Life cycle assessment of co-located wind and wave energy technologies in Portugal

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Abstract— **Meeting the projected growth in global electricity demand requires innovative and sustainable solutions aligned with net-zero ambitions. Co-located offshore renewable energy (ORE) systems, integrating wave energy converters (WECs) and floating offshore wind turbines (FLOW) offer a promising alternative to address space constraints, improve reliability, and reduce environmental impact. This study presents a Life Cycle Assessment (LCA) of a co-located ORE system in Portugal, featuring a 30 MW wave energy array and a 300 MW floating offshore wind farm. Results from a cradle-to-grave evaluation indicate a carbon footprint of 17.7 gCO_2eq/kWh, a carbon payback period (CPBT) of 1.4 years and an energy payback period (EPBT) of 2.0 years. The carbon intensity falls between that of standalone FLOW, typically less carbon-intensive, and wave energy, which have higher impacts due to their lower technological maturity and added complexity. By sharing infrastructure and streamlining operation and maintenance (O&M), the co-located system offsets some of the environmental effects while enhancing the potential of energy productions. The findings demonstrate a balanced trade-off between environmental impacts and energy benefits, also underscoring the potential of co-located ORE systems to support the development and commercial readiness of wave energy technologies, fostering innovation and cost reductions.**

Keywords—**floating offshore wind, wave energy, co-location, life cycle assessment, carbon footprint.**

I. INTRODUCTION

Global electricity demand is rising steadily, driven by economic growth, heatwaves, and the increasing use of technologies such as vehicles and heat pumps. Projections indicate that global electricity consumption could double by 2050 in conservative scenarios, and quadruple in more ambitious ones [1]. In parallel, renewable energy (RE) is expanding rapidly, accounting for over 90% of all newly installed power capacity worldwide [2]. As variable sources like wind and solar grow in share, maintaining a stable and reliable energy system becomes more complex, requiring investments in balancing technologies, storage, and additional capacity.

Space constraints are also a growing concern, with prime locations for onshore installations becoming scarce, highly competitive, or societally less preferred. Offshore environments offer higher resource availability; however, this increases system complexity and places additional pressure on protected areas. While higher densities of offshore wind farms may reduce electricity yields due to intra-park effects, careful planning and innovation in farm layout can mitigate these impacts.

Other offshore renewable energy (ORE) sources such as wave power, present emerging opportunities despite early-stage technical and financial challenges. As more experience has been gained among the involved stakeholders, these challenges tend to be minimised, paving the way for a more diversified energy mix. Research on the techno-economic potential of wave power indicates a considerable contribution of this emerging technology in the years and decades to come [3].

In recent years, the consolidation of offshore wind power technology and advancements in wave energy technology have made combining these technologies a viable alternative. The synergies of combined projects are grounded on enhanced energy yield, better predictability, smoothed power output, shared grid infrastructures, and to some extent, the shared logistics and resources associated with Operation and Maintenance (O&M), which ultimately can contribute to a reduction in costs.

Sustainable development of ORE requires careful planning that balances technical and economic viability with optimal use and disposal of resources, exploring the potential minimization of embodied carbon dioxide (CO_2) footprints. Although recent studies have addressed the

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life-cycle assessment (LCA) of ORE systems, there is a notable gap in research on multi-source energy parks due to their innovative characteristics. Existing studies mainly focus on offshore wind or show varied results for wave energy, reflecting the early stage and diversity of WEC designs.

A review covering 186 tidal and wave energy devices tested or deployed in real marine conditions found that their global warming potential (GWP) can vary from 15 to 105 g CO_2 eq/kWh, with an average of 53 ± 29 g CO_2 eq/kWh [4], [5]. This wide range reflects the diversity of technologies and configurations analysed, as well as differences in methodological approaches and assumptions used across studies. Even when analysing the same WEC, methodological discrepancies can significantly influence results, making straightforward comparisons difficult.

Studies on the Pelamis device conducted by [6] and [7] adopted different assumptions, resulting in notable variations in carbon footprint estimates (23 and 35 g CO_2 eq/kWh respectively). Similarly, recent assessments of Oyster 800 and Oyster 1 [8] reported values of 79 and 57 g CO_2 eq/kWh respectively, whereas earlier analysis [9] and [10] found emissions of 65.5 and 25 g CO_2 eq/kWh, respectively.

Across these studies, there is consensus that manufacturing consistently represents the most carbon-intensive phase of the lifecycle. However, challenges persist in capturing the impact of O&M, as simplified assumptions and limited field data often introduce uncertainty. Moreover, assumptions on the end-of-life (EoL) phase and allocation methods, particularly regarding material recovery and recycling credits, varies widely, adding another layer of complexity to cross-study comparisons.

Furthermore, most wave energy LCAs to date are based on single prototypes designed for limited demonstration periods. This makes it difficult to extrapolate full lifecycle impacts, especially when compared to commercial scale, which are designed to optimize efficiency and coordinate marine operations. Nevertheless, LCAs of wave and tidal technologies still provide valuable insights for benchmarking and guiding technology development.

In contrast, the carbon footprint of offshore wind energy systems tends to be reduced, typically between 11 and 23 g CO_2 eq/kWh, as noted in several literature reviews [5] [11] [12]. This narrower range reflects the advanced level of maturity of this type of technology, which have benefited from continuous enhancement over time.

To support decision-making on the environmental pillar of co-located renewable energy parks, this study presents the methodology used to carry out a LCA and quantify energy and carbon flows for a theoretical large-scale deployment. This analysis was conducted as part of EU-SCORES [13], an EU-funded project that aims to demonstrate the advantages of co-locating large multi-source offshore renewable energy farms.

A brief description of the floating offshore wind farm and wave energy array 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 and the assumptions considered within each phase are presented in Section IV. This framework is subsequently used to analyse the carbon and energy footprint of the base scenario in Section 0 and to draw the main conclusions and recommendations of the study in Section VI.

II. CASE STUDY

This study focuses on a renewable energy system that combines a floating offshore wind farm with a wave energy array, co-located off the coast of Aguçadoura, south of Viana do Castelo, Portugal. The key parameters of the project and location are indicated in Table I.

TABLE I
KEY PARAMETERS OF CO-LOCATED SYSTEM

Parameter	Value	Unit
Lifetime	30	years
Location	Aguçadoura, Portugal	-
Distance from shore	25	km
Distance to port	25	km
Average depth	80	m

The CorPower WEC concept features a point absorber type, with a composite buoy designed to interact with wave motion, driving a Power Take-Off (PTO). The buoy is connected to the seabed through the power conversion module and a mooring system. The system is composed by standard generators and power electronics, similar to those used in the wind energy industry.

For this study, the WEC technology is considered at a scale deployment, comprising 75 WECs (400 kW each) laid out in a cluster of 30 MWs. The configuration is comprised by 6 strings (3 with 13 units and 3 with 12 units) connected to a central collection hub. The floating collection hub gathers the electricity generated by the WECs in the array and delivers it to the substation via subsea cable.

The length of the array cables was estimated based on the shared array layout and materials breakdown for the specific cables, with ratings derived from a submarine cables datasheet available in the literature [14].

Core input data for the wave device was provided by CorPower, with additional data supplemented by [15].

The FLOW system consists of 20 semisubmersible platforms, each supporting a 15 MW wind turbine and moored with three catenary lines. The wind turbine selected as reference is the IEA 15-240-RWT [16], while platform-related data is based on [17]. The total length of array cables was estimated using an approximate correlation between the minimum turbine spacing and the local water depth. Similarly to the WEC system, the material breakdown was sourced from [14].

Both the WEC and FLOW arrays are designed to share export cables and a substation as part of the integrated offshore energy park. The length of the export cables was roughly estimated based on water depth and distance to shore. The mass of the floating substation's structure and topside was estimated based on the system requirements and data from [18], while the mass and material composition of the transformer were derived from [19].

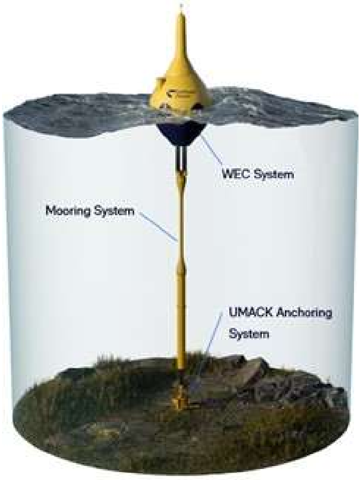

Fig. 1. Illustration of CorPower WEC [20]

Fig. 2. Illustration of co-located floating offshore wind and wave energy systems [20]

The average annual energy production (AEP) for the floating offshore wind system was estimated using wind resource data, while for the wave energy array it was derived from CorPower's power matrix. Both estimates refer to the Aguçadoura deployment site and are based on the ECHOWAVE hindcast dataset [21]. The metocean data was also used to support the modelling of O&M activities, including accessibility, weather windows, and operational planning.Main parameters representing both wind and wave systems are indicated in Table II and Table III.

TABLE II
KEY PARAMETERS OF THE FLOATING OFFSHORE WIND SYSTEM

Parameter	Value	Unit
Nominal rating	15	MW
# turbines	20	units
Array rating	300	MW
Capacity factor	38%	-
AEP	1116	GWh/year

TABLE III
KEY PARAMETERS OF THE WAVE ENERGY SYSTEM

Parameter	Value	Unit
Nominal rating	400	kW
# WECs	75	units
Array rating	30	MW
Capacity factor	40%	-
AEP	106	GWh/year

III. METHODOLOGY

LCA is a systematic methodology used to evaluate the environmental burdens of a product or process throughout its entire lifecycle, from raw material extraction to disposal. This methodology follows the guidelines set by the International Organization for Standardization (ISO) 14040 [22] and 14044 [23], 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 goal of this analysis is to assess the carbon and energy intensity associated to a co-located project. The functional unit (FU) is defined as 1 kWh of electricity delivered to the Portuguese electricity network.

The analysis follows a cradle-to-grave approach, covering all lifecycle phases of the system, including manufacturing, assembly, transportation, installation, operation, decommissioning, and disposal. The system boundaries include the main components of both the wind and wave technologies. For the wind system, this includes the floating platform, wind turbine components such as blades, rotor-nacelle assembly (RNA), and tower, mooring system, and array cables. For the wave system, it is considered the main components are the WEC hull, PTO unit, feeder hub, mooring system, array cables, and other minor elements of the related sub-systems. Common infrastructure, such as the floating substation and export cables to shore, is also included, as shown in Fig. 3. The components of the onshore electricity grid are outside the scope of this analysis.

No credit is provided for recycling within the project disposal scenario to allow comparison to other results obtained in the literature.

SimaPro 8 [24] was the software used to model the system, and background data sourced from the Ecoinvent database (v.3.5) [24]. The impact assessment is achieved by translating the environmental loads from the inventory results into midpoint impact categories using the ReCiPe 2016 Midpoint method. 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.

To facilitate the comparison with other studies, the impact of carbon emissions and energy intensity per unit of electricity produced are expressed in gCO_2eq/kWh and kJ/kWh, respectively.

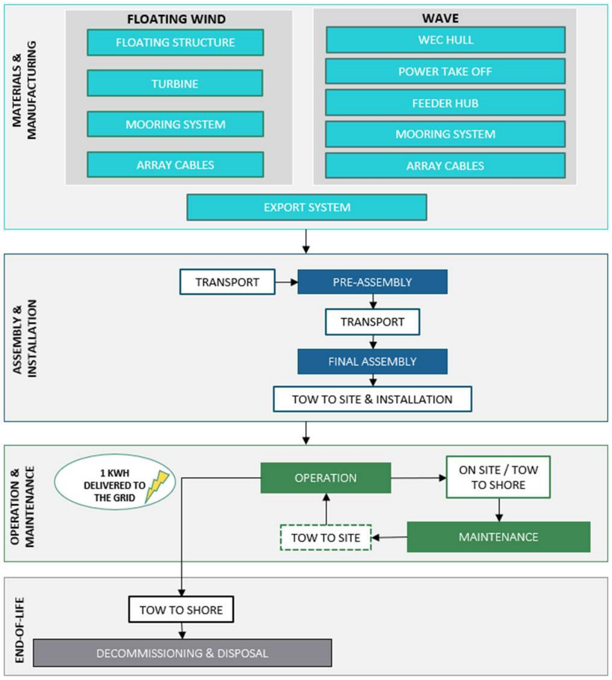

Fig. 3. Lifecycle flowchart: WEC and FLOW.

IV. DATA COLLECTION

The life cycle inventory (LCI) phase relies on collecting data on all inputs such as materials, processes and energy, and outputs such as emissions and waste, associated with each lifecycle phase. Foreground or primary data were collected mainly from the project team. All background or secondary data were derived from the Ecoinvent database and data sourced from the available literature. Some assumptions were necessary due to the current lack of data or uncertainty in data collection related to the WECs.

The installation and O&M strategies also considered premises based on discussions with technology developers as well as information gathered from relevant literature. An update of this study may be necessary in the future if significant discrepancies in the assumed data are identified.

A. *Materials and manufacturing*

The initial phase defined within the system boundaries begins with the processing of raw materials, followed by the manufacturing stage, where these materials are formed into sub-components of the device.

Due to the sensitivity of the design and configuration inputs, a detailed dataset cannot be publicly disclosed. However, based on a high-level LCI estimate, the mass distribution shows that the offshore wind energy system accounts for the majority of the total mass (86%), followed by the wave power array (8%) and the shared export system (6%).

Regarding the material composition of the co-located system, the estimated distribution is as follows: steel (89.2%), iron (3.2%), glass fibre (3.1%), copper (1.0%), plastics (0.7%), electronics (0.7%), and other materials (2.1%). Steel is used extensively across wind technology components, including the wind turbine tower, RNA and floater, as well as for the main WEC's internal structure, anchor and the PTO. Substation equipment, structures, and mooring systems for wind power, wave power, and export systems are also composed of significant amounts of steel.

The significant advantage of this material breakdown is the high recycling rate of steel (approximately 85%) during disposal, its substantial market value and a high reutilization rate after recycling.

The array cables are mainly composed of steel (41%), lead (28%), copper (21%), and other materials (10%). Key manufacturing processes, such as steel mining and welding, are considered, along with additional required materials and electricity.

It is assumed that structural steel passes through the processes of machining and welding. The energy consumption for the heavy machining was based on [25], while calculations for the welding process were completed assuming the need for 4.35 kg of welded steel per meter [26].

In the absence of a clearly defined supply chain, materials were assumed to originate from the EU when applicable and available in the database, otherwise, a global sourcing level was applied to reflect broader availability.

B. *Assembly and installation*

The assembly phase involves the road and sea transport of subcomponents to the final assembly yard near Aguçadoura site. Part of components for both the wind and wave technologies is assumed to be fabricated in the Scandinavian region, approximately 36% and 38%, respectively. For wind technology, this primarily refers to the wind turbine and its components. For the WEC, assumptions follow the references provided in [15], where is assumed the PTO being produced in Sweden.

Other components are considered to be manufactured in other European countries, with 58% for wind and 34% for wave, while local production in Portugal accounts for 7% and 28%, respectively. These percentages reflect the share of total array mass transported from each region.

After final assembly, specialized vessels are used to tow and deploy the devices and substation, as well as to install moorings, anchors, and cables. The installation strategy outlined in references [15] [17] and [27] served as a baseline for this analysis, providing information on vessel types, fuel consumption, and operation time. These inputs were adjusted as needed to reflect the specific configuration under study.

The set of vessels considered, or with comparable capabilities for the required tasks, include crew transfer vessel (CTV), platform supply vessel (PSV), heavy lift vessel (HLV), work vessel (WV), crane vessel (CV), survey vessel (SV), anchor handler tug vessel (AHTV), cable laying vessel (CLV), and tugboat (Tug).

Table IV provides a summary of the total fuel consumption over the project's lifetime, categorized by the vessels required for the installation, operation and maintenance (O&M), and decommissioning phases.

To estimate the impact of these marine operations in ton-kilometer (tkm) metric, the "Ferry" vessel entry from the Ecoinvent database was considered in the model and adjusted to reflect the fuel inputs in the model.

C. *Operation and maintenance*

The O&M phase of the offshore multi-source farm was analysed through simulations using WavEC's LMO tool, originally developed in the DTOceanPlus project [28] and further detailed in [29] and [30]. Preventive maintenance campaigns were assumed to be scheduled annually for both wind and wave technologies. In case of component failure, immediate corrective actions were assumed as the baseline approach, with interventions initiated as soon as failures are detected. The interventions are classified as minor repairs, major repairs, or major replacements, based on the extent of repairs needed. Failure rates and modes, defined in advance, inform all corrective actions. Tow-to-shore and tow-to-site operations are only factored in inspections or corrective actions at the port are deemed necessary.

At the early stage of this study, an initial approach is considered to guide the analysis. Given the limited data on the operational profile and maintenance needs of the WEC technology, preliminary assumptions were made using failure rates for key components provided by CorPower, while maintenance data of FLOW were derived from the literature [31][32]. To avoid introducing additional uncertainties and to keep the assumptions aligned with those used in existing studies for a more appropriate comparison, the present study does not include the impact of component replacements, in terms of raw materials, and manufacturing processes and logistics.

The summary of the vessels considered for this stage is detailed in Table IV and Table V.

D. *Decommissioning and disposal*

The decommissioning phase is expected to largely mirror activities involved in the installation phase. However, it is assumed that the site could potentially be repowered, allowing for the reuse of existing infrastructure such as cables and mooring systems, reducing the needs for vessel operations, as well as the demand for new raw materials in future projects. The final fuel consumption for this phase is indicated in Table IV.

The disposal scenario considers two different EoL approaches: recycling and landfilling. This study applies a recycling cut-off approach, which does not fully account for the benefits of recycled materials beyond the system boundary. As a result, recycling is not directly reflected as a reduction in impacts from avoided virgin material use but as minimization of net energy and carbon flows by reducing the amount of waste directed to landfill.

The transportation of materials to the final disposal site was considered to have minimal significance compared to other stages of the life cycle and it was excluded from the analysis. The assumed EoL scenarios are indicated in Table V.

TABLE IV
FLOATING OFFSHORE WIND AND WAVE ENERGY SYSTEMS: VESSEL FUEL CONSUMPTION FOR THE ENTIRE LIFETIME

Vessel	Fuel consumption [liters x 10^6]		
	Installation	O&M	Decommissioning
CTV	0.23	80.25	0.23
PSV	0.47	-	0.47
HLV	-	10.05	-
WV	-	1.32	0.47
CV	1.24	-	1.24
SV	-	0.31	-
AHTV	1.41	0.07	-
CLV	0.16	0.13	-
Tug	0.93	-	0.93

TABLE V
ASSUMPTIONS FOR END-OF-LIFE SCENARIOS

Parameter	Value
Steel	Recycle 85% Landfill 15%
Copper	Recycle 85% Landfill 15%
Aluminium	Recycle 85% Landfill 15%
Other metals	Recycle 80% Landfill 20%
Plastics	Recycle 60% Landfill 40%
Other materials	Landfill 100%

V. RESULTS AND DISCUSSION

A. *Carbon footprint*

The life cycle assessment of the co-located park, comprising both FLOW and WECs array, indicates a GWP of 17.7 gCO_2eq/kWh. Of this total, 79% originates from the manufacturing phase, which includes the transportation of materials to the assembly site, 1% from installation, 19% from O&M, and 1% from decommissioning and disposal activities, such as landfilling and incineration (Fig. 4). While no credit is attributed to recycled materials, the model accounts for both the avoided impacts of waste treatment and the emissions associated with the recycling processes.

During the manufacturing stage, the floating offshore wind system contributes approximately 91% of the total CO_2 emissions. This is primarily due to its larger installed capacity and higher material requirements compared to the WEC array. This trend continues across subsequent lifecycle stages, with the FLOW system consistently accounting for a greater share of emissions than the WEC system.

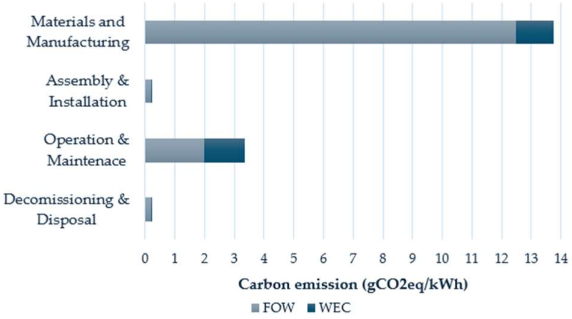

Fig. 4. Carbon footprint per phase and technology.

The results can be compared to values reported in other life cycle assessments of single-source energy parks. For floating offshore wind, carbon intensities range from 11.5 to 38.1 gCO_2eq/kWh, depending on local energy mixes, methodological choices, and design specifics [11]. For wave energy—still a developing technology—reported values vary widely, from 23 gCO_2eq/kWh [6] to 105 gCO_2eq/kWh [4], reflecting differences in design, maturity, and assumptions. A comparable CorPower wave array shows a carbon footprint between 25.1 and 46.0 gCO_2eq/kWh, influenced primarily by the adopted O&M strategies [15].

For comparison purposes, assessing each technology configuration as a single-source installation, rather than co-located, it shows carbon footprints of 15 gCO_2eq/kWh for FLOW and 33.6 gCO_2eq/kWh for a WEC array. These variations from the mentioned previous studies likely stem from park size, variations in site characteristics, specific O&M strategies, and uncertainties in assumptions. However, this comparison emphasises the potential advantages of co-locating wave power with offshore wind power projects. By sharing infrastructure and increasing total energy output, the combined approach can dilute the carbon intensity of the overall project. Additionally, WEC technology could benefit from the design and operational advancements gained from experience in commercial projects, further reducing carbon impacts over time.

Besides the CO_2 emissions per kWh produced serves as a key metric for comparing the environmental performance of the proposed technologies with conventional energy sources. CPBT represents the time needed for a system to offset the carbon emissions generated throughout its life cycle (1). This is compared against the emissions from the energy grid if conventional sources were used.

$$CPBT = \frac{Total\ CO_2eq\ emissions}{Annual\ CO_2eq\ avoided} \tag{1}$$

For the co-located system analysed in this study, the CPBT is approximately 1.4 years. However, the current life cycle inventory does not fully capture the recent growth in renewable energy within Portugal's electricity mix, which may lead to an overestimation of avoided carbon emissions. For example, between 2019 and 2023, Portugal increased its share of renewable energy in electricity generation by around 28% [33]. As the grid becomes less carbon-intensive, the emissions displaced by new renewable systems decrease, which could extend the CPBT slightly. Nevertheless, the calculated CPBT remains well below the system's expected operational lifespan, reinforcing its alignment with net-zero targets.

To assess the benefits of multi-source energy systems, CPBTs for standalone technologies were also evaluated under identical conditions. Results show CPBTs of 1.2 years for FLOW farm and 2.9 years for the WEC array. These findings highlight the advantage of co-located systems, which can achieve a lower CPBT than some individual configurations due to shared infrastructure and improved energy output.

While these comparisons offer valuable insights, it is important to note that they should not be directly compared with CPBT values from other individual LCA studies, as differences in system boundaries, assumptions, and methodological approaches can significantly influence life cycle results.

B. *Energy footprint*

From the data of inventory considered, the analysis indicates a cumulative energy demand (CED) of 237 kJ per kWh of electricity delivered to the grid.

In addition to the type and scale of industrial processes, the total energy demand is strongly influenced by the geographic location of component manufacturing and the energy mix in those regions. Differences in energy mix composition, efficiency, and the share of renewable energy sources in local grids can significantly impact the energy required for system production and deployment.

Evaluating the primary energy factor (PEF) reveals that the ratio between the primary energy required by the proposed system components and operation and the final electricity output is 0.07. This indicates a high lifecycle energy efficiency, especially when compared to the EU-27 average PEF for electricity, which was 2.1 in 2018. Nonetheless, it is important to regularly update PEF values at the European level to reflect ongoing changes in national and regional energy mixes.

Similar to CPBT, the energy payback time (EPBT) measures how long the system takes to generate the same amount of energy that was consumed during its deployment (2).

$$EPBT = \frac{Life\ cycle\ embodied\ energy}{Annual\ energy\ production} \tag{2}$$

For this case, the EPBT is estimated at approximately 2.0 years. For comparison, the standalone offshore floating wind system has a slightly lower EPBT of 1.4 years, while the wave energy array requires a longer period of 3.9 years to recover the energy consumed during deployment.

Looking at future perspectives, CED can be reduced mainly by lowering the energy requirements during manufacturing, installation, and other life cycle stages of a system. This can be achieved through energy-efficient manufacturing processes. These ongoing industrial innovations hold great potential for creating less energy-intensive technologies. While this report could not incorporate such advancements due to current limitations in data availability on industrial processes, their future integration remains a promising opportunity for enhancing sustainability.

Material optimisation is another key strategy. This includes design approaches that minimise material use, reduce dependence on energy-intensive materials, or integrate recycled or alternative materials with lower embodied energy. Additionally, localised manufacturing can significantly reduce transport-related energy consumption by establishing strategic supply chain hubs closer to key installation sites.

With CED reductions, the EPBT tends to decrease as the system can offset the lower initial energy investment more quickly.

VI. CONCLUSION

This study assessed the environmental impacts, particularly related to carbon and energy intensity of integrating co-located RE systems, focusing on wave energy array deployed alongside floating offshore wind farms in Portugal.

The carbon intensity resulting from the proposed configuration is indicated as 17.7 gCO_2eq/kWh, with the manufacturing phase accounting for roughly 80% of total emissions across both configurations, highlighting it as the most carbon-intensive stage. Steel dominates the material profile, underscoring the importance of implementing circular economy principles, such as material reuse, recycling, and design optimization.

While the standalone offshore floating wind system generally indicates lower carbon impacts due to their higher technological maturity and greater energy output, co-located systems offer key advantages. In particular, the integration of wave technology, although adding complexity and emissions, benefits from shared infrastructure and increased total energy output. This shared approach helps reduce the relative carbon footprint of less mature technologies and supports their transition to commercial viability. Moreover, co-locating brings added benefits not typically captured in LCA, such as shared use of the seabed, streamlined permitting and license processes, joint project development, and efficiencies in logistics, supply chain development, and overall infrastructural aspects.

The systems analysed are capable of offsetting their full lifecycle carbon emissions within their operational lifetimes, with CPBTs of 1.4 years, reinforcing their contribution to net-zero targets. The proposed configuration also shows strong energy performance, with an EPBT of 2.0 years, and PEF of 0.07. Future advancements in manufacturing processes, material optimization, and localized production have the potential to further reduce energy inputs, improving overall sustainability.

While co-location enables the use of shared logistics and existing offshore wind maintenance practices, a key limitation of this study is the lack of long-term operational data, which affects the accuracy of modelling the O&M phase. To mitigate this limitation, a more detailed evaluation is planned under the EU-SCORES project. There is also scope to further improve efficiency by expanding the shared use of vessels, operations, and teams, such as in preparatory activities and installation. This could lead to further reductions in vessel usage and associated carbon emissions.

In this paper, tow-to-port maintenance is considered for major component replacements in FLOW turbines. However, recent advancements in climbing crane technologies suggest that enabling on-site replacement of major wind turbine components can significantly streamline operations – reducing intervention time, enabling the use of smaller vessels, and shortening turbine downtime – thereby lowering carbon emissions per kilowatt-hour electricity generated, and the carbon intensity of the O&M phase.

Additional analyses are also recommended to explore the sensitivity of the results under more refined maintenance strategies and improved logistic.

Further reductions in environmental impacts can be achieved by strengthening recycling initiatives, reducing reliance on virgin raw materials, and promoting material efficiency. In parallel, continued research into industrial processes and recycling methods could open new market opportunities, attract investment, and stimulate economic activity and job creation.

Ultimately, integrating complementary renewable energy sources, supported by effective policies that target emission reduction and energy efficiency, is crucial for sustainable development. These initiatives not only enhance energy independence but also drive innovation, job creation, and the development of a more resilient and sustainable energy system.

The data quality in this preliminary assessment was constrained by the limitations in input data, mostly not yet available during this study development. As a result, some assumptions were drawn from existing literature and previous studies. While necessary, these secondary data sources may introduce uncertainties that can propagate through the analysis. The findings and conclusions presented are based on the current system concept and the assumed strategies for construction, installation, operation, and maintenance.

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