factors that may influence the potential emissions, by characterizing the material and process flows, including the main stages from cradle to grave.

The resulting carbon intensity of 32 g CO_2 eq/kWh and energy intensity of 515 kJ/kWh are generally comparable with previous studies for wave technologies and are very low compared to traditional means of power generation. This analysis is in line with previous studies on MRE technologies in concluding that the main environmental impacts are due to material use and manufacturing processes, while assembly and installation and O&M show minor impacts. Nevertheless, the types of materials considered hold considerable potential for recycling and reusing, showing the important role that a proper EoL strategy plays in the final impact outcome. From a structural optimisation perspective, by decreasing steel and increasing concrete demand, a reduction of almost 19% can be observed, mainly due to the assumed premise of reusing 90% of the concrete.

The LiftWEC device showed a lower carbon intensity in comparison to the French grid, resulting in approximately 60% less impact on GWP while generating the same amount of electricity. However, due to the primarily nuclear-based energy mix of France, the CPT, which is associated with the emissions avoided, is estimated to be around 14.5 years. Conversely, when evaluated in different locations, such as Portugal and Ireland, the CPT decreases significantly to 2.2 years and 7.4 months, respectively. This disparity highlights the effect of the distinct energy mix profiles in each region (primarily from fossil fuel sources in Portugal and Ireland), and the potential reduction of emissions rate resulting from the local energy production capacity, which is notably higher in Ireland. The EPT that is projected to be around 3.5 years for the French site and decreases to 3.4 and 1.8 for Portugal and Ireland respectively, as the energy production rises.

The study also assessed the impact of the use of light materials instead of steel. The results indicated, however, that the manufacturing phase of these alternative materials is substantially more carbon and energy-intensive, and thus, the reduction in their quantities is not sufficient to compensate for this impact. The use of composite materials can result in an even greater impact, as their separation and recycling processes are expensive and require energy-intensive operations, often leading to landfill disposal choices. Some recent studies have been investigating the possibility of using more recyclable materials, as such thermoplastic and bio-based composite materials, which have a lower manufacturing impact and allow better management at their EoL. This type of trade-off between materials could be a potential eco-design initiative in the MRE field, however, further studies need to be conducted to analyse the overall impact on design, performance, and environment.

Further investigations concerning the required improvement of the device in terms of load, fatigue, and failures should be done for harsher environments, as well as maintenance strategies, as well regarding materials manufacturing and EoL processes, and associated costs.

The data quality in this preliminary study was constrained by the lack of input data, mostly not yet available during this low development phase (currently around TRL3-4). Some assumptions were made from previously published studies and these secondary data estimates can be misleading and propagate undetected throughout the literature. The conclusions indicated in this analysis were based on the current concept and the assumed construction, installation, and operation strategies.

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