Life Cycle Assessment of Co-located Offshore Wind and Wave Energy Systems in Multi-source Offshore Energy Park

Methodology and Infrastructure Arrangement Comparison

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Preface

The transition towards a sustainable and resilient energy system is one of the defining global challenges of our time. Within this transition, offshore renewable energy—particularly wind and wave energy—plays an increasingly important role in decarbonising power generation. As offshore space becomes more constrained and marine technologies continue to expand, the concept of co-locating offshore wind and wave systems within multi-use energy parks offers a promising pathway to improve spatial efficiency while reducing environmental impacts.

This thesis was conducted as part of the course CIEM5000 at Delft University of Technology and represents the culmination of my specialization in Offshore Structures and Marine Renewable Energy within the Civil Engineering master's programme. It reflects both my academic development and personal interest in advancing sustainable offshore technologies. The research explores the environmental implications of shared infrastructure in co-located offshore wind–wave energy parks through a comprehensive Life Cycle Assessment (LCA). The study was motivated by notable gaps in existing literature, where most assessments focus on single-technology systems and provide limited insights into the environmental benefits of integration.

I am sincerely grateful to my supervisors, Dr. George Lavidas and Dr. Alessandro Antonini, for their continuous guidance, constructive feedback, and encouragement throughout this work. Their expertise has been invaluable in shaping the direction and depth of this thesis. I would also like to extend my appreciation to DMEC, an accelerator and knowledge centre for offshore renewable energy solutions, for serving as an external committee member and for their support during the progression of this research.

Finally, I express my heartfelt gratitude to my family and to everyone who supported me throughout this academic journey. Their unwavering encouragement has been a constant source of motivation and strength.

It is my hope that the insights presented in this thesis contribute to the growing knowledge base surrounding sustainable offshore energy development and inspire further research into integrated, multi-source offshore energy systems.

Nurlia A. Dewi
Delft, November 2025

Summary

This thesis outlines a thorough Life Cycle Assessment (LCA) study of co-located offshore wind and wave energy systems within multi-source offshore energy parks. The research is positioned within the broader context of sustainable energy transition and aims to address the environmental implications of shared infrastructure in offshore renewable energy (ORE) deployments.

The study is motivated by the increasing demand for renewable energy and the limited spatial availability for offshore infrastructure. Multi-source offshore energy parks, wherein wave energy converters (WECs) and floating offshore wind turbine (FOWTs) shared infrastructure such as cabling, substations, and vessels, offer a potential solution. However, the environmental benefits of such shared systems remain underexplored. This study provides insight focusing specifically on co-located systems and how shared infrastructure influence the green house gas emission in terms of global warming impact (GWP).

The primary objectives of the research are: (1) to evaluate how shared infrastructure affects lifecycle GHG emissions, (2) to compare the environmental performance of standalone versus co-located offshore renewable energy systems, and (3) to investigate how the choice of LCIA methodology influences the results for midpoint impact categories. The main research question is *How does shared infrastructure in co-located offshore wind and wave systems affect lifecycle GHG emissions compared to standalone installations?* Supporting sub-questions further explore emission variability across lifecycle phases and the influence of LCIA method selection.

The LCA methodology is based on Attributional LCA (ALCA) with a cradle-to-grave system boundary. It compares three scenarios of equal installed capacity (180 MW): (i) standalone floating offshore wind (15 MW × 12 turbines), (ii) standalone wave energy (400 kW × 450 WECs), and (iii) a co-located hybrid park (10 wind turbines and 75 WECs). The proposed site is located 20–25 km off the coast of Viana do Castelo, Portugal, with environmental data drawn from ERA5 (wind) and ECHOWAVE (wave) databases.

Prior to the LCA, the power output and layout of the ORE parks must be established. For wind energy, wind speed data at 138 m hub height are fitted to a Weibull distribution, and simplified wake losses are applied to represent aerodynamic interactions among turbines. Wave energy power output is modeled using the power matrix of a heaving point absorber device provided by the technology developer. This power matrix is multiplied by the joint probability distribution of significant wave height (Hs) and peak period (Tp) retrieved from ECHOWAVE. In the co-located scenario, the hybrid layout is designed by interspacing WECs between wind turbine rows, applying a 10D following the typical wind-farm practice with minimum distance between 9D to 20D to maximise the net energy produced over the wind farm's lifetime [33]. Total energy yield is calculated by scaling individual device outputs to the number of installed units. This approach captures hybrid-system synergies while accounting for partial wake effects and layout-induced variability. Additionally, the coefficient of variation (CoV) of wind and wave resources is computed to characterize their variability. Based on the resulting power output, cable power capacity and substation sizing are determined for subsequent material requirement calculations.

Following the definition of electrical infrastructure and offshore operations and maintenance (O&M)—which incorporate both scheduled maintenance from the literature and corrective maintenance derived from failure rates—the Life Cycle Inventory (LCI) is compiled through a structured three-step process: planning, data collection (from literature, technical reports, and the ecoinvent database), and finalization. The LCA is implemented in openLCA software. The LCIA applies the Environmental Footprint (EF) 3.1 methodology due to its alignment with European sustainability standards, while IMPACTWorld+ is used for sensitivity analysis, offering geographically differentiated characterization factors.

List of Abbreviations

ALCA	Attributional Life Cycle Assessment
AHTS	Anchor Handling Tug Supply vessel
AEP	Annual Energy Production
CF	Capacity Factor
CLCA	Consequential Life Cycle Assessment
CoV	Coefficient of Variation
CPBT	Carbon Payback Time
CTV	Crew Transfer Vessel
DEA	Drag-Embedment Anchor
EPBT	Energy Payback Time
EU	European Union
FOWT	Floating Offshore Wind Turbine
FU	Functional Unit
GPBT	Greenhouse Gas Payback Time
GHG	Greenhouse Gas
HVAC	High Voltage Alternating Current
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MU-ORE	Multi-Use Offshore Renewable Energy
O&M	Operation and Maintenance
OFWT	Offshore Floating Wind Turbine
OPS	Onshore Power Supply
ORE	Offshore Renewable Energy
OSV	Offshore Support Vessel
OWT	Offshore Wind Turbine
PTO	Power Take-Off
PWERM	Probability-Weighted Expected Return Method
RNA	Rotor Nacelle Assembly
ROV	Remotely Operated Vehicle
SA	Sensitivity Analysis
SOV	Service Operation Vessel
SRF	Solid Recovered Fuel
TLP	Tension-Leg Platform
WEC	Wave Energy Converter

Contents

1 Introduction

The global energy sector is undergoing an universal combat towards climate change and shifting to clean energy, to reduce its dependency on fossil fuels. The United Nations Sustainable Development Goal (SDG) 7, affordable and clean energy, emphasizes the need for accessible, reliable, and sustainable energy systems. SDG 7 also includes electricity access, clean cooking, renewable energy, energy efficiency, renewable capacity per capita, and international financial flows. Considering renewable energy is one of those parameters, Offshore Renewable Energy (ORE) plays a crucial role in this transition. From the vast types of ORE being developed and tested, offshore wind and wave energy have received more attention.

Over time, the demand for ORE has increased and simultaneously the space for offshore deployments has decreased. Multi-source offshore energy farm could solve both of these issues, by combining two or more energy generation technologies. This study shows how multi-source systems could enhance power density and reduce the space needed for power generation.

The rising interest in ORE has consequently stimulated extensive research and pilot projects exploring the potential synergies between multiple offshore energy sources. However, the rapid expansion of these projects also calls for a deeper understanding of their environmental implications throughout the entire life cycle. Life Cycle Assessment (LCA) works as a valuable tool for quantifying and comparing the environmental impacts of energy systems, enabling the identification of key contributors and improvement opportunities. However, these discussions usually focus on individual offshore renewable structures or multi-source platforms [27], rather than multi-source energy farms. Prior to this study, several studies have been conducted and identified that the highest contributors to the environmental impact of these structures arise from material extraction, manufacturing, installation, and maintenance activities. However, there is still a research gap in assessing how multi-source offshore energy farms and their shared infrastructure can influence emissions and environmental footprints.

To address this gap, this study conducts a comprehensive Life Cycle Assessment of co-located offshore wind and wave energy parks, focusing on the environmental implications of shared infrastructure. The objective is to quantify the potential reduction in greenhouse gas emissions from infrastructure sharing in integrated offshore energy systems.

1.1. Research Problems

1. **Impact Assessment of Wave Energy Converter (WEC)**
   The primary aim of conducting LCAs on WECs is to quantify their environmental impacts over their entire life cycle, from raw material extraction to disposal ("cradle-to-grave"). This helps in identifying the most significant environmental burdens associated with WECs, such as greenhouse gas (GHG) emissions, embodied energy, and other potential impacts on human health, ecosystems, and resource availability. Most studies methodology are by evaluating the environmental impacts of products, which involves identifying and quantifying the inputs (materials, energy) and outputs (emissions, waste) throughout the life cycle of the WEC.
   Most LCA studies conclude that the main environmental impacts are due to materials use and manufacture, particularly the high amounts of steel used in structural components like the panel, foundation, and mooring system. From previous studies, it is found that the carbon footprint for WECs vary across different technologies, ranging from 23 gCO2eq./kWh [68] to 105 gCO2eq./kWh [92] as summarized by Pennock et al. in [70]. Another study by Engelfried, et al [28] shows that material usage have influence the global warming impact parameters, which relatively WEC with

concrete have lower climate change impact. Besides material usage, the availability of the periphery plays a big role in the impact result. Overall, WEC without periphery will have up to 86% less of gCO2eq./kWh compared to those with periphery [28]. This disrepancy highhlights that material choices and boundary definitions can have major contribution to the impact assessment result. In line with existing studies, the preliminary LCA of the MegaRoller Wave Energy Converter confirms that the most significant environmental impacts are attributed to the manufacturing stage, primarily due to the high material requirements, especially steel and concrete. The study reported a carbon intensity of 33.8 g CO□eq/kWh, which is considered low when compared to conventional electricity generation technologies and largely consistent with values reported for other wave and tidal technologies [9].

2. **Impact Assessment of Offshore Wind Turbine (OWT)**
   Besides WEC, offshore wind energy plays a big role in energy transition, offering a cleaner alternative compared to fossil fuels. However, despite the sustainability it offers, offshore wind farms have environmental impacts that need to be carefully assessed. Life Cycle Assessment (LCA) is commonly used to evaluate these impacts, looking from the materials used in manufacturing turbines to their installation, operation, maintenance, and eventual decommissioning. Study by Benitez et al. in [16], highlights that factors like turbine size, material efficiency, and maintenance strategies can significantly influence their overall environmental footprint. As the industry moves toward larger, more advanced turbines and improved logistics, prospective LCA studies help predict future impacts and identify opportunities to make offshore wind more sustainable. Understanding these assessments is crucial for optimizing designs and ensuring offshore wind remains a minimal impact to the environment.
3. **LCA of multi-source System**
   Life Cycle Assessment (LCA) has been widely applied to assess the environmental impacts of offshore renewable energy systems, but most studies have focused on individual technologies such as offshore wind farms or wave energy converters (WECs). Recent researches, such as by De Luca Pena et al. in [69] and by Elginoz et al. in [27], have expanded LCA applications to multi-source offshore platforms that integrate different renewable energy sources. These studies have provided insights into the environmental impacts of multi-source offshore farms (MUOFs) and multi-source offshore platforms (MUPs), highlighting key factors such as material selection, installation processes, and lifecycle emissions.
   However, existing research has primarily examined energy-food integration (e.g., offshore wind combined with aquaculture) or single-platform co-location (e.g., floating wind-wave platforms), rather than multi-source offshore energy parks where offshore wind and wave energy systems share infrastructure such as cabling, substations, and installation vessels. This study aims to bridge this research gap by conducting an LCA of multi-source offshore wind and wave energy parks, focusing on the environmental benefits of shared infrastructure. This will therefore provide new insights into how ORE contributes to sustainability by quantifying emissions reduction potential and its sustainability improvements.

1.2. Research Objectives

The general aim of this study are to assess the environmental implications of single technology (e.g. offshore wind energy park or wave energy park) farm and multi-source (e.g. co-located offshore wind-wave energy park), to analyze the needs of supporting infrastructure further, while maintaining minimum emission. Following that, to assess how shared infrastructure (cabling, substation, installation vessels) can influence lifecycle emissions.

To achieve this aim, the following specific objectives are defined:

- Quantify lifecycle GWP impact emission of offshore renewable energy systems.
- Conduct a cradle-to-grave Life Cycle Assessment (LCA) of three scenarios with equal installed capacity (180 MW): a standalone floating offshore wind park, a standalone wave energy park, and a co-located hybrid park.
- Identify the dominant lifecycle stages (manufacturing, transport, installation, operation and maintenance, and end-of-life) contributing to emissions in each scenario.

- Assess the impact of shared infrastructure on emissions reduction.
- Analyse how sharing of cabling, substations, and vessels in multi-source offshore parks influences lifecycle GWP impact emission compared to standalone installations.
- Determine which lifecycle phases are most affected by infrastructure sharing and quantify the relative contribution of these phases to overall emission reductions.
- Evaluate methodological sensitivity in impact assessment.
- Compare results obtained using two Life Cycle Impact Assessment (LCIA) methods, Environmental Footprint (EF) 3.1 and IMPACTWorld+, to examine how methodological choices affect the estimation of GWP impact emission.
- Calculate the Energy Payback Time (EPBT) and Greenhouse Gas Payback Time (GPBT) for all scenarios to provide a broader perspective on the sustainability performance of multi-source offshore energy parks.

1.3. Research Scope

This research will provide report regarding the LCA of three ORE park with the same rated capacity, 180 MW, with two different LCIA methodologies, named EF 3.1 and IMPACTWorld+. The three park are 12 FOWT park, 450 WECs park, and the combination between 10 FOWT and 75 WECs within the same area. This includes the manufacturing stage, production of the assembled devices, logistics, power plant maintenance, and the end-of-life management up to the disposal and its returning to the environment whether it's reused or recycled. However, this research will emphasize on how the shared infrastructure can influence CO_2 production in comparison between single device and multi-source ORE park. This shared infrastructure includes the electromechanical equipment which refers to subsea cables and offshore substation, in addition to the vessel for operation and maintenance. Figure 1.1 shows the system boundary for the three power ORE park system, called "cradle-to-grave" that covers assessment through a product's life from raw material extraction through manufacturing, application, and ultimately to the end-of-life phase.

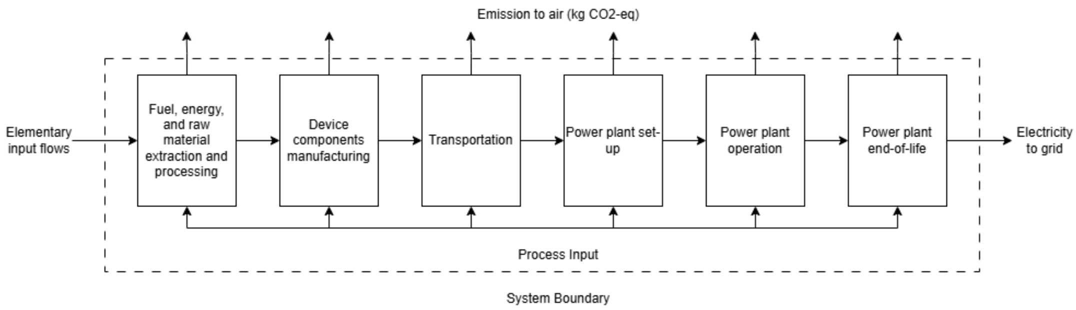


Figure 1.1: LCA Scope for a 180 MW Offshore Renewable Energy Park

To comply the LCA scope as in the above, several processes have been considered:

- **Production of the devices:** This includes the information of parts and components such as materials, weights, manufacturing operations, and scrap rates received from the technology developer.
- **Manufacturing:** Manufacturing includes the area of production, including the electricity grid sources.
- **Transport:** includes everything to mobilize raw materials to the production facility, the device components from the production site to the installation spot, and finally, their transport from the power plant site for end-of-life disposal.
- **Installation:** of the power plant site, including the usage of vessels such as tugboats, cable layers (CLV), anchor handlers (AHTS) and offshore support vessels (OSV).

- **Operations and maintenance:** of the entire plant site throughout the technology service lifetime. This study uses two types of maintenance in which corrective and scheduled maintenance. Both maintenance utilize the combination of vessel operation duration, vessel type and its fuel rate. However, while the scheduled maintenance uses literature approach in determining the maintenance frequency, corrective maintenance used the failure rate of the technology components.
- **End-of-life treatment:** of the entire power plant including decommissioning activities.

1.4. Research Question

Looking at the problems stated above, it led to a question of ***"How does shared infrastructure in co-located offshore wind and wave energy systems impact lifecycle Global Warming (GWP) impact emission compared to standalone installations?"***, with sub-research questions:

- How does the shared infrastructure influence the fluctuation of these emissions?
- Which lifecycle phase is most affected by infrastructure sharing in multi-source offshore energy parks?
- How do LCIA method choices (e.g., IMPACTWorld+ vs EF3.1) influence the assessment of GWP impact emissions in offshore renewable energy systems?

1.5. Research Outline

This study mainly provides the overview about how the multi-source co-located wind and wave offshore energy park can reduce the emission of a stand-alone offshore energy park with the same total rated capacity. Additionally, this study look into the sensitivity of the GWP impact emission fluctuation when the co-located offshore energy park acts as either paralel and hybrid system. To thoroughly describes it, the structure of this study as follows:

- **Chapter 2** provides literature review, including the wind and wave energy infrastructure, the LCA of wind and wave renewable energy, LCIA methods and a summary of previous studies regarding LCA in offshore renewable energy, either single type of device or hybrid.
- **Chapter 3** is Research Methodology, which describes the methodology of the study, where it provides the lifecycle framework for LCIA, resource assessment for wave and wind with specific location which eventually act as an input for functional unit in creating the life cycle inventory for modeling in openLCA and sensitivity analysis. To give broader picture about the benefit of the co-located offshore wind-wave energy park, therefore chapter 3 also give preview about the calculation of payback indexes, both energy and emissions.
- **Chapter 4** details the inventory analysis for each scenario: the floating offshore wind turbine (FOWT) park, the wave energy converter (WEC) park, and the co-located wind–wave park. It outlines the material requirements, cabling, substations, installation activities, operation and maintenance (O&M), and end-of-life considerations.
- **Chapter 5** presents the results of the LCA. It reports cradle-to-grave GWP impact emission for each scenario under EF 3.1 and IMPACTWorld+ methodologies, compares shared versus separated infrastructure arrangements, and discusses sensitivity analysis outcomes. It also includes the calculated energy and greenhouse gas payback times.
- **Chapter 6** provides the discussion, offering interpretation of the key findings in relation to the research questions. It reflects on the role of shared infrastructure in emission reduction, the lifecycle phases most affected, methodological sensitivities, validation against literature benchmarks, system-level and policy implications, study limitations, and future research needs.
- **Chapter 7** concludes the thesis with concise answers to the research questions, highlighting the main contributions of the study. It also provides recommendations for industry practitioners, policymakers, and researchers regarding the development of multi-source offshore energy parks and future LCA applications.

2
Literature Review

2.1. Literature Review Methodology

In this research, the state-of-the-art is reviewed to answer the following question:

1. How does shared infrastructure in co-located offshore wind and wave energy systems impact lifecycle greenhouse gas (GHG) emissions compared to standalone installations?
2. How does the shared infrastructure influence the fluctuation of these emissions?
3. Which lifecycle phase is most affected by infrastructure sharing in multi-source offshore energy parks?
4. How do LCIA method choices (e.g., IMPACTWorld+ vs EF3.1) influence the assessment of GHG emissions in offshore renewable energy systems?

To identify relevant literature, several databases will be included (e.g. Google Scholar, ScienceDirect, and Scopus). Combinations of article title, keywords, and abstract that will be used for this research are as follows:

1. ”LCA” AND ”Offshore Renewable Energy” OR ”multi-source”
2. ”LCA” AND ”Offshore” AND ”Wave Energy”
3. ”LCA” AND ”Offshore” AND ”Wind Energy”
4. ”LCA” AND ”Offshore” AND ”Mooring”
5. ”LCA” AND ”Offshore” AND ”Infrastructures”
6. ”LCA” OR ”Offshore Substation”

Following the required combination of article title, keywords, and abstract, relevant papers should discuss the following element:

- They discuss LCA methodologies used in offshore renewable energy studies.
- They provide quantitative analysis of emissions reduction from shared infrastructure.
- They compare different functional units, system boundaries, and impact assessment methods in LCA.

Based on the insights gathered from these sources, I compiled a research gap table that includes the following elements:

1. Authors, Title, and Year of Publication: To track trends and developments in Life Cycle Assessment (LCA) of offshore renewable energy.
2. Study aim: To identify the study aim of the study, whether it’s related to offshore wind and wave energy systems and their environmental impact.
3. Methodology: The LCA approach used, including system boundaries, functional units, impact assessment methods, and whether it considers shared nfrastructure.
4. Findings: Key insights on GHG emissions, energy payback, and material usage in offshore renewable energy parks.

5. Research Gaps: Identified by authors or through critical evaluation, including the role of shared infrastructure (cabling, substations, installation vessels), emissions reduction potential, and integration challenges in multi-source offshore energy parks.

2.2. Literature Review

2.2.1. Overview of Co-located Offshore Wind–Wave Systems in European Union

The alarming change of climate leads to ecological crisis and climate emergency, making remarks of high temperatures and extreme weather events attributed to climate change worldwide. Therefore, Paris Agreement produced an objective of limiting the rise of global temperature to 1.5^{o}C to prevent further climate degradation [93]. Following that, the European nations aim to become the first climate-neutral continent by 2050 with European Green Deal, despite the complicated geopolitical landscape [37]. This initiatives embedded in Fit for 55 package —seeking to reduce net Greenhouse Gas (GHG) by minimum 55% in 2030 [30] and the Clean Energy for All Europeans —National Energy and Climate Plans (NECPs) [31].

A study by Mahmood, et al [55] shows that Renewable Energy Transition (RET) in the Western Europe from 1995 - 2020 helped reduce CO_2 emissions. Additionally, European Union set an overall renewables target of at least 42.5% by 2030. As of late 2024, Europe had installed more than 21 GW offshore wind, growing steadily but below the deployment trajectory needed for 2030 targets. For ocean energy (wave and tidal), pilot, demonstration, and early commercial projects are in the water, though progress is hampered by slower than expected permitting and investment: the EU ocean energy target for 2025 is 100 MW, moving toward 1 GW by 2030, with deployments spread across multiple sea basins [32]

With the emerging marine spatial usage for offshore renewable energy, the EU's MSP directive obligates all member to designate marine zones for key activities, including renewables, and mandates Strategic Environmental Assessment of all plans to manage cumulative impacts [65]. MSP helps manage sea use conflicts, prepares for cross-border transmission infrastructure, and integrates offshore energy ambitions with conservation and blue economy priorities [100]. Based on the EU Strategy to harness the potential of offshore renewable energy, it is found that North and Baltic Sea has a high potential for offshore wind, EU's Atlantic ocean has high natural potential for offshore wind, wave, and tidal energy, as well as the Mediterranian sea. Additionally, the Black Sea offer potential for offshore wind and localised wave energy [30]. Recent work in Italy illustrates how spatial planning tools can identify suitable zones for co-located wind–wave energy, balancing high resource potential with environmental and sectoral constraints in areas such as the Tyrrhenian Sea and southern Adriatic [13].

While the resources of offshore wind and wave often coexist in the same locations, it needs a complex and comprehensive multi-level decision-making to evaluate and rank the various options. Different indexes and methods are proposed to evaluate the wind-wave co-location; platform stability and power reliability for power system operation [60], co-location feasibility (CLF) index [12], and MCDM (multi-criteria decision-making) methods to be able to consider goals and decision maker preferences [84].

Co-located offshore wind-wave projects are an emerging paradigm in Europe's pursuit of cleaner energy, offering spatial, technical, and systemic benefits that align with the EU's energy ambitions and marine spatial planning frameworks [60]. Recent studies classify combined offshore wind-wave systems as co-located arrays (sharing grid and O&M resources) or fully integrated arrays (sharing both infrastructure and marine space). Literature by Pérez-Collazo, et al. [71] and Meng, et al. [60] highlights multiple benefits:

- Enhanced resource complementarity: wind and wave energy provide complementary production profiles, improving power reliability and system stability.
- Synergies in logistics: sharing marine area, electrical infrastructure, and maintenance resources can reduce costs and environmental footprint.
- Flexibility in spatial planning: co-location requires less marine space compared to separate deployments, easing pressures from sectoral competition and conservation goals.

In summary, co-located offshore wind-wave systems stand as solution option of EU energy demand, technical innovation, and marine spatial planning, providing a robust path toward both efficient space management and ambitious renewable deployment for Europe's future.

2.2.2. Marine Renewable Energy Life Cycle Assessment (LCA)

The development of offshore renewable energy infrastructure, particularly wave and wind energy systems, is crucial for transitioning to low-carbon energy sources. However, these technologies require extensive material and logistical support, influencing their environmental impact over their entire life cycle. Align with the objective of this study, thus, the literature review regarding LCA in marine renewable energy will be limited to wave and floating wind technologies.

1. Wave Energy Converter LCA
   Wave energy infrastructure consists of wave energy converters (WECs), moorings, and sub-sea transmission cables that connect the generated electricity to the grid. Various WEC designs have been studied, including oscillating wave surge converters, point absorbers, buoy-rope-drum converters, and overtopping wave energy converters. The Pelamis device is one of the most well-known examples of a floating attenuator-type WEC. Despite the diversity in designs, the wave energy industry is still in an early stage of commercialization, leading to reliance on assumptions about material lifespan, maintenance strategies, and decommissioning practices in environmental assessments. Several studies have highlighted that material selection, particularly steel use in structural components, is a dominant contributor to environmental impact [[70], [103], [51], [87], [28], [9]]. For example, Apolonia and Simas [9] analyzed the MegaRoller WEC and found that reducing steel usage could significantly lower its lifecycle environmental footprint. In another research, it is mentioned that steel has the highest impact within the materials and manufacturing life cycle stage is steel, since the array is made of 83% steel [70]. However, despite these findings, comparative assessments between wave energy and other offshore technologies remain limited, and further research is needed to optimize material use and reduce operational emissions.

Table 2.1: Summary of Life Cycle Assessment Results for Various Wave Energy Converters

Study	**System Type**	**Functional Unit**	**GHG Emissions (g CO_2-eq/kWh)**	**Remarks**
Thomson et al. (2019) [87]	Pelamis (Attenuator type)	1 kWh	Estimated ∼24–30 (carbon payback in 24 months)	Cradle-to-grave for attenuator type; impacts from steel and vessels
Karan et al. (2019) [51]	Oyster 1 and Oyster 800 (Surge WEC)	1 kWh	Oyster 1: 79; Oyster 800: 57	Cradle-to-grave and found oyster 800 outperforms Oyster 1, seabed-mounted
Apolonia & Simas (2021) [9]	Oscillating Wave Surge	1 kWh	33.8	Cradle-to-grave; Foundation manufacturing accounts for 42%
Zhai et al. (2021) [103]	BRD (Buoy-rope-drum WEC)	1 kWh	Not specified	Cradle-to-grave, uncertainty analysis and sensitivity-driven study
Pennock et al. (2021) [70]	Point Absorber, 350 kW × 28 WECs	1 kWh	25.1–46.0	Cradle-to-grave for steel-intensive, early-stage prototype
Bruno et al. (2022) [18]	OWC, Oscillating Floater, Seabed Buoy	1 kWh	OWC: 203–270; Floater: 94–374; Buoy: 105–158	Cradle-to-grave with area of deployment in Mediterranean Sea designs, high emissions from short durability
Engelfried et al. (2025) [28]	Generic Point Absorber WEC	1 kWh	52–77 (without periphery); 300–325 (with periphery)	Detailed transparent cradle-to-grave LCA; cables & vessels significant

2. Floating Offshore Wind Turbine LCA
   There are broadly two types of offshore wind turbines, i.e., fixed-support and floating. Furthermore, the fixed support consists of a monopile and 4-legged jacket, meanwhile floating offshore wind turbine consists of tension leg platform, spar buoy, and semi-submersible type [11]. However, in this research the author will focus on semi-submersible floating wind turbines, with 3 anchored vertical column that interconnected/solidary to each other. Generally, floating offshore wind infrastructures include the floaters, mooring system (i.e. mooring chains and anchors), transmission system (i.e. offshore substation, submarine cables), and installation and O&M vessels [105].

   Previous LCA studies on floating offshore wind have explored various aspects. For instance, the environmental impacts of 40 floating turbines of 5 MW [99], Raadal et al. [74] that focuses in GHG emissions and energy performance of 100 turbines of 5 MW with different offshore foundation designs, environmental benefits of different FOWT deployment distance [91], to the LCA for multi-source offshore wave-wind floating platform [27]. Besides, there are comparative studies about LCA in FOWT in different environmental states and capacities such as Chipindula et al. [22] that conducted comparative study of three small-scale windfarm at onshore, shallow, and deep-water locations. Additionally, another LCA comparative study between barge-type floating wind turbines with other types of wind turbine by Yildiz et al. [101], and study by Garcia-Teruel et al. [36] about environmental impacts of two floating OWFs based on two pilot projects —Hywind and Kincardine.

Table 2.2: Summary of Life Cycle Assessment Results for Various Offshore Wind Turbine

Study	**System Type**	**Functional Unit**	**GHG Emissions (g CO_2-eq/kWh)**	**Remarks**
Weinzettel (2009) [99]	Spar FOWT, 5 MW × 40 turbines	1 kWh	15–22	Steel-intensive design
Raadal et al. (2014) [74]	Spar FOWT, 5 MW × 100 turbines	1 kWh	9.3–11.7	Different foundation and grid connection scenarios
Tsai et al. (2016) [91]	Semi-submersible FOWT, 5 MW × 1 turbine at varying distances	1 kWh	10.2–13.4	Impact of grid distance and mooring type
Elginoz et al. (2017) [27]	multi-source semi-submersible hybrid floating wave-wind	1 kWh	15.1	Floating hybrid concept
Chipindula et al. (2018) [22]	Small-scale wind farms (5–25 MW)	1 kWh	5.3–14.8	Onshore, shallow, and deep water comparison
Yildiz et al. (2021) [101]	Barge-type vs. Semi-submersible	1 kWh	12–19	Comparison of floating platform concepts
Garcia-Teruel et al. (2022) [36]	FOWT – Hywind (Spar) and Kincardine (Semi-submersible)	1 kWh	11.2–16.7	Based on two pilot projects
Yuan et al. (2023) [105]	Semi-submersible FOWT, 6.7 MW × 100 turbines	1 kWh	25.76	Chinese supply chain, focus on steel impact
Brussa et al. (2023) [19]	Semi-submersible platform, 14.7 MW × 190 turbines	1 GWh	31	The presence of large size wind turbines (15 MW) installed on floating foundations as the core feature.

Refering to table 2.1 and 2.2, the comparative review of WEC and FOWT studies highlights several consistent trends and gaps relevant to this study. First, both technologies are dominated by steel-intensive components—moorings, hulls, and foundations for WECs, and substructures and towers for FOWT, which explains why material production is repeatedly identified as the largest driver of lifecycle emissions across studies. Second, the reported GW emission intensities differ by an order of magnitude between wave and wind: while mature floating wind systems typically fall in the range of 7–31 g CO_2e/kWh, wave energy studies report much higher and more scattered values (25–325 g CO_2e/kWh) due to prototype-scale assumptions, uncertain maintenance regimes, and inclusion or exclusion of peripheral infrastructure. This discrepancy underlines both the relative maturity of floating wind technology and the methodological variability in assessing emerging WECs. Finally, the literature demonstrates that while installation and O&M phases contribute significantly to both systems, most studies treat them in isolation rather than exploring the potential synergies of shared infrastructure with other technology. This study therefore addresses a clear gap by explicitly modelling co-located wind–wave energy parks and quantifying how cabling, substations, and vessels can shift the balance of lifecycle emissions compared to standalone energy park.

2.2.3. Life Cycle Assessment Strategies

Life Cycle Assessment (LCA) is a widely used methodology for evaluating the environmental impacts of energy systems from raw material extraction to decommissioning. LCA itself have two main types, called attributional (ALCA) and consequential (CLCA). The ALCA addresses on how the environmental impact associated with this specific product life cycle, while CLCA seeks to understand the environmental consequences that arise from specific decisions or actions [83]. Since the aim for research is to understand about how shared infrastructure can influence the emission throughout the whole lifecycle, thus, ALCA will be carried out. ALCA is preferred over the CLCA for this study as this study disregard the impact of market-induced effects, but limited to direct technology life cycle assessment.

Based on the International Standards ISO 14040 and ISO 14044, LCA follows an four steps of iterations: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.

1. Goal and Scope Definition
   The first phase of LCA is to define the system boundaries and functional unit (FU). This phase enquired to ensures that all comparisons are made on a consistent basis and clearly define what is included and excluded in the assessment. System boundaries may range from cradle-to-grave (including all lifecycle phases) to cradle-to-gate (excluding end-of-life processes). For this study, we've set the system boundary as cradle-to-grave, describing the entire lifecycle from raw material acquisition to end-of-life.
   As for the functional unit (FU), it is defined as 1 kWh. This represents the delivery of 1 kWh of electricity from the offshore floating wind farm to the onshore national grid. All inventory flow unit (e.g. material weight, vessel fuel usage) have been scaled linearly with the designed power output to align with this functional unit. This process retrieved by dividing the inventory flow quantity with the total energy production per offshore energy park used in this study. Therefore, the life cycle impact for each structure type will presents the result per 1 kWh for all process of the offshore energy park used in this study.
2. Life Cycle Inventory (LCI) Analysis
   LCI analysis is the second phase of the LCA study, to compile and quantifying each inventories associated with each life cycle stage, with regard to the defined system boundary. During this phase, input and output flows of a product across its whole life cycle stages is determined [72]. This flows includes raw material, energy, and other physical resources from the environment as inputs, as well as emissions to air, soil, and water as outputs. The LCI data of many processes required to implement the inventory analysis phase can be derived from literature review [34] or obtained from various well-known life cycle inventory databases, such as ecoinvent, Greet, GaBi, U.S. LCI, and openLCA [72]. Since the choices are vary, this study utilized the ecoinvent v3.11 database as the flow and processes background data.
3. Life Cycle Impact Assessment (LCIA)
   LCIA translates inventory data into impact assessment, which generally considering three areas

of protection: human health, natural environment, and issues related to natural science. The three areas of protection then derived to impact categories considered in LCIA, namely climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related), respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion [46]. Impact categories and assessment indicators (e.g. Midpoint and Endpoint indicators assessment) should be chosen prior to choosing the LCIA methodology. However, in the last decade, it is found that many impact categories, the impact depends on where it occurs and have site-dependent characterization factors [41]. Several LCIA methods have been developed to quantify environmental impacts across different categories, namely:

Table 2.3: Overview of LCIA Methods and Their Characteristics, (source: [25], [63], [79], [23])

LCIA Method	Impact Categories	Assessment Indicator	Temporal Boundary	Spatial Boundary
Environmental Footprint (EF)	∼16	Midpoint only	Baseline of 100 years	Regionalized (EU-wide)
ReCiPe 2016	∼18	Midpoint and Endpoint	Long-term, includes 100-year GWP	Global (non-regionalized)
ILCD 2011	∼16	Midpoint only	Long-term focus	European (global average CFs)
CML-IA baseline	∼10–12	Midpoint only	Generally 100 years (for GWP)	Global (non-spatial)
IMPACT 2002+	∼15 midpoint / 4 endpoint	Both Midpoint and Endpoint	Long-term estimates	Global average CFs
IMPACTWorld+	∼18 midpoint / 21 endpoint	Both Midpoint and Endpoint	Time-horizon varies by category (e.g., 100-year GWP)	Regionalized (10+ global regions)
USEtox 2.0	2 (toxicity only)	Midpoint only	Variable (days–years)	Regionalized for exposure modeling
LC-IMPACT	∼14	Midpoint only	Varies by category	Highly regionalized (global grid-based)

4. Interpretation and Sensitivity Analysis
   The final phase involves interpreting the results and assess the result reliability. To implement that, either sensitivity or uncertainty analysis can be done. Whereas sensitivity analysis involves calculating different scenarios to analyze the influence of input parameters on either LCIA output result or rankings [40].

2.2.4. Impact of Shared Infrastructure

The integration of multi-source offshore energy parks allows for shared infrastructure, including cabling, substations, and installation vessels, potentially reducing overall lifecycle emissions. However, quantifying these benefits remains a challenge.

De Luca Peña et al. (2024) [69] assessed the impact of shared marine transportation between an offshore wind farm (OWF) and an offshore mussel farm (OMF). Their findings indicate that sharing vessels for monitoring and decommissioning activities can reduce fuel consumption, lowering emissions related to transportation. However, the overall lifecycle impact reduction was modest (<5% in most impact categories), as the primary environmental burdens stem from manufacturing and material extraction.

Elginoz and Bas (2017), [27] evaluated a multi-source offshore platform combining wind and wave energy. While their study did not isolate the specific emissions reduction from shared infrastructure, it emphasized that the largest contributor to environmental impact was material consumption for the platform itself. This suggests that while shared infrastructure can offer operational efficiencies, its overall impact on lifecycle emissions is highly dependent on the material and energy requirements of the combined system.

While the concept of multi-source offshore parks is promising, quantifying the environmental benefits of shared infrastructure requires more detailed LCA studies. Recent LCA studies on offshore renewable energy systems in table 2.4 reveal significant methodological diversity, from impact assessment frameworks (ReCiPe, EF 3.1, IMPACT2002+, CML) to modelling scales (component-level, array-scale, and multi-source configurations). Thematically, most research focuses on single-technology assessments for either offshore wind Benitez, et al. [16] and Elginöz & Bas [27] or wave energy converters such as in [70] and [9] with limited work on integrated namely multi-source offshore platforms [69].

Across these studies, variations in system boundaries, allocation methods, and scenario assumptions drive substantial differences in GWP values (e.g., 5–12 gCO_2-eq/kWh for offshore wind vs. 52–325 gCO_2-eq/kWh for wave devices). Notably, dual-technology studies often exclude spatially explicit LCIA, potentially underestimating region-specific marine impacts. By including both EF 3.1 and IMPACT-World+, the present study explores how methodological choices, including the presence or absence of spatial differentiation can influence the assessment of co-location benefits.

A summary of the selected literature review can be seen in the table below:

Table 2.4: Literature Review Meta Analysis

Title	Author, Year	Research Aim	Methodology	Findings
Life Cycle Assessment of a multi-source offshore platform: Combining wind and wave energy production	Elginoz, 2017 [27]	Determine life cycle environmental impacts of a floating multi-source offshore platform in Atlantic Ocean Cantabrian	• CML 2001 Method • LCA sensitivity and scenario analysis • Life Cycle Inventory with GaBi • Comparative study	• The manufacturing and processing (MTI) phase of the offshore wind turbine (OWT) and wave energy converter (WEC) platform is the main contributor to all environmental impact categories (except abiotic depletion potential - ADP). • Within the MTI phase, the fixed parts, moving parts, and mooring system of the wind turbine are responsible for most of the environmental burdens due to high material usage. • Wave energy converters (WECs) have a minor contribution to the total environmental impacts. • multi-source system in different offshore locations resulted in variations in total environmental impacts due to changes in wind turbine capacity factor, transportation distances, and high voltage cable length
An LCA of the Pelamis Wave Energy Converter	Thomson, 2019 [87]	• Presents a full life cycle assessment (LCA) of the first-generation Pelamis WEC • Examine any potential trade-offs or co-benefits across the broad range of environmental impacts	ReCiPe and CED impact assessment	• Pelamis WEC have significantly lower environmental impacts than conventional fossil generation • The greatest impact were from steel manufacture and sea vessel operations • Pelamis WEC performs relatively well in climate change and cumulative energy demand, with a carbon payback period of around 24 months and an energy return on investment of 7.5.

Title	Author, Year	Research Aim	Methodology	Findings
Full Life Cycle Assessment of Two Surge Wave Energy Converters	Karan, 2019 [51]	To carry out a detailed full LCA of two versions of the Oyster wave energy converter and to identify whether the focus on carbon and energy has overlooked any key impacts or life cycle stages that significantly contribute to them	ReCiPe and CML 2001	• Oyster 800 demonstrated better environmental performance than the Oyster 1 across all impact categories • Oyster 800 requires maintenance visits once every 5 years, whereas Oyster 1 requires it 3 times per year • Specific impact scores for both Oyster devices across various environmental categories.
Life cycle assessment of a point-absorber wave energy array	Pennock, 2021 [70]	Life cycle assessment of the full scale CPO point-absorber WEC within a 10 MW array, with cabling and marine operations assumptions at array scale	• SimaPro v.9.1.0 • ISO 14040 and ISO 14044 framework	• LCA of a 10 MW array of CorPower Ocean WECs shows that it performs similarly to other offshore renewable energy technologies. • It consistently outperforms fossil-fuelled thermal generation over six impact categories, including embodied carbon and energy. • The array is mostly comprised of steel (83% of total mass), with fibreglass hulls also making up a significant proportion (12%). • The array corresponds to a 38% capacity factor.
Life cycle assessment of a wave energy converter: Uncertainties and sensitivities	Zhai, 2021 [103]	Investigate the uncertainty propagation of the life cycle impact assessment (LCIA) and sensitivities of the output of the variations of inputs and key issues	• IMPACT 2002+ • Monte Carlo analysis (n = 10,000)	• Significant result from the uncertainty analysis was the wide range of carbon intensity, estimated to be between 49 and 1823 gCO2/kWh • Midpoint impact category results, ranged from -4.21% to 82.1% • Impact of key parameters including mooring weight of 20%, Buoy steel weight of a 20% increment was also tested, and Operation and maintenance (O&M) effort of a 20% increment was analysed • Electricity consumption for manufacturing moorings and the buoy structure was a major contributor to Ionizing radiation, Ozone layer depletion, and Respiratory organics, while the manufacturing of the buoy mainly contributed to Aquatic eutrophication

Title	**Author, Year**	**Research Aim**	**Methodology**	**Findings**
Life Cycle Assessment of an Oscillating Wave Surge Energy Converter	Apolonia, 2021 [9]	Preliminary Life Cycle Assessment (LCA) of the MegaRoller wave energy converter to contribute to decision-making regarding the least carbon- and energy-intensive design choices and comparative study between other renewable technologies and traditional generator	ReCiPe and CED impact assessment	• The main environmental impacts of the MegaRoller wave energy converter are due to materials use and manufacture, particularly the high amounts of steel used • The resulting impact assessment is generally comparable with earlier studies for ocean technologies and very low when compared with other power generating technologies • A reduction in the quantity of steel by studying alternatives could potentially reduce the environmental impacts
Life cycle assessment of floating offshore wind farms: an evaluation of operation and maintenance	Garcia-Teruel, 2022 [36]	Assess the environmental impacts of floating offshore wind farms with detailed O&M modelling and vessel operations	• LCA of Hywind and Kincardine OWFs • ReCiPe Midpoint (H) • Advanced O&M vessel modelling	• O&M vessel choice shifts GWP up to 34.8%. • Export and inter-array cables are significant hotspots. • Floating OWFs have higher impacts than bottom-fixed but remain lower than fossil generation.
Floating wind power in deep-sea area: Life cycle assessment of environmental impacts	Yuan, 2023 [105]	Evaluate the lifecycle environmental impacts of large-scale floating OWFs in Chinese deep-sea regions	• Cradle-to-grave LCA of 100 × 6.7 MW turbines • CLCD and ecoinvent databases • Scenario analysis of steel production pathways	• Steel production dominates lifecycle impacts. • Export cable and floating platform also major contributors. • GWP intensity 25–40 gCO_2-eq/kWh, depending on scenario.
Life cycle assessment of a floating offshore wind farm in Italy	Brussa, 2023 [19]	Conduct a cradle-to-grave LCA of a large floating offshore wind farm in the Mediterranean	• ISO 14040/44 framework • International EPD (2018) + CED • Case study: 190 × 14.7 MW turbines, 2.8 GW	• Steel in turbine and floating system is main hotspot. • HVDC export and inter-array cables contribute strongly to abiotic depletion. • GWP intensity 31 gCO_2-eq/kWh; CPBT ≈ 2 years, EPBT ≈ 3 years.

Title	Author, Year	Research Aim	Methodology	Findings
Environmental Life Cycle Assessment of multi-source of marine space: A comparative analysis of offshore wind energy and mussel farming in the Belgian Continental Shelf with terrestrial alternatives	De Luca Peña, 2024 [69]	Comprehensive LCA study on a marine multi-source offshore farm (MUOF), more specifically on the combination of an offshore wind and a blue mussel farm (OWF and OMF, respectively)	• ReCiPe 2016 and multi-source scenario • Uncertainty Analysis using Monte Carlo simulation (n = 1000)	• The mussel farm (OMF) contributes relatively the most to the net environmental impacts of the MUOF across all three Areas of Protection (HH: 71.1%; EQ: 68.95; NR: 58.5%). • The supply chain of materials required to manufacture the MUOF components, followed by operational activities, contribute significantly to the environmental footprint. • Compared to terrestrial benchmarks (cradle-to-gate), the MUOF had a larger impact on human health and natural resources, mainly due to the manufacturing supply chain.
Scenario-based LCA for assessing the future environmental impacts of wind offshore energy: An exemplary analysis for a 9.5-MW wind turbine in Germany	Benitez, 2024 [16]	Evaluate potential future environmental impacts, especially related to emerging technologies of offshore wind energy (OWE)	• prospective LCAs (pLCA) • Premise	• The Global Warming Potential (GWP) of an 8 MW OWT was estimated in a cited study to range from 5 to 12 g CO2-eq/kWh. • Differences in GWP are attributable to system boundaries, impact assessment methods, and adaptation of prospective databases. • The optimistic scenario for a 9.5 MW OWT projects the lowest GWP per kWh, up to 50% lower than the pessimistic scenario in 2030. • For a 20-year lifetime, the mean GWP for a 9.5 MW OWT could reach 13 ± 3 g CO2-eq/kWh by 2030, decreasing to 10 ± 3 g CO2-eq/kWh by 2050

Title	Author, Year	Research Aim	Methodology	Findings
Life cycle assessment of a point absorber wave energy converter	Engelfried, 2025 [28]	Assess environmental impacts of a generic point absorber WEC under different materials and deployment conditions	• LCA with openLCA 2.3 and ISO 14044 framework • LCI with ecoinvent v.3.9 • Environmental Footprint (EF) 3.1	• Potential impacts of a single WEC highly depend on its electrical transmission system, vessel operations, maintenance regimes, and hull material. • The export cable can have a remarkably high contribution to the overall impacts of a WEC, a finding not previously highlighted. • Using fibre-reinforced concrete as an alternative hull material can significantly reduce environmental impacts (10–78%) across all impact categories compared to steel. • Vessel operations contribute significantly to the impact of a WEC without periphery, mostly in categories dominated by fuel combustion, with towing the floater back to shore for maintenance having the largest impact. • GWP for WEC with periphery(cable + mooring): 325.4 gCO_2-eq./kWh for steel hull and 299.9 gCO_2-eq./kWh for concrete hull • GWP for WEC without periphery: 77.7 gCO_2-eq./kWh for steel hull and 52.2 gCO_2-eq./kWh for concrete hull
Life Cycle Assessment of Co-Located Floating Solar and Offshore Wind	Sadikaj & Smith [81]	Analyze the impact and environmental trade-offs of co-located VLFS with New Jersey's future offshore wind farms	ReCiPe 2016 Endpoint (H) V1.08 / World (2010) / Damage Assessment	• Co-location of OWF and FPVs can prove to be a power output maximization for renewable energy creation, taking advantage of the same marine infrastructure and grid connection • Further decarbonization capabilities is anticipated; however, the results of the LCA will highlight environmental trade-offs. • While the hybrid model is beneficial in producing more carbon free electricity, its effects on the environment will be bigger than OWF or FPV have separately

Table 2.4, the literature collectively shows that most existing LCAs assess offshore wind and wave energy technologies separately, with only limited attention given to hybrid or co-located configurations. Although prior studies extensively analyse manufacturing burdens, cabling impacts, O&M modelling, and methodological uncertainties, they rarely quantify the environmental implications of sharing infrastructure such as substations, export cables, or installation vessels. Moreover, almost none compare multiple LCIA methods for the same system configuration. This gap is particularly relevant for multi-source offshore energy parks, where shared assets may significantly influence lifecycle GHG emissions but remain insufficiently explored in current research.

In this context, Table 2.4 shows that while offshore wind and wave LCAs are methodologically advanced, multi-source offshore parks remain underexplored, particularly in allocating shared infrastructure impacts. No study has yet combined EF 3.1 and IMPACTWorld+ to test the sensitivity of methodology dependence. This study addresses these gaps by applying a two different LCIA method, cradle-to-grave assessment of a wind–wave park, comparing it to standalone systems of equal capacity and quantifying the life cycle effects of shared infrastructure at 1 kWh.

Additionally, Table 2.5 further links the literature review to the research questions by mapping studies against the identified gaps (G1–G3). It shows whether the previous work quantified GWP savings from sharing (G1), identified lifecycle phases most affected (G2), or tested LCIA method dependence in the case of utilisation of different LCIA methodologies (G3). This highlights the limited coverage of co-located systems and clarifies the gaps this study fills.

Table 2.5: Research Gap Map of Reviewed Literature

Title	Author, Year	G1: △GW from Sharing	G2: Sensitivity	G3: LCIA Method Dependence
Life Cycle Assessment of a multi-source offshore platform: Combining wind and wave energy production	Elginoz, 2017 [27]	✓(qualitative only)	-	-
An LCA of the Pelamis Wave Energy Converter	Thomson, 2019 [87]	-	Partial (vessel operations highlighted)	-
Full Life Cycle Assessment of Two Surge Wave Energy Converters	Karan, 2019 [51]	-	✓(maintenance frequency impact)	-
Life cycle assessment of a point-absorber wave energy array	Pennock, 2021 [70]	-	✓AEP, O&M fuel burn and transportation distance	-
Life cycle assessment of a wave energy converter: Uncertainties and sensitivities	Zhai, 2021 [103]	-	✓(tested O&M vs materials)	Partial (uncertainty in LCIA results)
Life Cycle Assessment of an Oscillating Wave Surge Energy Converter	Apolonia, 2021 [9]	-	✓(steel dominance)	-
Life cycle assessment of floating offshore wind farms: O&M focus	Garcia-Teruel, 2022 [36]	-	✓(O&M vessel modelling affects GWP)	-
Floating wind power in deep-sea area: LCA of environmental impacts	Yuan, 2023 [105]	-	Partial (scenario analysis on steel routes)	-

Continued on next page

Title	**Author, Year**	**G1: △GW from Sharing**	**G2: Sensitivity**	**G3: LCIA Method Dependence**
Life cycle assessment of a floating offshore wind farm in Italy	Brussa, 2023 [19]	-	✓(End-of-Life scenario and transmission systems)	Partial (EPD vs harmonised values)
Environmental LCA of multi-source marine space (wind + mussel farming)	De Luca Peña, 2024 [69]	-	Partial (operational activities vs supply chain)	-
Scenario-based LCA of future offshore wind energy	Benitez, 2024 [16]	-	✓(distance to shore)	✓(prospective LCIA methods)
Life cycle assessment of a point absorber WEC	Engelfried, 2025 [28]	-	✓(maintenance phases and structural component)	✓(explicit EF 3.1)
Life Cycle Assessment of Co-Located Floating Solar and Offshore Wind	Sadikaj & Smith, 2025 [81]	✓(qualitative)	Number of Very Large Floating Structures (VLFS)	-
This study - Life Cycle Assessment of Co-located Offshore Wind and Wave Energy Systems in Multi-source Offshore Energy Parks	-	✓	✓(Infrastructure arrangement & LCIA methodology)	✓(EF 3.1 and IMPACT-World+)

3
Research Methodology

3.1. Goal & Scope Definition

This study aims to present the influence of shared infrastructure on emissions throughout the entire life cycle, with the goal of developing strategies to optimize the performance of the energy system and reduce emissions. To achieve this, a detailed cradle-to-grave analysis of a multi-source offshore park combining Wave Energy Converters (WEC) and Floating Offshore Wind Turbines (FOWT) will be conducted with functional unit of 1 kWh. In this study, the scope will be focused on how shared infrastructure in a multi-source wind-wave offshore park would influence the overall emission compared to single technology ORE. Therefore, there will be scenarios based on the equivalence of installed capacity rather than the number of devices or technology types. The comparison focuses on how shared infrastructure, specifically cabling, offshore substations, and the operational sharing in which maintenance vessels affects lifecycle CO_2 emissions per unit of electricity produced. However, the study will focus on how shared infrastructure in a multi-source offshore park would influence the overall emissions compared to stand-alone ORE.

First, comprehensive spatial planning will determine the study location, guided by a literature review and techno-economic criteria such as resource potential, logistics, economics, marine conditions, and socio-political factors [7]. Once the location has been chosen, it will provide a boundary conditions and physical constraints for designing 180 MW ORE park in three cases of FOWT, WEC park, and wind-wave park. Details of the devices number and rated capacity is as in the table

Table 3.1: Technology Details

Technology	Rated Capacity	Number of Device
FOWT Park	15 MW	12
Wave Park	400 kW	450
Wind-wave Park	15 MW and 400 kW	10 FOWT and 75 WEC

Within the same devices configuration, three scenarios for the LCA will be conducted: (i) standalone offshore wind, (ii) standalone wave energy, and (iii) co-located wind-wave multi-source parks. These technologies will have equal installed capacity of 180 MW and the comparison focuses on how shared infrastructure—specifically cabling length, offshore substations, and installation/maintenance vessels—affects lifecycle influence the Life Cycle Inventory (LCI) and the infrastructure sharing potential. This approach of comparing the same rated capacity across different devices configuration is to keep the consistent functional unit and ensure the three scenarios provide the same output. Despite the different AEP in each scenario, the same rated capacity ensure there is no misleading results, as higher rated capacity can lead to higher activity and higher AEP which eventually lead to incomparable devices capacity and environmental impact.

The Life Cycle Impact Assessment (LCIA) phase converts Life Cycle Inventory (LCI) data into environmental impact results by applying characterization factors and impact models. This study primarily focuses on the climate change category, expressed in Global Warming Potential over 100 years (GWP100), to evaluate the influence of shared offshore infrastructure on lifecycle greenhouse gas (GHG) emissions [14].

In performing the impact assessment, openLCA software was utilized together with the Environmental Footprint (EF) 3.1 method is selected as the primary LCIA method. EF 3.1 is the current European Commission-recommended method for product environmental footprinting and is widely accepted in academic and policy contexts for its robustness in carbon footprint calculation and alignment with EU sustainability reporting standards. EF 3.1 provides midpoint indicators for 16 impact categories, with climate change (GWP100) being among the most relevant for offshore renewable energy assessments [21], whereas mentioned will focus on total climate change with impact category indicator of $kgCO_2eq$. In

Table 3.2: EF3.1 midpoint impact categories with their indicator and unit, source: [21]

Impact Category	Indicator	Unit
Climate Change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2eq
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11_{eq}
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh
Particular matter	Human health effects associated with exposure to PM2.5	Disease incidences
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBqU^{235}
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	$kgNMVOC_{eq}$
Acidification	Accumulated Exceedance (AE)	$molH+_{eq}$
Eutrophication, terrestrial	Accumulated Exceedance (AE)	$molN_{eq}$
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kgP_{eq}
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kgN_{eq}
Ecotoxcity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe
Land use	Soil quality index	Dimensionless (pt)
Water use	User deprivation potential (deprivation weighted water consumption)	m^3 world eq. deprived water
Resource use, minerals and materials	Abiotic resource depletion (ADP ultimate reserves)	$kgSb_{eq}$
Resource use, fossil	Abiotic resource depletion - fossil fuels (ADP-fossil)	MJ

Figure 3.1 illustrates the system boundary and life cycle framework applied in this study for the co-located offshore wind–wave energy park. Distinct use-phase processes are shown for the wave energy converters (WECs) and floating offshore wind turbines (FOWTs), while shared processes such as substation, mooring, electrical connection, and fuel usage for towing are placed in the central layer. The functional unit of the study is defined as 1 kWh of electricity delivered to the grid, indicated at the system output boundary. Waste flows are modelled through dismantling, recycling, and landfill routes, with recycling credits applied where applicable. This framework thus reflects the whole modelling process in order to result impact assessment per 1 kWh for all scenarios. The detailed life cycle inventory for each stages therefore will be explained in chapter 4

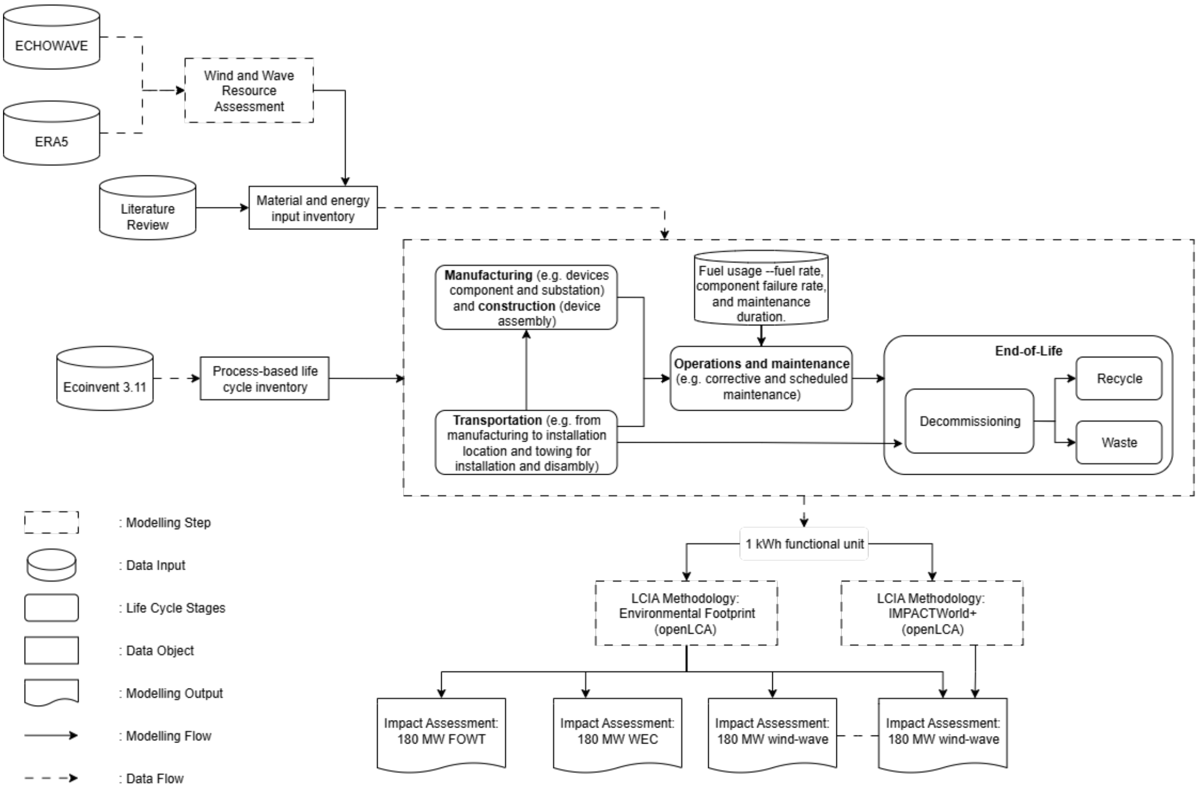


Figure 3.1: Life Cycle Impact Assessment Framework of 180 MW FOWT, WEC, and Co-located Wind-wave Energy Park

3.2. Resource Assessment

This study area refers to the Offshore Renewable Energy Zoning Plan (PAER), whereas six potential areas have been identified for marine renewable energy development. Based on the document, one of it is 25 km off coast Viana do Castelo at an average water depth of 80 meters. Once the location is determined, the latitude and longitude coordinates will then be used to retrieve wind speed data from ERA5 and significant wave height (H_s) and wave peak period (T_p) from ECHOWAVE [5], with 30 years hourly data. Following that table 3.3 summarizes the energy performance of the co-located, wave-only, and wind-only offshore parks.

Table 3.3: Comparison of energy performance between co-located, wave-only, and wind-only offshore parks

Parameter	Value
Rated Installed Capacity	
Installed capacity (wind)	150.0 MW
Installed capacity (wave)	30.0 MW
Total installed capacity	180.0 MW
Co-located Park (Wind + Wave)	
AEP wind (net)	772,520 MWh/yr
AEP wave (net)	77,026 MWh/yr
AEP total (net)	849,546 MWh/yr
Capacity factor total (park)	0.581
Energy share wind	90.9%
Energy share wave	9.1%
Wave-only Park	
Installed capacity (wave)	180 MW
Park AEP	561,836.8 MWh/yr
Park capacity factor	0.356
Wind-only Park	
Installed capacity (wind)	180 MW
Park AEP	601,358 MWh/yr
Park capacity factor	0.381

3.2.1. Wind Power Resource Assessment

The wind resource assessment started by retrieving wind speed data at the elevation of 100 m from ERA5 [43], for both east-west axis (u100) and the north-south axis (v100). Vector wind speed at 100 m, $V_\infty(h_{ref})$, was obtained as $\sqrt{u_{100}^2 + v_{100}^2}$. Following that, to represent conditions at the turbine hub height h = 138 m (V236-15 MW), speeds are vertically extrapolated with a neutral logarithmic law using a sea-surface roughness of $z_0 = 2 \times 10^{-4} m$ using the equation below:

$$V_\infty(h) = V_\infty(h_{ref}) \left(\frac{ln\frac{h}{z_0}}{ln\frac{h_{ref}}{z_0}} \right) \tag{3.1}$$

Equation 3.1 is appropriate for offshore conditions, where the weak surface roughness and near-neutral stability dominates. With wind speed at hub height, the wind rose plot shown in figure 3.2 visualize the wind patterns. Based on the picture, the site proposes consistent winds predominantly from the west with wind speed ranging from 4 m/s to 20 m/s.

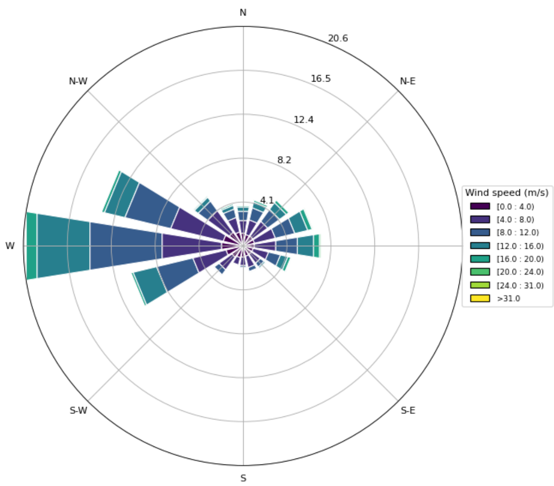


Figure 3.2: Windrose at the hub height 138 m

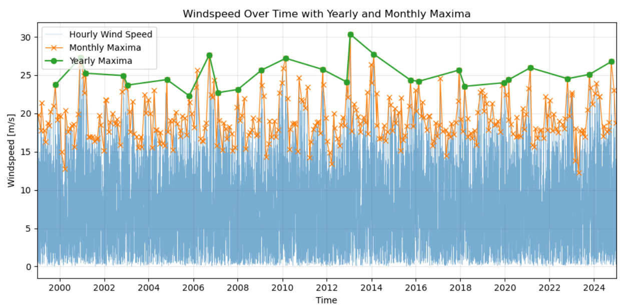


Figure 3.3: Monthly and Annual Maxima of Wind Speed at Hub-height

From the hub-height series, the wind-speed frequency distribution was modeled with a Weibull law to support energy calculations. Specifically, the empirical histogram was fitted (via maximum likelihood) to a two-parameter Weibull, and the fitted parameters were then used to evaluate the probability density function (PDF) for subsequent integrations. The resulting shape $k = 1.92$ and scale $= 9.06$ (Figure 3.4) indicate a moderately right-skewed regime with variability close to a Rayleigh distribution ($k \approx 2$) meaning the variability is moderate in the area.

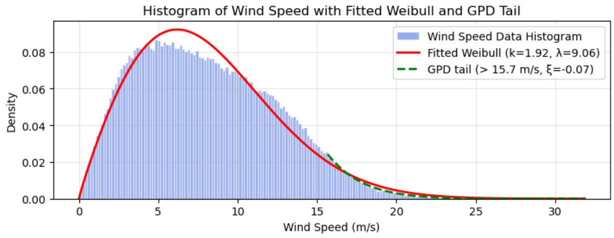


Figure 3.4: Fitted Weibull Distribution

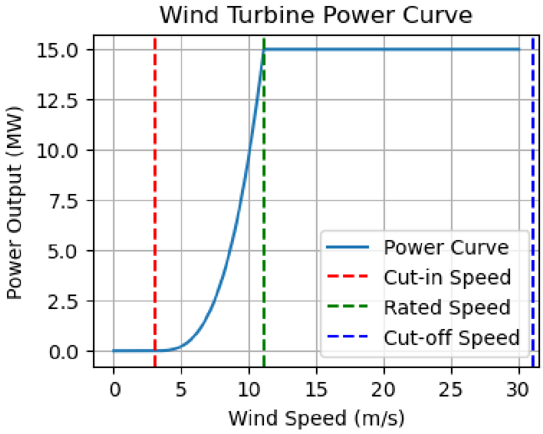


Figure 3.5: 15 MW Wind Turbine Power Curve

Energy conversion is mapped through the 15 MW turbine power curve in Figure 3.5: production is zero below cut-in ($U_{ci} = 3m/s$), increases cubically to rated power at $U_r = 11.1m/s$, remains flat at 15 MW up to cut-out ($U_{co} = 31m/s$), and is turns into idle mode above cut-out for structural safety. The Annual Energy Production (AEP) is obtained by utilizing power with the wind-speed PDF over the operating range. The mathematical form of the AEP calculation is described in the equation 3.2 below.

$$AEP = T \int_{U_{ci}}^{U_{co}} P(U) \cdot f(U) dU \tag{3.2}$$

where T is the total number of hours per year —8760 hours. In practice, $f(U)$ is the Weibull PDF truncated to $[U_{ci}, U_{co}]$ and normalized so that the integral equals one over that interval. Park-level AEP multiplies the turbine-level result by the number of devices.

Aerodynamic interaction between turbines is treated in two ways. For baseline estimates, this study assumed wake loss of 10% to the no-wake AEP, reflecting typical losses for moderate spacings. For sensitivity and layout-resolved analysis, a Gaussian wake model is used to propagate turbine-induced deficits downstream; deficits are governed by the thrust coefficient of $C_T = 8/9$. This number represents the maximum theoretically efficiency for horizontal axis wind turbine to extract kinetic energy from the wind. The resulting rotor-averaged inflow determines each machine's power by using $P = \min(\frac{1}{2}\rho C_p A\bar{U}^3, 15MW)$, and summing across turbines at each wind speed before integrating recovers a wake-adjusted AEP. Once the AEP is found, therefore the capacity factor or ratio between the AEP and the rated power in one year can be found (i.e. $CF = AEP/(8760 \times \text{n device} \times 15MW)$.

3.2.2. Wave Power Resource Assessment

To characterize the local wave climate, time series of significant wave height (H_s) and peak period (T_p) are retrieved and processed from data covering period 1991 - 2021 from echowave [5] with hourly timestep. Same as the wind resource power assessment, the wave data retrieved in the location of 41.639°N, -9.142°E. The latitude and longitude were first matched to the nearest available grid point in the dataset by identifying the closest indices from the latitude and longitude arrays. Subsequently, additional processing steps were applied to derive the wave parameters of interest. The continuous time series of H_s and T_p was then resampled into yearly and monthly maxima to identify extreme conditions and temporal variability. For each resampling interval, both the maximum values and their corresponding timestamps were extracted, providing insights into the monthly and yearly maxima of the wave climate as shown in figure 3.6.

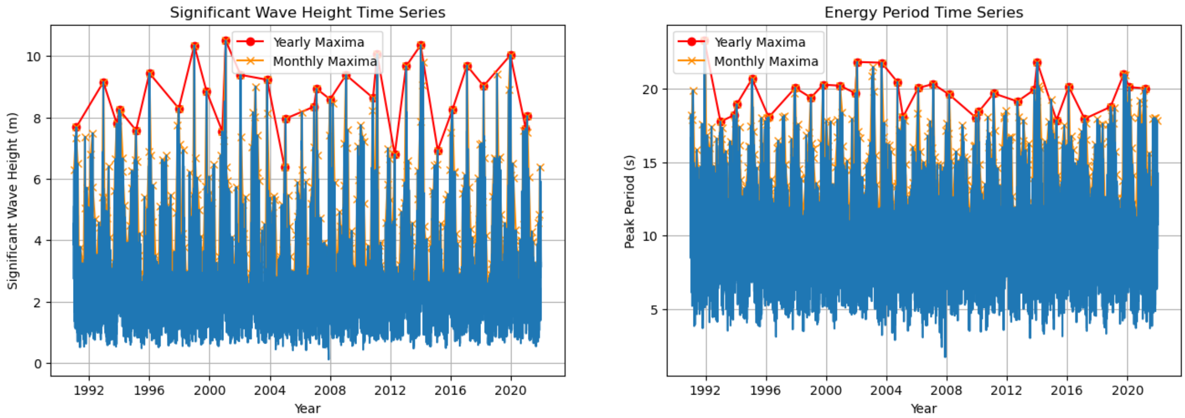


Figure 3.6: Significant Wave Height and Peak Period Monthly and Yearly Maxima

To estimate the energy production potential of the wave energy converter (WEC) park, a stepwise methodology was applied that combines resource characterization, device performance modeling, and system-level loss factors. A joint probability distribution of $H_s - T_p$ was derived using histogram, to be able to identify the probability over all bins. This represents the long-term occurence frequency of different sea states.

Device Performance was modeled using the manufacturer power matrix, which tabulates expected electrical output (kW) as a function of binned H_s and T_p as shown in figure 3.7. As the joint probability is found, therefore, multiplying the aligned joint probability matrix and the power matrix resulted the expected mean power output per device. The mathematical form of the wave energy output is as described in equation 3.3 below:

$$E_{el} = \sum_{i,j=1}^{T} \sum_{i,j=1}^{H_{m0}} p_{i,j} \sum_{i,j=1}^{n_P kDir} \cdot p_{i,j} \cdot PM_{i,j} \cdot P_{kDiri,j} \tag{3.3}$$

where:

- $T_{i,j=1}$ and $H_{m0i,j=1} p_{i,j}$ represents the wave peak periods, significant wave height classes, and the number of occurences in a certain directionality respectively,
- $p_{i,j}$ represents the joint probability matrix of the sea states occurences expressed in fractional form (sum to 1).
- $PM_{i,j}$ is the power matrix from particular device in every significant wave height and peak period or energy period, and
- $P_{kDiri,j}$ describes the directionality of the WECs array in which disregarded in this study. However, applying the WEC array directionality can results to a constructive power output with highly dependency on the sea states of the area.

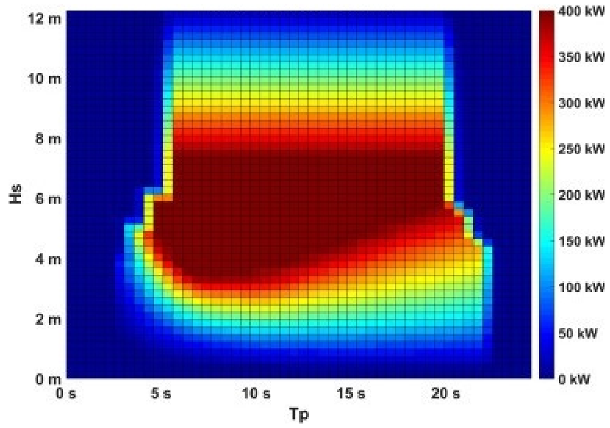


Figure 3.7: Power Matrix of the Selected Device

Finally, the capacity factor (CF) was computed to assess performance relative to the installed rated capacity. For the device level, CF was defined as the ratio of the gross annual energy production to the product of the rated device power and the number of annual hours. At the park level, the net CF was similarly calculated using the net AEP and the total installed park capacity. This approach provides measure of the efficiency of energy capture, accounting for both resource variability and system-level constraints.

3.2.3. Co-located Wind and Wave Power Resource Assessment

Having characterized wind and wave resources individually, the next step is to evaluate their combined performance when deployed in a co-located offshore energy park. In such hybrid systems, power outputs from wind turbines and wave energy converters (WECs) are aggregated to assess total production, installed capacity, and generation shares. This integration not only reflects the absolute contribution of each resource but also highlights potential benefits such as reduced variability and complementary generation patterns.

The combined power output is constructed by aligning the wind and wave time series to a common temporal index and summing the contributions:

$$P_{\text{total}}(t) = P_{\text{wind}}(t) + P_{\text{wave}}(t) \tag{3.4}$$

where $P_{\text{wind}}(t)$ represents the turbine power time series derived from ERA5-based hub-height wind speeds and turbine power curves, and $P_{\text{wave}}(t)$ represents the expected device power estimated from the joint probability distribution of H_s–T_p conditions and the device power matrix. For the baseline configuration, the park consists of 10 offshore wind turbines of 15 MW each (150 MW total) and 75 WECs rated at 0.4 MW each (30 MW total), leading an installed rated capacity of 180 MW.

Installed shares of wind and wave were computed by normalizing each technology's rated capacity against the total installed capacity. Temporal variability of combined output was evaluated by calculating the coefficient of variation (CoV), defined as the ratio of the standard deviation to the mean of the aggregated time series. A lower CoV indicates improved stability, illustrating the smoothing effect of resource complementarity.

Annual Energy Production (AEP) for the co-located park was derived by using integration of capacity factors, with capacity factors determined from the wind and wave resource assessments. The AEP for each subsystem is given by:

$$AEP_x = CF_x \cdot P_{\text{rated},x} \cdot T \tag{3.5}$$

where x denotes wind or wave, $P_{\text{rated},x}$ is the installed capacity, CF_x is the capacity factor, and $T = 8760$ is the annual number of hours. The total AEP of the hybrid park is then:

$$AEP_{\text{total}} = AEP_{\text{wind}} + AEP_{\text{wave}} \tag{3.6}$$

From this, the park-wide capacity factor is computed as:

$$CF_{\text{total}} = \frac{AEP_{\text{total}}}{P_{\text{rated,total}} \cdot T} \tag{3.7}$$

with $P_{\text{rated,total}} = P_{\text{rated,wind}} + P_{\text{rated,wave}}$. By construction, CF_{total} is equivalent to the capacity-weighted average of the two subsystems' CFs, ensuring consistency. Loss factors reflecting realistic operational constraints are included, with assumption of wind availability (95%), wake losses (12%), electrical losses (3%), wave availability (90%), array interaction losses (15%), and wave electrical/control losses (5%).

3.3. Life Cycle Inventory

Life cycle inventory (LCI) is one of the phase of an LCA that involves data compilation to quantify resources use and emissions for each process in a predefined system. LCI is determined by identifying and quantifying materials, including resources, products, or wastes that enter and leave the boundary. To satisfy the input parameters needed, life cycle inventory will be retrieved from ecoinvent inventory. The methodology of building an LCI is by quantifying the inputs and outputs in all processes of the life cycle. Besides, the quantification needs to be adjusted to the readiness level of a technology by doing scale-up to be as close as possible to the real industrial process [2]. According to Saavedra-Rubio et al in [80], the LCI phase requires structured data collection to ensure reproducibility and transparency. This study will follow a three-step LCI framework:

1. **Planning Data Collection:** The first step involves defining system boundaries and functional units, as well as outlining the required data sources. The study will consider cradle-to-grave system boundaries, covering raw material extraction, manufacturing, transportation, installation, operation and maintenance (O&M), and decommissioning. For this study, data collection will come from both primary and secondary source, including industry reports and offshore energy studies and LCA databases for emission factors of materials and energy use.
2. **Data Gathering Process:** This involves collecting primary data from technical reports, industry databases (e.g., ecoinvent), and literature, as well as integrating secondary data for missing information. Given the complexity of offshore renewable energy projects, LCI blocks for different system components will consists of turbines, wave energy converters (WECs), shared transmission system (e.g. HVAC cabling and offshore substations), and shared transport vessels.
3. **Finalizing LCI Blocks:** The last step involves ensuring data consistency, filling gaps using proxy datasets, and performing quality checks. Sensitivity analysis will be conducted to assess the influence of key assumptions on LCA results.

By conducting a detailed LCI, therefore, the potential environmental benefits of sharing offshore infrastructure can be derived. Especially in identifying GWP emissions from reducing vessel trips, adjustment of the cable power capacity, and redundant substations and to provide insight into whether co-location reduces material and energy consumption.

3.3.1. Allocation and Proportion of Co-located Wind–Wave Offshore Energy Park

To ensure comparability of process inputs and to assess how the burden of shared infrastructure is distributed between technologies in the co-located offshore energy park, this study defines the Balance of Plant (BOP) as the shared component. The BOP includes the offshore substation, inter-array cables, and the offshore export cable. The allocation of these elements between wind and wave follows the rated capacity contribution of each system within the co-located park.

$$M_{\text{BOP,wind}} = \frac{\frac{5}{6} \cdot m_{\text{BOP}}}{E_{y,\text{wind}}}$$
$$M_{\text{BOP,wave}} = \frac{\frac{1}{6} \cdot m_{\text{BOP}}}{E_{y,\text{wave}}}$$

Here, $M_{\text{BOP,wind}}$ and $M_{\text{BOP,wave}}$ represent the share of the BOP burden attributed to the wind and wave systems, respectively. The fractions $\frac{5}{6}$ for wind and $\frac{1}{6}$ for wave correspond to their rated capacity contributions, with wind accounting for 150 MW and wave for 30 MW of the total 180 MW. The parameter m_{BOP} denotes the benchmark mass of the BOP component, derived from a combination of literature values and engineering calculations. Finally, $E_{y,\text{wind}}$ and $E_{y,\text{wave}}$ represent the lifetime energy yield share (25 years) of the respective systems, used to normalize the allocated burdens. Using this approach, the environmental burden share for each technology therefore can be ensured, dependent to the energy yield of each technology. The illustration of determining the shared infrastructure burden in the co-located system is as described in the following chart below:

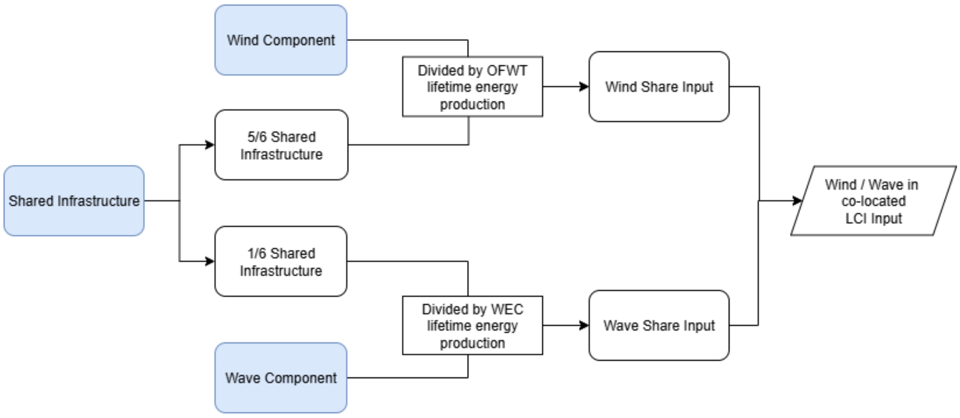


Figure 3.8: Life Cycle Inventory (LCI) Input in Co-located Wind-Wave Energy Park

3.4. Modeling in openLCA

Following the process of collecting data of the LCI, the choosing of the LCI with a proper system process (e.g. consequential or cut-off). As provided in 2.2.3, whereas this study aims to understand about how shared infrastructure can influence the emission throughout the whole lifecycle, thus, the cut-off system process is chosen. This choosing is based on how the system process works, which designates material flows and truncates life cycles at recycling or waste treatment, thereby avoiding allocation of recycling benefits upstream to prevent double carbon counting. While this choice may underestimate the potential benefits of material recycling particularly relevant for steel-intensive components it aligns with the attributional scope of this study and ensures comparability with the majority of offshore renewable LCAs [28], [16].

Subsequently, the processes in openLCA were constructed in accordance with the relevant units and the system processes for raw materials, manufacturing, and end-of-life stages. This step involved aligning the dependent and precedent relationships within the life cycle inventory and adjusting the corresponding providers. In this context, the selection between “market” flows and “production” flows was considered. A market dataset represents the average supply chain of a product, encompassing production and transportation within a specific geographic region, and is typically used for a general representation of a flow. A production dataset, in contrast, focuses on a specific process or method for producing a product, without default transportation or market aspects, and is generally selected when detailed information on the process, transportation, and other related parameters is available.

Following this, a product system was created in openLCA by selecting all foreground processes and using the auto-connect function to link precedent and dependent processes. Once the product system was generated, a verification step was carried out to review the input–output consistency of each process and ensure the correctness of the dependent–precedent relationships across the system.

3.5. Sensitivity Analysis

The purpose of undergo sensitivity analysis in Life Cycle Assessment (LCA) is to evaluate the robustness of the result and their dependence on the input parameters assumptions, and models. It allows identifying the most influential parameters and how we can actually improve the data quality to enhance LCA outcomes. A critical aspect of conducting proper Sensitivity Analysis (SA) in LCA is addressing correlations within LCI data and interactions within the LCA calculation model.
Once the correlation within LCI data and LCIA for further use in LCA is determined, then it'll be followed with choosing an appropriate SA method, between Local Sensitivity Analysis (LSA) or Global Sensitivity Analysis (GSA). The main distinction between these two methodology is in the insight they provide, whereas LSA provides a snapshot of sensitivity at a specific point, while GSA provides a broader picture of sensitivity across the entire range of uncertainty.

In this study, SA also involves evaluating the sensitivity of GWP impact category results to the choice of LCIA method, specifically comparing EF 3.1 and IMPACT World+. EF 3.1 is the official method adopted by the European Commission for environmental footprint and is suited for policy-compliant carbon reporting. On the other hand, IMPACT World+ offers a regionally differentiated perspective and additional analytical depth, particularly relevant for marine and offshore contexts. This comparison illustrates how methodological choices can influence LCA outcomes and supports the need for transparent and robust evaluation.

Additionally, to assess the impact of shared infrastructure in a multi-source offshore energy park, an analysis was carried out for a scenario where the substation, inter-array cables, and export cables are separated for each technology, in addition to the baseline scenario where all supporting infrastructure is combined. Since the total power transmitted through the cables and received by the substation will differ in this case, the cable capacity was recalculated, including both capacity and loss calculations. For the offshore substation, due to time constraints, the topside mass was estimated through extrapolation based on the topside mass of existing offshore substations in the market, while the jacket mass was derived using linear regression against water depth and topside mass.

To implement SA, OpenLCA can be utilized to define uncertain parameters and execute SA model to generate sensitivity. With this result, thus, the most impactful parameters can be found for further planning about improvement efforts of the infrastructures. As the final step, validation of the SA needs to be completed to ensure reliability and completeness of the results.

3.6. Payback Indexes

The energy and environmental performances of renewable energy plants can be evaluated by the payback indexes, either the carbon payback time (CPBT) or energy payback time (EPBT). When CPBT estimates the time required to compensate the greenhouse gasses (GHGs) emission, EPBT estimates the time required to recover the primary energy consumption throughout the entire life cycle of the wind farm [19].

When the location for resource assessment taken is in Portugal, the whole supply chain and construction is not necessarily bound to Portugal area. Therefore, the assumption is made that the supply chain will circulates within Europe. This can help to prevent potential errors that may arise. Following that, based on International Energy Agency (IEA), Europe has total energy supply of 76,102,749 TJ with total energy supply per capita of 62,680.541 MJ/Capita or 0.0174 GWh/capita. The main biggest contributor for energy supply in Europe is from oil with 32.3% with the least contribution from hydro with 2.6%. Besides the two, total energy supply by source in Europe is detailed as in the table below.

Table 3.4: Europe Energy Mix Source (2023)

Mix Sources	**Coal**	**Oil**	**Natural Gas**	**Nuclear**	**Hydro**	**Wind, solar, etc**	**Biofuels and waste**
Value (GWh)	10,304,261	24,580,658	18,760,293	8,191,618	1,995,482	4,125,035	8,108,179
Percentage	13.50%	32.30%	24.70%	10.80%	2.60%	5.40%	10.70%

To calculate the EPBT, therefore, the parameter needed would be total energy production of the renewable energy and total energy used for the turbine's consumption, including its manufacturing, operation, transport, dismantling, disposal and the expected average energy production [57]. The energy payback period is calculated using:

$$EPBT = \frac{E_{used}}{E_{produced}} \tag{3.8}$$

In addition to EPBT, it is possible to calculate the time required for the system to mitigate the GHG emissions from the wind turbine production, the GHG payback time (GPBT),

$$GPBT = \frac{Em_{LCA}}{AEm_{avoided}} \tag{3.9}$$

Where,Em_{LCA} is the total GHG emissions for the manufacture, installation, operation and disposal of the wind turbine (obtained via LCA). On the other hand, $AEm_{avoided}$ is calculated as difference between emissions that would be generated by the electricity grid consumption and the emissions from the renewable energy technology [35].

4 Inventory Analysis

To address the defined goal and scope, the Life cycle inventory (LCI) is the data collection phase of a LCA. It involves detailed data regarding all the inputs and outputs of the system, including materials, resources, energy and emissions throughout the process or product life cycle [67]. The outline of life cycle inventory used in this study is pictured in figure 3.1 with each color corresponding to each processes.

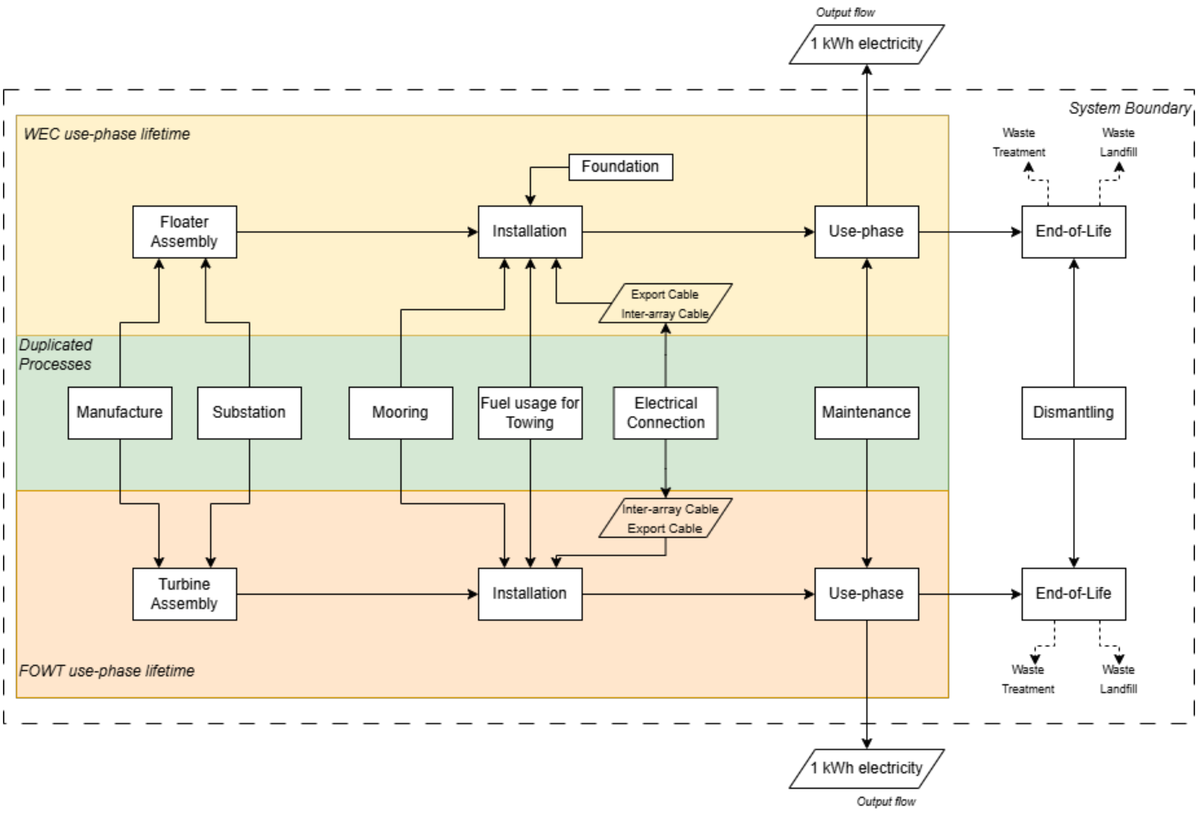


Figure 4.1: Life Cycle Inventory Framework for Offshore Energy Park and Technology Specific Processes

4.1. Floating Offshore Wind Turbine

Due to the absence of primary data, approximations and assumptions are required to include in the analysis of the FOWT whole life cycle stages. The analysis has been conducted using openLCA software, based on the utilization of the database ecoinvent 3.11 with system model "Allocation, cut-off by classification". In this study, the wind power technology assessed is 15 MW floating wind turbine with technical data retrieved from developer along with its semi-submersible support structure based on the model developed by University of Maine in [8], whereas they developed the floating support structure for 15 MW IEA offshore wind turbine. The energy park consists of 12 devices extending on an area of 42.2 km^2. A diagram of the offshore floating wind turbine input tree can be seen in the figure 4.2 below.

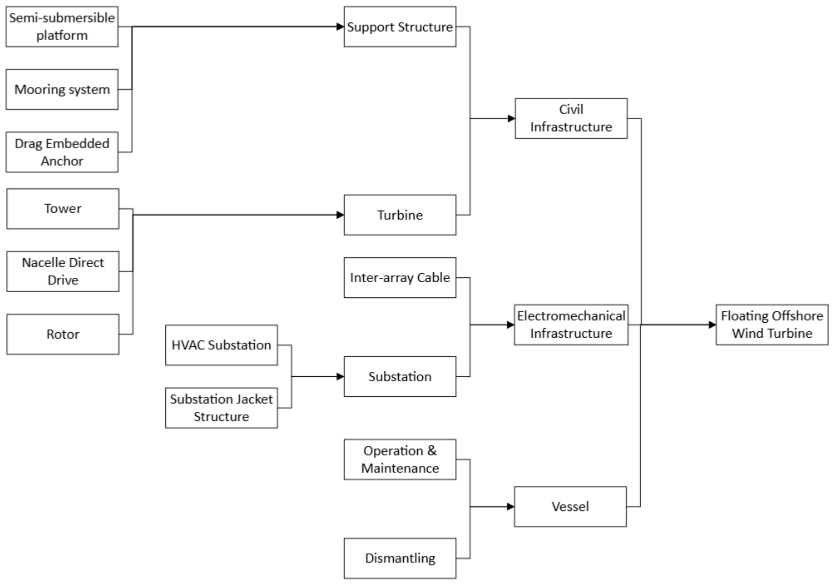


Figure 4.2: Offshore Floating Wind Turbine Input Tree

From previous studies, it is found that the installation of semi-submersible FOWT carried out with the utilization of several vessels. The vessels include tugs, AHTSs (Anchor Handling Tug and Supply) and ROV-Support cable-lay vessel. Since the study location for this ORE park is 25 km from Viana do Castelo, thus, these vessel supplied from The berthing terminal of Ferol, Spain, to the location of deployment with total distance of 155 nautical miles or 287.06 km [15]. In recent years, the installation of the FOWT can be divided into two classes: integrated transport and on-site installation [45]. Considering the chosen substructure for this study is semi-submersible, therefore, the assumed installation of the FOWT would be dry-dock assembly of the hull, tower, and turbine and followed by towing to the side and tied to a pre-installed mooring using tugboat vessels. Once it's arrived to the deployment site, the mooring hook-up will be assisted with anchor handling vessel [50]. The FOWT energy park layout that will be used in this study is as in figure 4.3 below.

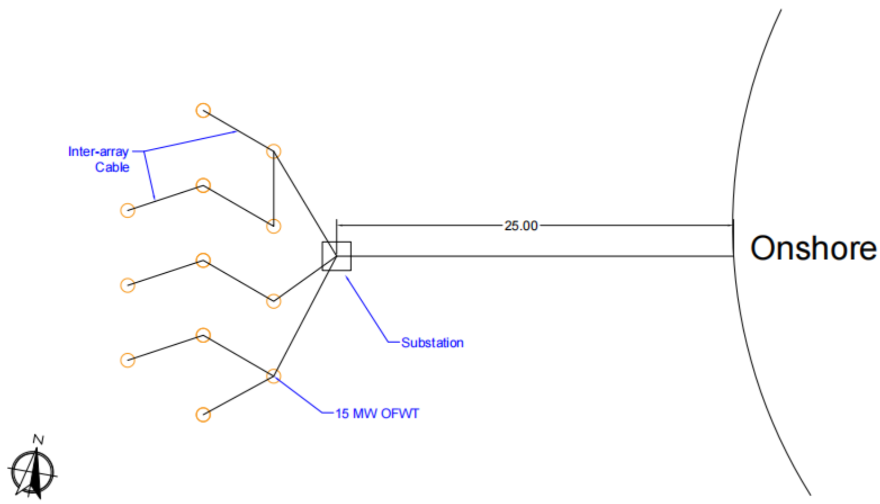


Figure 4.3: Floating Offshore Wind Turbine Energy Park

4.1.1. Support Structure

Floating support structures provide the necessary stability for wind turbines without being anchored rigidly to the seabed. This allows deployment in a wider range of water depths and seabed conditions. Based on the reference [49], each support structure presents different structural and operational advantages depending on local site characteristics:

- Spar-buoy platforms rely on deep draft ballast systems, limiting their use to water depths typically exceeding 100 meters and complicating in-port assembly and towing.
- Tension-leg platforms (TLPs) achieve stability through high-tension vertical moorings but demand specialized anchoring and installation systems, increasing project complexity.
- Semi-submersible platforms, by contrast, use distributed buoyancy and catenary mooring systems that allow for moderate draft designs.

The reference platform used in this report is a three-column, steel semi-submersible developed in the framework of IEA Wind [8], followed with extrapolation over tower mass carried by the semi-submersible platform. This steel semi-submersible structure therefore modeled with structural steel mass, equipped with fixed ballast using iron ore concentrate and fluid ballast modeled using water.

Besides the semi-submersible platform, a part of the FOWT support structure is the mooring chain connected to a drag-embedment anchor. The modeling of mooring chain follows a structured computational process to represent the suspended geometry of the mooring line and determine key parameters such as fairlead position and tension forces [3]. The process assumes the usage of R4S mooring chain with EA $= 1.725 \times 10^9$N and weight per meter of 379.1 kg/m [97] The process of modeling includes iteration of the total length of mooring, using inverse hyperbolic functions and square root terms to reflect the natural curve formed under gravity and tension. Following the iteration of the mooring length, it confirms that the assumed length of 200 m with total of 600 m per structure is sufficient for a water depth of 80 meters, with the suspended segment, not resting on the seabed is 150 m. This mooring chain therefore connected to 20 tonnes steel Drag Embbeded Anchor (DEA) [90]. A diagram of processes and product of the support structure for Life Cycle Assessment can be seen in the following figure.

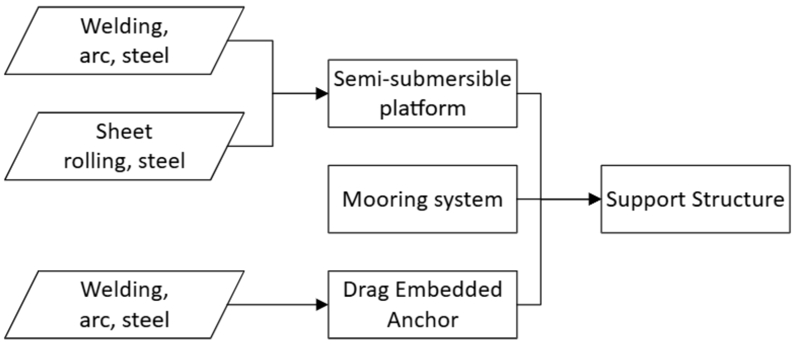


Figure 4.4: FOWT Support Structure Tree Diagram

4.1.2. Turbine

In this report, the technical specification of the wind turbine follows the technical specification of offshore wind turbine V236 which has 15 MW rated capacity. The assumption for turbine dimension in this study is 138 m hub height with rotor diameter of 236 m. As the main supply chain node, the selected port is located 25 km off the deployment location. Port of Viana do Castelo serves as the logistical cornerstone of FOWT deployment in northern Portugal. Previously used for the assembly and deployment of the project, the port is capable of handling large wind turbine components and subsea structures [73]. Besides the steel structure, turbine also consists of mechanical component, namely Rotor Nacelle Assembly (RNA). This RNA is a combination of essential structural components, i.e. nacelle, gearbox, and rotor (i.e., hub and blades combined) that transform wind energy to electrical power [6].

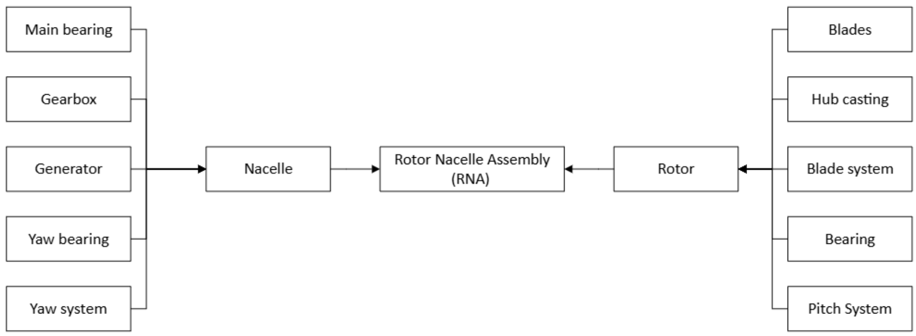


Figure 4.5: Rotor Nacelle Diagram Tree Diagram

4.1.3. Inter-array Cable 66 kV

Due to the relatively short transmission distances within the park, all inter-array cables used in this report operate with three-phase alternating current (AC) systems. The dynamic inter-array cables are rated at 66 kV, in line with current industry practice for floating wind applications [56]. For the submarine cable specifications, the 66 kV cable design provided by ABB is used as a reference.

To determine the appropriate cable dimension, an iterative power calculation was conducted using Equation 4.1:

$$P = U \cdot I \cdot \sqrt{3} \tag{4.1}$$

Based on the reference provided by [1], with each turbine having a rated capacity of 15 MW and each array consisting of up to 3 turbines, the suitable 66 kV cable has a cross-sectional area of 240 mm^2. This cable has an ampacity of 480 A, resulting in a transmission capacity of 54.87 MW and power losses of 0.06 MW.

The total required length of inter-array cabling across the entire floating offshore wind turbine (FOWT) park is approximately 84.78 km. Given the cable weight of 31.3 kg/m, the total inter-array cable mass in the park amounts to 2,653 tonnes. A detailed material breakdown is presented below.

Table 4.1: Inter-array Cable Inventory Breakdown

Material Classification	Value	Unit	Percentage
Steel, low-alloyed	610.3	t	23.00%
Lead	610.3	t	23.00%
Copper	796.1	t	30.00%
Polyethylene	557.3	t	21.00%
Polypropylene	79.6	t	3.00%
Processing			
Wire drawing, steel	447.15	t	
Wire drawing, copper	508.13	t	

4.1.4. Offshore Export Cable

For the purpose of calculation simplicity and conservative assumption, all export cables are assumed to be 220 kV cable with 500 mm^2 [66]. The selected cable has copper conductor offers an optimal balance between electrical capacity and mechanical flexibility for floating offshore wind applications. It has a nominal outer diameter of 88.8 mm and weighs approximately 81.30 kg/km [66]. The conductor is made of circular compacted, plain annealed copper, designed with water-blocking tapes to prevent moisture ingress. Insulation is provided by cross-linked polyethylene (XLPE), encased between inner and outer semiconducting thermosetting layers, ensuring excellent dielectric performance.

Table 4.2: Export Cable Inventory Breakdown

Material Classification	Details / Value	Unit	Percentage
Steel, unalloyed low alloyed	447.15	tonne	22.00%
Copper	508.13	tonne	25.00%
Lead	406.50	tonne	20.00%
Polyethylene	630.08	tonne	25.20%
Polypropylene	40.65	tonne	2.00%
Activity			
Wire drawing, copper	508.13	tonne	–

4.1.5. Offshore Substation

The offshore substation in this study includes both the jacket structure and the substation topside. Since detailed substation modeling lies outside the scope of this research, their sizing was determined using a transparent, literature-based parametric approach supported by regression calibration. Benchmark data were obtained from [39], which provide information on park capacity, topside weight, and jacket structure weight.

Because this study focuses on assessing the influence of shared infrastructure on the Global Warming (GWP) impact of a multi-source offshore energy park, necessary adjustments were made to the estimated topside and jacket mass.

$$y = 6.4477\text{x} - 75.549 (R^2 = 0.75) \tag{4.2}$$

Furthermore, the jacket mass, which is influenced by both the topside mass and water depth, was calculated using the following equation derived from the multivariate regression approach:

$$\text{Jacket Mass} = a \cdot \text{Topside Mass} + b \cdot \text{Water Depth} + c \tag{4.3}$$

Whereas based on the calculation, it is found that the value of a, b, c are as below:

- a = 0.39585
- b = 30.109
- c = -111.29
- R^2 = 0.87

Equations 4.2 and 4.3 both demonstrate relatively high coefficients of determination. The R^2 of 0.75 suggests that 75% of the variability in topside mass is explained by the model, indicating a moderately strong relationship that makes it suitable for adoption in this study. The of 0.87 for jacket mass indicates a stronger correlation, showing that topside mass and water depth are reliable predictors of jacket mass.

Applying these equations, the estimated topside and jacket weights for a 180 MW offshore energy park are 1,085 t and 2,727 t, respectively. In a multi-source offshore energy park combining wind and wave technologies, the values differ because each substation transports energy from its respective technology to the export cable. For a 30 MW WEC installation, the substation mass is estimated at 219 t for the topside and 2,384 t for the jacket. The offshore wind turbine (FOWT) substation is estimated at 949 t for the topside and 2,673 t for the jacket.

The proportional material breakdown is shown in Table 4.3, where steel, aluminium, copper, lubricating oil, and gravel account for the majority of inputs. These distributions were applied to the calculated masses of each substation variant to generate the Life Cycle Inventory (LCI).

Table 4.3: Percentage contribution for the offshore substation [27]

Material	Percentage
Sand	0.4311%
Epoxy resin	0.0540%
Steel, low-alloyed	0.5721%
Aluminium	0.2361%
Nickel	0.0192%
Alkyd paint	0.0011%
Cast iron	0.0023%
Chromium steel	0.0092%
Copper	0.3156%
Glass fibre	0.0133%
Kraft paper	0.0002%
Lubricating oil	0.5763%
Polycarbonate	0.0001%
Polyester resin	0.0002%
Polyethylene	0.0005%
Sawn timber	0.0001%
Silver	0.0000%
Sulphate pulp	0.0636%
Sulphur hexafluoride	0.0115%
Synthetic rubber	0.0043%
Gravel	12.4609%
Processing	
Average metal working, steel	30.8009%
Welding, arc, steel	0.0241%

4.1.6. Installation

For the installation phase I expressed vessel use in tonne-kilometres (t·km). This reflects the fact that installation activities are dominated by the transport of very heavy components (e.g., semi-submersible structures, turbines, anchors, long cables) over fixed distances from port to site. In this context, the mass and distance moved are the primary drivers of energy demand and emissions, and duration is secondary. Using t·km is therefore consistent with how maritime transport is represented in ecoinvent and ensures comparability with other LCAs of offshore structures.

Prior to the installation of the structure, there are transport steps that have been included in this study, which includes:

- The assumption for the transportation of the pre-manufactured component is 140 km for transport by road from the manufacture area to the port [28] which continued with water transportation. Within that 140 km, based on the ICCT WORKING PAPER 2021-20, the distribution of lorry >32t divided and limited into 60% of EURO6 and the remaining 40% is distributed between EURO 1 - EURO 4. However, to support the acceleration from EURO 4 to EURO 6, this study will assume the remaining 40% of lorry follows EURO 4 emission standard.
- Transport of moving wind plant components from technology developer and submarine cable factories with normalization to the assembly port [95], as in table 4.4

Table 4.4: Transport Distances of Wind Turbine Components from Factory to Assembly Port

Component	Lorry [km]	Ship [km]
Nacelle	140	1000
Blades	140	1000
Tower	140	1000
Mooring Chains	100	1000
Offshore Substation	100	1000
Site Cables	150	1000

For the offshore installation itself, vessel activity is first characterised in terms of operational hours and installed cable length, and subsequently converted into fuel use (litres). For mooring and anchoring operations, this study assumes 35 hours of mooring hook-up per FOWT and 12 hours per anchor for drag-anchor tensioning. For cable installation, the laying rate is assumed to vary between 0.13 km h^{-1} for since the cables assumed to be buried using water jetting [86]

These durations, combined with typical fuel consumption factors for each vessel class, are used to calculate the total volume of fuel burned (in litres) for each installation activity. The corresponding emissions are then linked to ecoinvent maritime transport processes expressed in t·km for component transport and in litres of fuel used during the on-site installation.

4.1.7. Operation & Maintenance

Floating offshore wind turbines (FOWTs) operate in harsh marine environments, leading to component failures primarily due to two causes: (1) aging and degradation of electronic systems, and (2) physical damage to structural elements [54]. Ren et al. [76] classify maintenance strategies into two major types: *corrective maintenance*, which is reactive and performed after failures, and *proactive maintenance*, which includes *time-based preventive* and *sensor-based predictive* approaches.

According to Zhang et al. [104], optimizing maintenance frequency is essential for balancing reliability, operational cost, and energy availability. Their study emphasizes that while primary components such as generators, gearboxes, and blades generally follow maintenance cycles of 1–3 years, auxiliary systems like control electronics may require more frequent attention—up to semi-annually or quarterly. Hosseini et al. [44] further report that failure rates for subsystems average between 0.2 and 1.0 failures per turbine annually, with control and electrical systems being the most failure-prone.

To mitigate critical failures, periodic inspections are conducted as outlined in Table 4.5. These frequencies reflect practical requirements for ensuring structural and electrical integrity of both turbine and substructure systems.

Table 4.5: Inspection Schedule for Major FOWT Subsystems

Inspection	Frequency	Duration [h]	Vessel Type
Sub-sea inspections of cables, mooring lines, and floater hull	2-yearly	12	Crew Transfer Vessel (CTV) or SOV in certain scenarios
Sub-sea inspection of export cable	2-yearly	12	Crew Transfer Vessel (CTV) or SOV in certain scenarios
Inspection of structural elements above water (e.g., deck, transition piece)	Annual	24	Crew Transfer Vessel (CTV) or SOV in certain scenarios
Inspection of wind turbine components	Annual	24	Crew Transfer Vessel (CTV) or SOV in certain scenarios
Inspection of offshore substation (OSS)	Annual	24	Crew Transfer Vessel (CTV) or SOV in certain scenarios

Recent advances include opportunistic maintenance models, as demonstrated by Mingxin et al. [53], who applied a Non-Homogeneous Continuous-Time Markov Process over a 10-year simulation for a 15 MW FOWT. Their model integrates preventive and corrective strategies by clustering maintenance activities across multiple components within the same service window [53]. Complementing this, data from the GROW initiative provide failure rates and maintenance expectations for substructure components. The cumulative probability of failure over the 25 years of wind turbine lifetime calculated upscaled from the failure rate for each component is summarized in Table 4.6.

Table 4.6: Repair Probability and Maintenance Frequency of FOWT Park

Subsystem	Category	Failure Rate (fail./yr)	# Maintenance (per 25 yr)
Floating platform	Major replacement	0.033	10
	Minor repair	0.010	3
Mooring line	Major replacement	0.013	4
	Major repair	0.015	5
	Minor repair	0.120	36
Anchor	Major replacement	0.015	5
	Minor repair	0.120	36
Dynamic cable	Major replacement	0.025	8
	Minor repair	0.016	5
Electrical subsystem		0.010	4
Drive train		0.030	11
Generator		0.030	8
Rotor blade		0.010	4
Rotor hub		0.003	1
Electrical control		0.001	1
Yaw system		0.020	5

Following to the previous studies regarding O&M for semi-submersible FOWT ([36], [104], [53], [44]), this study will implement a preventive maintenance schedule where high-failure-probability components—the floating platform, mooring lines, anchors, and dynamic cables—will receive maintenance every six months using a Crew Transfer Vessel (CTV). Electrical subsystems, conversely, will be maintained annually with a Service Operational Vessel (SOV).

In the O&M phase, vessels assumed to be not transporting heavy cargo but rather servicing equipment and personnel at offshore site. Therefore, the dominant driver of emissions is the time spent at sea rather than the weight of cargo moved. For this reason, fuel consumption is used to capture the emissions by converting liters of diesel which converted to marine diesel oil (MDO) into energy (kWh) and multiplied with the frequancy of maintenance through the technology lifetime. This method represents the intensity of vessel and fuel use during repeated maintenance campaigns.

4.1.8. End-of-Life

The decommissioning EoL strategy can be divided into the five phases as in figure 4.6. However, different removal methods can be employed based on factors such as weight and size, impacting the lifts and time required for the process. In compliance with policies such as the new EU Circular Economy Action Plan [58] and national-level legislation on wind turbine waste, there is now a consensus among industries to aim for 100% recyclable wind turbine blades. There are four types of waste management; landfill, incineration with municipal waste, incineration in cement kilns, mechanical recycling with landfilling of residual waste materials, and mechanical recycling with incineration of residual waste materials [42]. These processes of both decommissioning and post-decommissioning including its waste management have four distinct scenarios that can be used for further LCA processes. With the turbine composition that primarily composed of 83% steel, 11% cast iron, 1% copper, and 5% other materials including glass fiber reinforced epoxy, glass fiber reinforced plastics, and carbon fiber [88] can have 83% recyclability rate covering major components like the tower, gearbox, main shaft, generator, castings, bearings, and parts from the nacelle and hub [38].

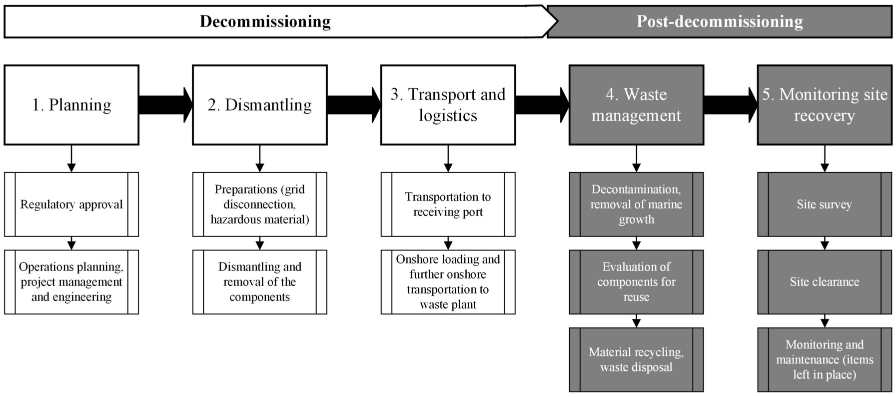


Figure 4.6: End-of-Life Scenario, source: [96]

In this study, the decommissioning and post-decommisssioning that taken into account for End-of-Life Life Cycle Inventory are dismantling, transport and logistics, and waste management. Dismantling process includes the wind turbine removal, anchor removal, offshore substation removal, cable removal, and seabed clearance [48]. These removed components of the offshore wind then being transported to the nearest Solid Recovered Fuel (SRF) pre-processing site, and continue to the cement factory [64].

4.2. Wave Energy Converter Park

In this study, the chosen type of Wave Energy Converter (WEC) is the point absorber with rated power and dimensions following CorPower Ocean as described in [70]. However, due to the limitations and undisclosed material details of the product, thus, this study will use the same point absorber arrangement as in [28]. The point absorber WEC is broken down into a floater, the PTO for power conversion, and a foundation acting as the reference to the heaving body with configuration as in figure 4.7

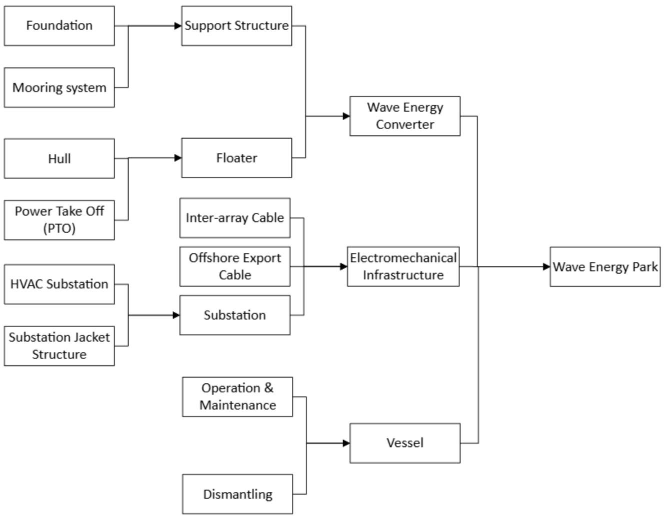


Figure 4.7: WEC Input Tree

The Wave Energy Converters (WECs) are arranged following the deployment layout of installed wave energy array, which in this study is referred to as an array. Each array consists of 28 WEC devices with a total rated power output of 10 MW. To achieve the target capacity of 180 MW, the energy park is therefore composed of 18 clusters with each clusters consists of 25 devices.

Within each array, the distance between individual devices is 150 meters following the deployment arrangement modelled in detail using analytical calculations based on expert knowledge [70]. This distance therefore resulting 6 kilometers length and 2.035 kilometers width, following the spacing between each parallel row is 185 meters. The entire array is oriented such that there is a 10-meter offset between the front row and the offshore substation connection point, ensuring efficient cable routing. As illustrated in Figure 4.8, the layout includes inter-array cables that link devices within each cluster, collection hubs that connect multiple rows, and an export cable that transmits the collected power to the offshore substation. In this section, the modelling assumptions for each of the wave energy converter farm are explained.

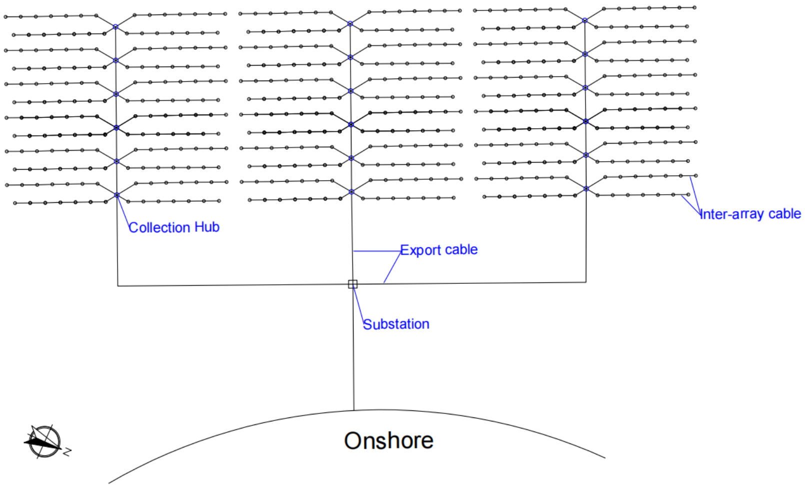


Figure 4.8: Wave Energy Farm Layout

4.2.1. Wave Energy Converter

Each Wave Energy Converter (WEC) unit is designed with a cylindrical floating structure, with dimensions of 9 meters in diameter and 18 meters in length. The device incorporates a direct-drive linear generator housed within the floater, serving as the Power Take-Off (PTO) mechanism. The rated power output of each unit is 400 kW, and the system is assumed to have a lifetime of 25 years, consistent with standard design expectations for marine energy technologies.

The specification of the point absorber percentage is following the detail of materials described in [70] and [28]. The material composition of a single Wave Energy Converter (WEC) unit has been analyzed to determine the relative contribution of each component to the total structural mass. Steel dominates the overall weight, accounting for approximately 86.8% of the total mass when combining its use in the hull, PTO, foundation, and mooring system. The mooring chains alone contribute around 59.7%, representing the single largest share, followed by the hull structure (8.7%) and foundation (5.1%). Power Take-Off (PTO) components represent about 1.6% of the total mass, distributed among iron (0.4%), copper (0.4%), permanent magnets (0.3%), epoxy (0.01%), and steel (0.02%). Paint and electronics together account for less than 0.1% of the total weight. This breakdown highlights the steel-intensive system of the structure.

Besides the core material for the WEC system, a protective paint is applied to the component, considering the highly corrosive environment of the system. Following a study by Thomson et al [87], this study will use the same percentage of corossion-resistant paint as proposed for Pelamis WEC. The percentage of each composition for the painting is as below:

Table 4.7: WEC Painting Material Composition Breakdown

Material Classification	Percentage
Xylene	4.78%
N-butanol	2.54%
Phenol	0.65%
p-phenylen diamine	0.17%
o-phenylen diamine	0.17%
Ethanol, without water, in 99,7% solution state, from ethylene	0.26%
Ethyl benzene	0.01%
Ethylene diamine	0.21%
O-aminophenol	0.17%
Epoxy resin, liquid	41.66%
Naphtha	0.79%
Dimethenamide	0.90%
Flat glass, uncoated	47.69%

4.2.2. Inter-array Cable 33 kV

To determine the suitability of the 33 kV, 95 mm^2 cable for the inter-array connections in the WEC farm, a power transmission calculation was performed using specifications from the manufacturer (Nexans). The cable is rated for a continuous current of $300\,\mathrm{A}$ and a nominal voltage of $33\,000\,\mathrm{V}$. Using the three-phase power equation $P = \sqrt{3} \cdot V \cdot I$, the cable is capable of transmitting approximately $17.15\,\mathrm{MW}$ of apparent power. Assuming an active power output of $11\,\mathrm{MW}$, the line experiences power losses of $0.0234\,\mathrm{MW}$, or approximately 0.136%, based on the resistive loss formula $I^2 \cdot R$. Given that each WEC cluster has a maximum output of $10\,\mathrm{MW}$, the 33 kV cable configuration is technically sufficient to handle the power flow between devices and the collection hub without exceeding its thermal or electrical limits. Therefore, the selected 33 kV, 95 mm^2 cable is appropriate for use as an inter-array in this WEC array layout, ensuring both efficiency and compliance with operational constraints.

The material weight distribution of the 3-core 33 kV XLPE cable that form 665 kg/100 m [66] is as below:

Table 4.8: 33 kV Inter-array Cable Inventory Breakdown

Material Classification	Percentage
Copper	33.60%
Lead	43.07%
Polyethylene	10.14%
Polypropylene	6.66%
Steel, low-alloyed	6.53%

4.2.3. Offshore Export Cable

Following the studies by Elginoz [27] and Engelfried [28], the selected export cable is a 3-core XLPE-insulated cable with a voltage rating of 132 kV. Through iterative calculations using various conductor cross-sectional areas to meet the required capacity, it was found that a cross-sectional area of 630 mm^2 is sufficient to transmit up to 180 MW. Based on the specifications in [1] and using the three-phase power equation $P = \sqrt{3} \cdot V \cdot I$, the calculated power transmission capacity reaches approximately 188.62 MW with a losses of 0.177 MW. The percentage distribution of the materials used in the cable is presented in table 4.9.

Table 4.9: Material composition of the 132 kV export cable

Material	Percentage (%)
Copper	25.06%
Lead	25.19%
Polyethylene	8.92%
Polypropylene	4.98%
Steel, low alloyed	35.85%

4.2.4. Offshore Substation

Considering the same total rated capacity generated by WEC and the FOWT, therefore, the material composition of the substation in WEC park can still be referred to section 4.1.5.

4.2.5. Operations & Maintenance

Following the same configuration as the operation & maintenance of FOWT Park, the maintenance will include scheduled maintenance and corrective maintenance. Based on the previous study, table 4.10 outlines the sufficient frequency for scheduled maintenance of a point absorber WEC.

Table 4.10: Availability of scheduled maintenance guidance for main WEC subsystems

Subsystem	Scheduled Maintenance Info	Remarks
Foundation / Structure	2-yearly	[36]
Mooring System	2-yearly	[36]
Hull (Buoy Structure)	Yearly	[28]
Power Take-Off (Hydraulic)	Semi-annually	[77]
Substation / Grid Interface	Yearly	[36]

To develop an effective corrective maintenance strategy, it is essential to quantify the failure rates of key subsystems in the wave energy converter (WEC). Failure rate, expressed in failures per year, represents the expected number of failures of a component per year under normal operating conditions. This parameter directly informs the expected frequency of corrective maintenance interventions. The values presented below derived from surrogate data and adjusted for offshore conditions using environmental correction factors, as outlined in Rinaldi et al. [77] and Mueller et al. [62]. Table 4.11 presents the estimated failure rates for the most critical subsystems in a hydraulic point absorber WEC.

Table 4.11: Estimated Corrective Maintenance throughout the Device Lifetime of 25 Years, source [77]

Subsystem	Failure Rate (failures/year)	Device Maintenance Frequency (maintenance/25 years)
Hull (buoy structure)	0.001	1
PTO control system	0.006	1
Power electronics	0.028	1
Electric generator	0.145	4
Grid (SCADA system)	0.041	2
Mooring	0.114	3
Substation	0.053	2

The installation, operation, and maintenance of the wave energy converter (WEC) park require the deployment of multiple specialized vessels, each fulfilling a specific function across various life cycle stages. These vessels include crew transfer vessels (CTV), tugboats, heavy lift vessels (HLV), and anchor handling tug supply (AHTS) vessels. The selection of vessel types is based on their operational suitability and availability within typical offshore renewable energy projects. Table 4.12 presents the hourly fuel consumption of each vessel under different operational modes—transit, towing, and operation—sourced from Garcia-Teruel et al. [36]. These values provide a basis for estimating fuel usage and emissions associated with marine logistics throughout the WEC park's life cycle.

Table 4.12: Vessel fuel consumption by operational mode, source: [36]

Vessel Type	Fuel Use (l/h)		
	Transit	Towing	Operation
CTV	396.41	–	238.26
Tugboats	429.09	334.86	–
HLV	2266.00	–	113.00
AHTS	1046.00	1942.00	1046.00

Following the frequency of maintenance on table 4.11, table 4.10, and table 4.12, the vessel usage and fuel consumption throughout the 25-year operational lifetime of the wave energy park can be quantified. The assumed distance for a round-trip distance of 112.21 km to the offshore site as depicted in figure 4.8. Fuel consumption rates and operational profiles are adopted and upscaled from García-Teruel et al. [36]. Due to the limitation and studies about the common duration for operating hours during the maintenance, hence either corrective or the scheduled maintenance assumed to have 6 hours operating duration.

Table 4.13: Scheduled Maintenance Vessel Usage and Fuel Consumption over 25 Years

Subsystem	Vessel	Transit Duration (h)	Total Fuel Consumption (25 yrs) (L)
Foundation / structure	CTV	2.42	7,000,771.22
	Tugboats	4.49	9,767,696.96
Mooring	CTV	2.42	7,000,771.22
	Tugboats	4.49	9,767,696.96
Hull (buoy structure)	CTV	2.42	14,001,542.44
	Tugboats	4.49	19,535,393.91
Power Take Off (PTO)	CTV	2.42	28,003,084.89
	Tugboats	4.49	39,070,787.83
Substation	CTV	2.42	14,001,542.44
	Tugboats	4.49	19,535,393.91
Auxiliary	CTV	2.42	14,001,542.44
	Tugboats	4.49	19,535,393.91

Besides the scheduled maintenance, dependent with the failure rate and recommended device maintenance frequency based on the failure rate as in table 4.11. The total number of interventions for the whole park was derived by multiplying the failure rate for each component with the total lifetime duration and total number of device. Therefore, it arrives to the value of total fuel consumption for the corrective maintenance as in the table below:

Table 4.14: Corrective Maintenance Fuel Consumption Estimates (25 Years)

Component	Total # Maintenance (all devices /25 years)	Operation duration (hr.)	Total fuel consumption (L)
Hull (buoy structure)	450.00	6	305,100.00
PTO control system	450.00	6	305,100.00
Power electronics	450.00	6	305,100.00
Electric generator	1800.00	6	1,220,400.00
Grid (SCADA system)	900.00	6	610,200.00
Mooring	1350.00	6	915,300.00
Substation	2.00	6	1,356.00

The cumulative fuel consumption for corrective maintenance alone over the 25-year period exceeds 1.2 million liters, while scheduled maintenance contributes an additional 1.0 million liters. These figures highlight the significance of vessel operations in the overall life cycle environmental impact of the wave energy system.

4.2.6. End-of-Life

Following the 25-year operational lifetime of the wave energy converter (WEC) park, all components are assumed to be fully dismantled and transported back to shore for subsequent processing. Alavi et al. [4] identified several common end-of-life (EoL) strategies for marine renewable energy systems, including landfilling, mechanical recycling, chemical treatment, reuse in construction, and energy recovery through incineration. In this study, it is assumed that all WEC components will undergo complete decommissioning, using reversed installation procedures with the same vessel types. Consequently, the dismantling durations are assumed to be 12 hours per mooring line, 13 hours per foundation unit, 8 hours per mooring separation, and 10 hours per foundation separation, based on [28].

Building upon the approaches presented by [28] and [78], the proposed EoL treatment strategy for the WEC park following dismantling is summarised in Table 4.15.

Table 4.15: End of Life - Material Treatment

Component / Activity	Recycle	Treatment%	Treatment Type	Landfilling
Steel	90%			10%
Iron	90%			10%
Copper	90%			10%
Polyethylene	1%	44%	Municipal incineration	55%
Polypropylene	1%	44%	Municipal incineration	55%
Magnets	90%			10%
Electronics	60%			40%
Aluminium	90%			10%
Epoxy	33%	34%	Mechanical treatment	33%
Mineral oil		100%	Mineral oil regeneration	

4.3. Wind-Wave Energy Park

In order to be able to answer the research questions which mainly regarding how the shared infrastructure in multi-source wind-wave offshore energy park effects the GHG emission compared to the stand-alone wind or wave energy park, therefore, to model the energy park with the same rated capacity is necessary. In this scenario, the park will consists of 10 offshore wind turbine with 15 MW capacity each and 75 wave energy converter devices with 400 kW capacity each. As the device types and capacities remain consistent across scenarios, the life cycle inventory for each technology may refer to 4.1 and 4.2 for the stand-alone wind turbine and WEC parks, with the exception of components related to cabling and operation and maintenance (O&M) vessels, which are treated separately.
As for the layout, the distance of wind turbine with the WEC perpendicular to wave rays are approximately 10D, while the distance between wind turbine which are aligned with the wave rays are approximately 4D. Following the same layout as in section 4.2, the distance between each WEC is defined as 150 m as shown in figure 4.9.

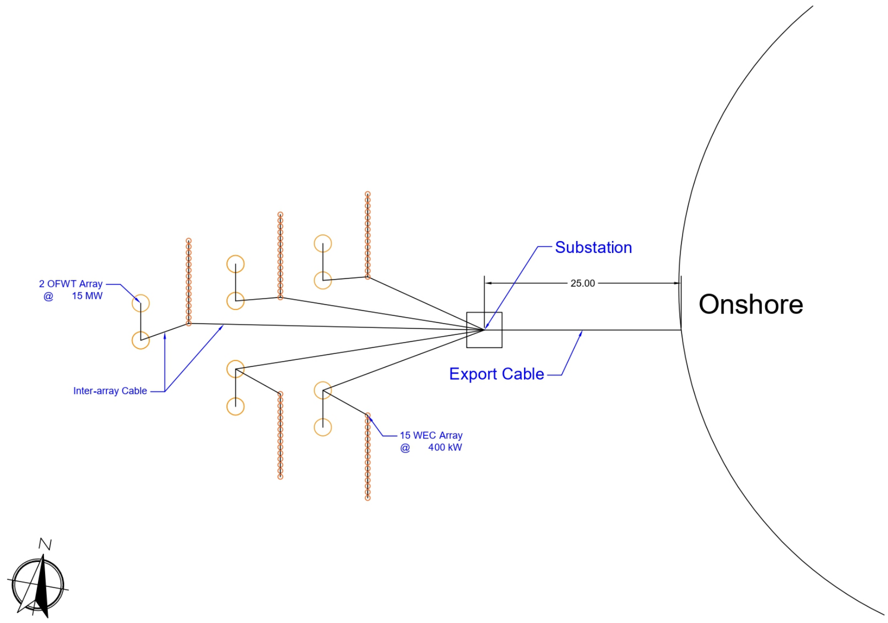


Figure 4.9: multi-source Wind-Wave Offshore Energy Park

4.3.1. Inter-array Cable

This study modeled the inter-array cable for both it shared between the wave and wind, as well as wind and wave have a different system and infrastructure and only share sea space.

Firstly, for study to assess the life cycle midpoint impact for co-located wind and wave with shared infrastructure, the total power carried by each array is calculated to be 36 MW, with configuration of 15 WECs and 2 FOWTs. In order to find the sufficient cable dimension, therefore, based on [1], it is found that the suitable offshore subsea cable is 66 kV with cross-section cable area is 120 mm^2 with 340 A current rating and maximum power of 38.9 MW. With the weight per meter of 31.3 kg/m, the distribution of each material weight of the cable is as below.

Table 4.16: Wind-Wave Inter-array Cable Material Breakdown

Material Classification	Value (kg/m)	Percentage
Steel, low-alloyed	8.76	28%
Lead	6.57	21%
Copper	7.2	23%
Polyethylene	6.57	21%
Polypropylene	2.19	7%

On the other hand, for the study of co-located wind and wave energy system with separated infrastructure, the active power transported by the cable for each array is 30 MW from wind energy and 6 MW from the wave energy. Therefore, using the same approach of $P = V \cdot A \cdot \sqrt{3} \cdot 1$ in finding the power holds by the cable, it is found that the suitable inter-array cable for the wind array is 120 mm^2 66 kV and 95 mm^2 33 kV for the wave array. The distribution of each material weight for both technology is as below.

Table 4.17: Inter-array Cable Material Weight Distribution in Paralel Scheme [tonne]

Material Classification	Wave Inter-array	Wind Inter-array
Copper	80.93	380.91
Lead	103.73	488.21
Polyethylene	24.43	144.99
Polypropylene	16.03	75.46
Steel, low alloyed	15.73	74.04

4.3.2. Offshore Export Cable

Considering the same total rated capacity generated by the other two scenarios of energy park, therefore, the material composition of the substation in the co-located offshore energy park with shared infrastructure can still be referred to section 4.2.3. However, to adjust the export cable in separated infrastructure, the wind export cable uses 150 kV with 400 mm^2 cross-section area and 66 kV with 95 mm^2 for to transport 30 MW. With each weight per length (kg/m) of 57.30 kg/m and 21.60 kg/m respectively, the average material weight increases by 3% compared to in the shared infrastructure scenario.

Table 4.18: Export Cable Composition and Weight for Wind and Wave

Material	Cable weight (kg/m)	Total weight (kg)
Export Cable Wind (150 kV, 400 mm^2)		
Steel, unalloyed low alloyed	20.58	514,622.05
Copper	7.83	195,783.66
Lead	15.94	398,385.65
Polyethylene	6.47	161,872.50
Polypropylene	6.47	161,872.50
Total cable weight (kg/m)	**57.30**	
Export Cable Wave (66 kV, 95 mm^2)		
Steel, unalloyed low alloyed	7.76	193,993.65
Copper	2.95	73,803.26
Lead	6.01	150,176.79
Polyethylene	2.44	61,020.00
Polypropylene	2.44	61,020.00
Total cable weight (kg/m)	**21.60**	

4.3.3. Offshore Substation

Considering the same total rated capacity generated by the other two scenarios of energy park, therefore, the material composition of the substation in WEC park can still be referred to section 4.1.5. However, in the separated infrastructure scenario, each wind and wave energy will have its own substation that transport 30 MW electricity from wave energy and 150 MW of electricity from wind energy. In order to find the topside mass and jacket mass with alignment with each power capacity and water depth following equation 4.2 and 4.3.

Following the equation, therefore, the topside mass for 30 MW is 219 tonne which led to 2384 tonne jacket mass to be placed in 80 m water depth. Additionally, for the wind energy, the expected topside mass for 150 MW capacity is 949 tonne with 2673 tonne of jacket mass as the substructure. The separation of substation leads to 63.3% weight increase in total.

4.3.4. Operations and Maintenance

The integration of wind and wave energy devices in a multi-source offshore wind-wave energy park can have different operational and maintenance (O&M) frequency and fuel consumptions compared to stand-alone offshore energy park. In such configurations, several infrastructure such as export cable, inter-array cable, offshore substations, including the O&M vessels are shared accross subsystems. Studies conducted by Mbasso, et al. [59] indicates that power flow is a crucial factor in the analysis of energy systems while compatibility and sharing of various energy sources are ensured and all device capable of being repaired. Considering this study is looking into the infrastructure and O&M frequency of systems with different power, the Probability-Weighted Expected Return Method (PWERM) is used as it can estimate value when recognising not all parameters carry equal likelihoods of materializing [52]. Following that, the weighted frequency F_{shared} for the shared infrastructure is computed as:

$$F_{shared} = W_{wind} \cdot F_{wind} + W_{wave} \cdot F_{wave} \tag{4.4}$$

Where:

- F_{wind} and F_{wave} are the maintenance frequencies (scheduled or corrective) for wind and wave systems, respectively.
- W_{wind} and W_{wave} are the weighting coefficients derived from the installed capacity or unit count of each system.

Following the equation above, therefore the weighted maintenance frequency over the whole system lifetime (25 years) for shared infrastructure are as below:

Table 4.19: Maintenance Frequency for Shared Infrastructure

Component	Wind System	Wave System	Co-located System
Scheduled Maintenance			
Export Cable	12.5	12.5	13
Substation (OSS)	25	25	25
Inter-array Cable	12.5	12.5	12
Corrective Maintenance			
Export Cable	96	4.00	81
Substation (OSS)	12	5.00	11
Inter-array Cable	96	4.00	81

5 Results and Interpretation

This chapter presents the life cycle impact assessment (LCIA) results for the three modelled scenarios with the same rated capacity of 180 MW:

- Standalone offshore wind farm (FOWT)
- Standalone wave energy converter park (WEC)
- multi-source offshore renewable energy park (MU-ORE) combining wind and wave

Results are reported for the Global Warming Potential (GWP), Energy Payback Time (EPBT), Greenhouse Gas Payback Time (GPBT), and selected additional impact categories under both EF 3.1 and IMPACTWorld+ (IW+) methods. All results are presented per functional unit of 1 kWh delivered to shore, with the system boundaries described in Chapter 3 and inventory results from Chapter 4.

The results represented in this chapter will cover the results of each modeled 180 MW energy park with LCIA methodology of environmental footprint (EF 3.1) and IMPACTWorld+ midpoint impact categories as below:

Table 5.1: Comparison of midpoint impact categories and abbreviations between IMPACTWorld+ and EF 3.1

IMPACTWorld+		Environmental Footprint EF 3.1	
Midpoint Impact Category	**Abbreviation**	**Midpoint Impact Category**	**Abbreviation**
Climate Change, LT	GW, LT	Acidification	AC
Climate Change, short term	GW, nLT	Climate Change	GW
Fossil and nuclear energy use	FD	Ecotoxicity: Freshwater	FET
Freshwater Acidification	ADF	Energy Resources: Non-Renewable	FD
Freshwater Ecotoxicity	FET	Eutrophication: Freshwater	FE
Freshwater Eutrophication	FE	Eutrophication: Marine	ME
Human toxicity: carcinogenic	HTc	Eutrophication: Terrestrial	TE
Human toxicity: non-carcinogenic	HTnc	Human toxicity: carcinogenic	HTc
Ionising Radiation	IR	Human toxicity: non-carcinogenic	HTnc
Land Occupation, Biodiversity	LU	Ionising Radiation	IR
Land Transformation, Biodiversity	LT	Land Use	LU
Marine Eutrophication	ME	Material resources: metals/materials	MD
Mineral Resources Use	MD	Ozone Depletion	OD
Ozone Layer Depletion	OD	Particulate matter formation	PM
Particular Matter	PM	Photochemical Oxidant Formation	POF
Photochemical Oxidant Formation	POF	Water use	WU
Terrestrial Acidification	ADT		
Water Scarcity	WS		

5.1. Floating Offshore Wind Turbine Energy Park

The life cycle inventory of the 180 MW FOWT Park, using the cradle-to-grave approach across all impact categories, is provided in Appendix 7.2.4. Based on this inventory, the main contributors to the life cycle assessment (LCA) can be grouped into three key phases: installation (including manufacture), maintenance, and end-of-life. The installation phase includes the materials and manufacturing processes of wind turbines, electrical systems, and substructures. Maintenance involves both scheduled and corrective actions, as discussed in Section 4.1.7. Derived from the modeled life cycle inventory, resulting to the life cycle impact contributions as below:

Table 5.2: 180 MW FOWT Impact Assessment

Impact Category	Unit	Value
AC	mol H+-Eq	1.53E-04
GW	g CO2-Eq	18.30
FET	CTUe	1.50E-01
FD	MJ, net calorific value	1.38E-01
FE	kg P-Eq	9.00E-06
ME	kg N-Eq	2.70E-05
TE	mol N-Eq	2.74E-04
HTc	CTUh	1.82E-11
HTnc	CTUh	8.68E-10
IR	kBq U235-Eq	9.63E-04
LU	dimensionless	5.93E-02
MD	kg Sb-Eq	1.01E-06
OD	kg CFC-11-Eq	1.43E-10
PM	disease incidence	1.13E-09
POF	kg NMVOC-Eq	8.14E-05
WU	m3 world Eq deprived	4.10E-03

Following the table above, figure 5.2 further illustrates the distribution of each life cycle impact. The graph shows that the installation phase is the most dominant contributor across almost all impact categories, with an average share of 50-98% depending on the indicator. Specifically, in the Global Warming Potential (GWP), installation contributes 87.50% of the total 18.30 gCO_2-eq/kWh, followed by the maintenance at 6.61%, and end-of-life stage at 5.85%. The dominance of installation underlines that the material intensity and complexity of floating substructures can heavily influence the life cycle, especially the usage of metal susch as copper, steel, and aluminium material which contributes to most parts of the manufacturing process such as turbine, tower, and mooring parts. If we reflect to the literature, the calculated GWP falls within the lower bound of literature values for floating offshore wind, reported between 7–31 gCO_2/kWh [95, 91, 19].

The main contributor process to the GWP impact is the usage of steel for turbine manufacture. This process also contributes as a major part in FD, HTc, PM, POF, and WU. These are due to the various metal processing processes, such as blasting, smelting, mining, and up to the electricity production used for material processing. On the other hand, the major contributor for other impact category is dominated by the sheet rolling process for copper material. The contribution of copper sheet rolling towards toxicity parameters is due to the direct impact from NMVOC emission. The outlier appears in OD parameter, whereas the main process contributor is the usage of glass fibre in the manufacturing process.

Compared in other categories, the maintenance stage contributes a larger share in categories sensitive to recurring vessel trips and component replacements, such as marine eutrophication (34.5%), terrestrial eutrophication (37.30%), and photochemical ozone formation (34.40%). Looking deeper to the flow emission of the impact categories, this higher number of maintenance compared to other categories is due to NO_x, SO_x, and NMVOC emissions that scale with fuel and failure rates, vessel duration, and the total fuel usage.

Finally, the end-of-life stage contributes less intensely, averaging 5–15% depending on the category (e.g., 15.20% to ionising radiation, 12.20% to water use). This reflects both the partial recyclability of major wind turbine components and the relatively smaller scale of decommissioning compared to installation. In the End-of-Life (EoL) phase, steel recycling is the dominant contributor, accounting for more than half of the total EoL burden (5.03% of overall impacts). This outcome is strongly influenced by the modelling choice of applying the cut-off approach in openLCA, where the recycling process is included as a burden but no credits are granted for the avoided production of virgin steel. This choice is due to the limitation of detailed heat or energy and electricity needed from the recycling process. As a result, the steel fraction —and other metal materials treatment— appears as a net contributor rather than a potential environmental benefit.

The detailed processes distribution across all impact categories is described in the picture below.

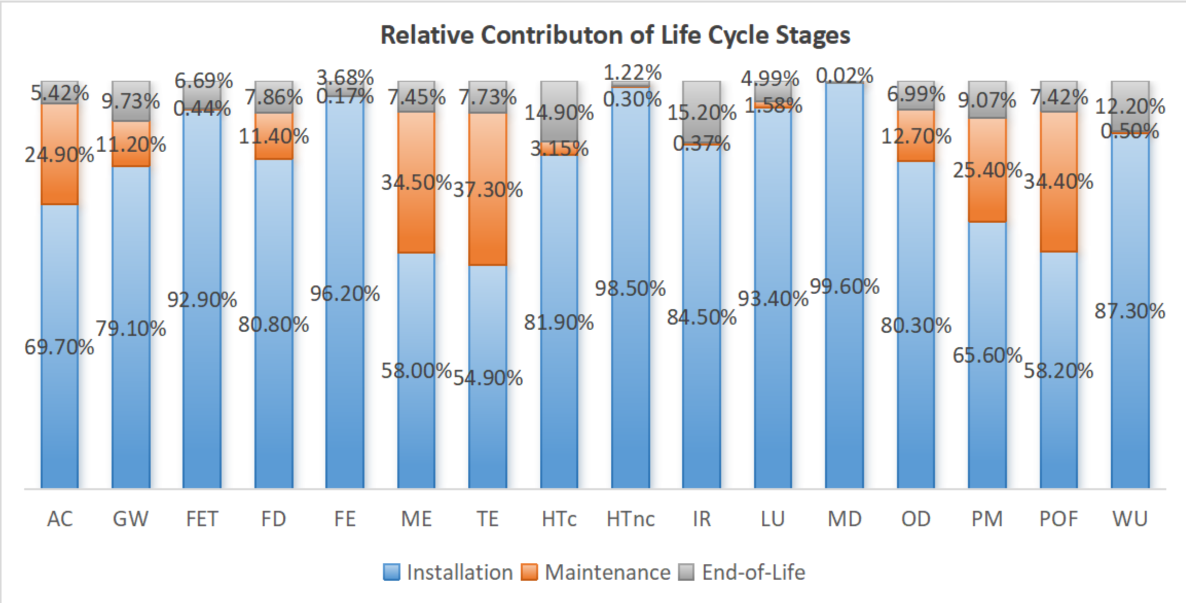


Figure 5.1: Relative Contributon of Life Cycle Stages to Midpoint Impact Categories for a 180 MW FOWT

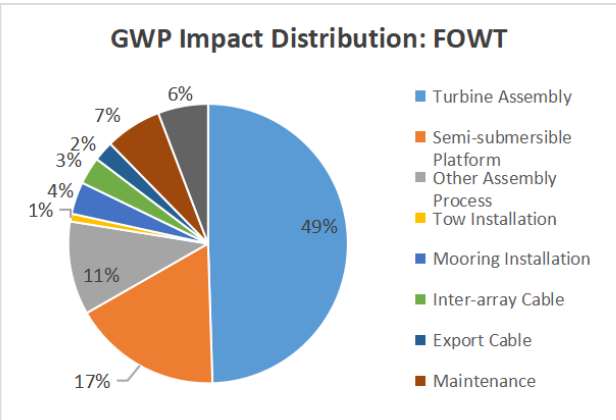


Figure 5.2: Global Warming Impact Distribution in 180 MW FOWT Energy Park

A breakdown of installation processes reveals turbine assembly as the single largest hotspot, for example, it is responsible for 76.12% of the total GWP impact (Figure 5.2). The biggest percentage to contribute to the turbine assembly is the process prior to that —manufacturing process. Since wind turbine is steel-intensive structure, its process gives a large impact towards the FOWT manufacturing process. In this study, the semi-submersible platform is assumed to be using hot-rolled steel with fixed ballast made of iron ore concentrate that contributes 17.23% of total turbine manufacturing process. Across other categories, turbine assembly contributes 40-50%, with inter-array and export cables adding another 10–20%. These results highlight the heavy dependence of floating offshore wind on steel and copper, whose production is associated with significant ecotoxicity and metal depletion due to mining and smelting processes.

Additionally, as turbine assembly emerges as the single largest hotspot in the installation stage (87.50% of GWP impact), the end-of-life (EoL) stage follows closely with a share of 5.85%. This similarity shows that material EoL management can exert an impact of similar magnitude to primary manufacturing processes. The similarity arises from the factor that in the turbine assembly lies turbine manufacture, which is steel-heavy activities, including the metal working and consumption of steel and the highest contributor in EoL turns out to be also the steel related process. Therefore, the ratio between recycling efficiency and landfill can influence the percentage of distribution.

In summary, installation emerges as the dominant life cycle stage, driven by turbine assembly and mooring installations. Maintenance is particularly critical for terrestrial eutrophication, human toxicity, and photochemical ozone formation due to vessel operations, while EoL exerts a smaller but non-negligible influence, especially depending on recyclability assumptions. Overall, the analysis underscores that reducing the environmental footprint of floating offshore wind requires material-efficient design, low-carbon supply chains for steel and copper, and the adoption of cleaner O&M fuels and advanced recycling solutions.

5.2. Wave Energy Converter Energy Park

The life cycle inventory of the 180 MW WEC Park, using a cradle-to-grave approach, is available in Appendix 7.2.4. The life cycle stages are divided into three key phases: installation, maintenance, and end-of-life. The installation phase includes the assembly and offshore installation of components such as floaters, foundations, mooring systems, towing, and both 33 kV and 220 kV electrical systems. Maintenance includes both scheduled and corrective actions, following table 4.11. Furthermore, most of the end-of-life phase assumes 90% of the materials are recycled meanwhile the other 10% are either landfilled or treated. Following the assumptions, the life cycle impact contributions from 450 devices of 0.4 MW point absorber devices are as follows:

Table 5.3: 180 MW WEC Impact Assessment

Impact Category	Unit	Value
AC	mol H+-Eq	2.05E-03
GW	kg CO2-Eq	98.65
FET	CTUe	6.24E-01
FD	MJ, net calorific value	1.22E+00
FE	kg P-Eq	2.72E-05
ME	kg N-Eq	5.56E-04
TE	mol N-Eq	5.32E-03
HTc	CTUh	8.43E-11
HTnc	CTUh	1.37E-09
IR	kBq U235-Eq	4.05E-03
LU	dimensionless	2.86E-01
MD	kg Sb-Eq	1.16E-06
OD	kg CFC-11-Eq	1.24E-09
PM	disease incidence	1.72E-08
POF	kg NMVOC-Eq	1.48E-03
WU	m3 world Eq deprived	1.89E-02

Across categories, installation and maintenance dominate, with average contributions of 62% and 30.98%, respectively, while end-of-life remains minor at 7.01%. Maintenance exerts the largest influence on categories linked to vessel operations, such as acidification (63.30%), marine eutrophication (57.00%), terrestrial eutrophication (65.20%), particulate matter (57.50%), and photochemical ozone formation (64.00%). These impacts stem from NO_x, SO_2, and PM emissions associated with long-term marine diesel oil (MDO) use, which scale with the large number of units requiring inspection and part replacement.

By contrast, installation is particularly dominant for freshwater ecotoxicity (94.8%), ionising radiation (92.00%), and mineral depletion (98.9%), reflecting the heavy reliance on copper, steel, and concrete in floater assembly and cabling systems. On average, floater assembly alone accounts for more than 40% of impacts across categories, underlining the material dependence of the technology.

End-of-life processes remain relatively minor, averaging 7–9%, though their share rises to 12.40% in terrestrial eutrophication and 12.20% in photochemical oxidant formation (POF) category. The relatively high GWP contribution is attributable to the dismantling and reprocessing of large material masses, which, despite assumed high recyclability, still gives significant transport and reprocessing energy. The sensitivity of this result to recycling efficiency highlights that improved composite recycling and logistics optimisation could substantially mitigate the end-of-life burden.

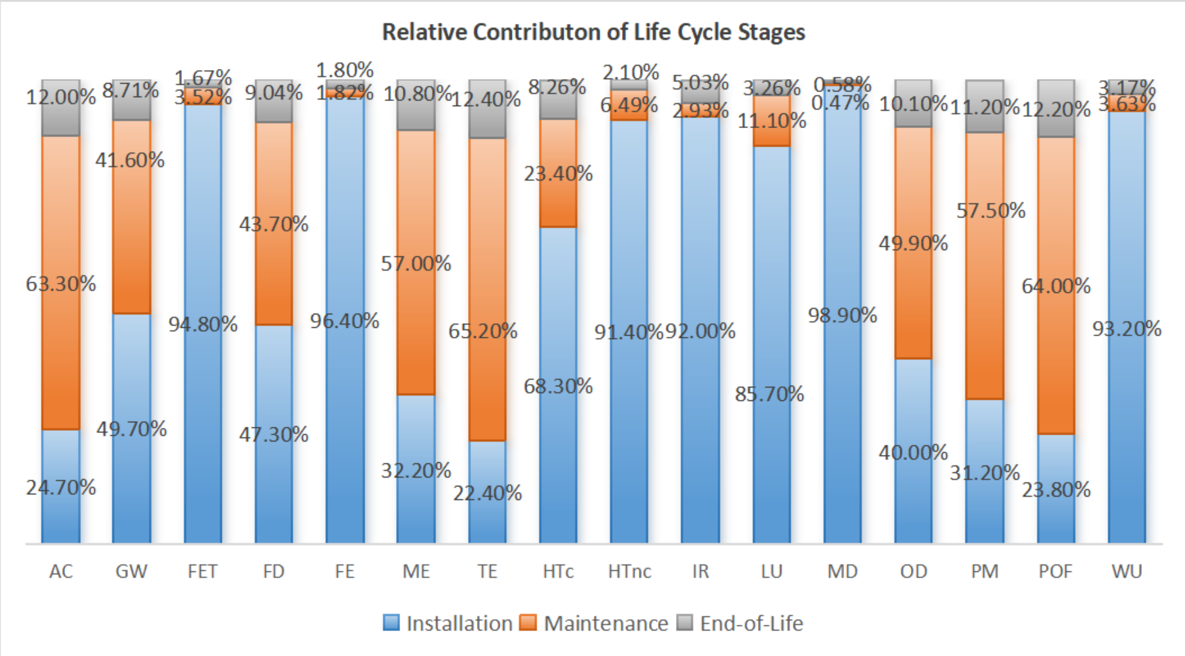


Figure 5.3: Contribution Analysis of the WEC 180 MW

Looking into the details of the GWP impact, maintenance contributes 31.20% from the total GWP impact of 98.65 gCO_2-eq/kWh. When these results are compared against state-of-the-art literature 2.1, the global warming impact of this WEC park falls in the upper-mid range. Compared to LCA studies for WEC with point absorber system, Pennock, et al. [70], the literature reported 25-46 gCO_2-eq/kWh for 350 kW x 28 WEC array, which represents 6.2% of total devices used in this study.

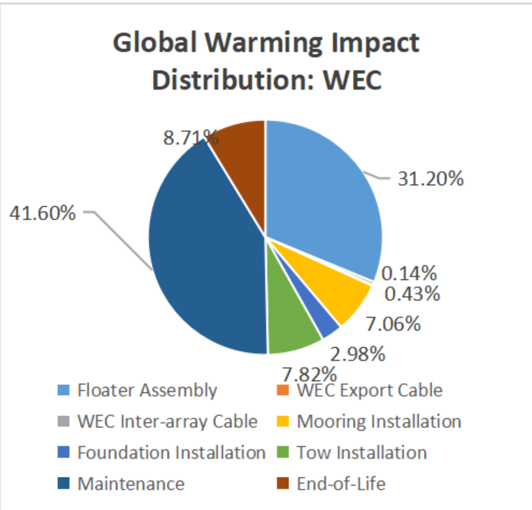


Figure 5.4: Global Warming Impact Distribution in 180 MW WEC Energy Park

On the other hand, this result is within range of Engelfried et al. [28] for a generic point absorber comprised of steel and concrete, with GWP impact of 52–77 gCO_2-eq/kWh without periphery and 300–325 gCO_2-eq/kWh with periphery. Additionally, older study by Uihlein [92] found that the global warming impact of a point absorber device is approximately 105 gCO_2-eq/kWh. The findings of this study is therefore consistent with the three studies as the impact of large-scale deployment and inclusion of periphery systems can influence the GWP impact. However, it is noteworthy that the results of this study differ more significantly from Pennock than from Engelfried and Uihlein. One reason for this discrepancy is that while the detail assumption of Pennock's study remains confidential, it mentioned that the assumption for installation, maintenance, and decommissioning activities are shared across the entire array and fuel consumption assumed to be averaged per kWh of array output. In contrast, this study, along with Uihlein and Engelfried, adopts a more conservative approach by detailed single-unit analyses, leading to higher GWP impact value.

Based on figure 5.4, installation emerges as the dominant driver, accounting for 49.70% of GW emissions. Again, the device assembly contributes majorly to the installation process. In WEC case, the assembly process dominated by steel manufacture and process. Following installation, maintenance contributes 41.60% of throughout the whole life cycle. This reflects the reliance on frequent vessel operations for inspections, component replacement, and corrective interventions across 450 devices over 25 years. The high share of O&M indicates that operational strategies, fuel types, and vessel efficiency critically shape the impact distribution of wave energy.

In summary, in the 180 MW WEC energy park that composed of 450 devices of 400 kW point absorber, installation dominates the overall impact categories because of the huge number of steel devices. This process is then followed by maintenance process, which is amplified due to the number of devices and led to total vessel usage duration. On the other hand, end-of-life process contributes a small percentage to the overall impact categories. As maintenance is the main contributor in almost all impact categories, mitigation for installing large rated capacity of wave energy park lies in decarbonizing O&M and optimizing maintenance strategies such as maintenance route efficiency, rather than focusing solely on material reductions.

5.3. Multi-source Energy Park: FOWT and WEC

5.3.1. Cradle-to-Grave: Shared Infrastructure with LCIA Method Environmental Footprint 3.1

Besides calculating the life cycle impact of the same rated capacity in the wave energy park and offshore wind park, this study conducted a calculation to life cycle impact towards the co-located wind and wave, which consits of 75 devices of 400 kW WECs and 10 devices of 15 MW FOWTs. Within this same sea space, the technology shared 66 kV inter-array cable and 220 kV export cable that connects the shared substation 25 km offshore to the onshore substation.

The total impacts of the functional unit for the impact categories are reported in table 5.4.

Table 5.4: 180 MW Co-located Wind and Wave Impact Assessment

Impact Category	Unit	Value
AC	mol H+-Eq	1.55E-03
GW	kg CO2-Eq	7.56E-02
FET	CTUe	1.00E+00
FD	MJ, net calorific value	9.39E-01
FE	kg P-Eq	2.69E-05
ME	kg N-Eq	4.09E-04
TE	mol N-Eq	3.90E-03
HTc	CTUh	7.41E-11
HTnc	CTUh	1.84E-09
IR	kBq U235-Eq	3.56E-03
LU	dimensionless	2.47E-01
MD	kg Sb-Eq	1.92E-06
OD	kg CFC-11-Eq	9.48E-10
PM	disease incidence	1.28E-08
POF	kg NMVOC-Eq	1.09E-03
WU	m3 world Eq deprived	1.59E-02

The contribution of each process in the whole lifecycle to the life cycle impact is described in figure 5.5. From the graph, note that the installation includes the manufacturing of each devices technology, one offshore substation (capacity 180 MW), and one offshore inter-array cable of 66 kV with cross-section 120 mm^2 and one export cable of 630 mm^2 220 kV. The approach used to calculate the LCI for the shared infrastructure (i.e. offshore substation, inter-array cable, offshore export cable) is described in section 3.3.1. From such an approach, therefore, the contribution analysis in order to identify the hotspots of impact assessment is presented in figure 5.5.

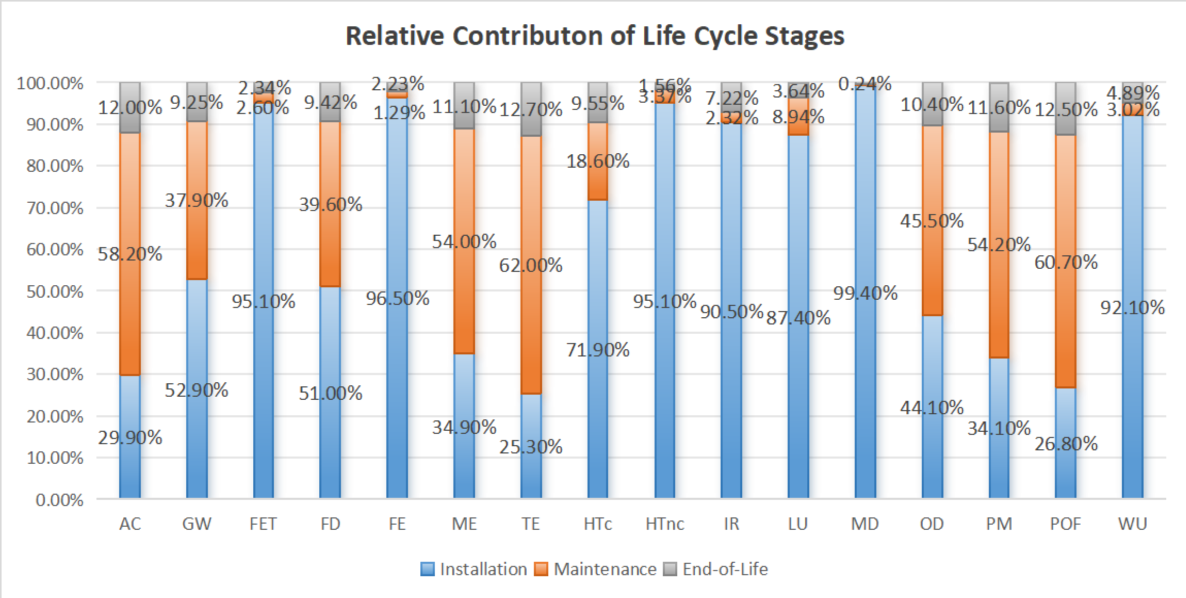


Figure 5.5: Contribution Analysis of the multi-source Wind and Wave Energy 180 MW

From Figure 5.5, it is shown that the main contributors in the life cycle are still manufacture and installation, followed by maintenance across impact categories. On average, installation accounts for 64.19% of the total impact, with 30% sourced from the floater assembly for WEC. This process includes the raw materials and its processing, in which steel is the major component of the structure. The installation process remains most influential in resource- and material-related categories, reflecting the high metal demand together with its processing of floaters and mooring systems combined with the energy-intensive production of cabling and substation infrastructure.

Maintenance contributes 28.28% on average, a modest difference compared to installation, with wave-related maintenance dominating (27.63%) and wind-related maintenance negligible (0.65%). This stage is particularly impactful in emission-driven categories such as acidification, eutrophication, particulate matter formation, and photochemical oxidant formation, due to recurring vessel operations across the 25-year lifetime. The reliance on marine diesel oil (MDO) results in significant emissions of NO_x, SO_x, and particulate matter, underscoring the role of vessel activity as the largest single operational hotspot.

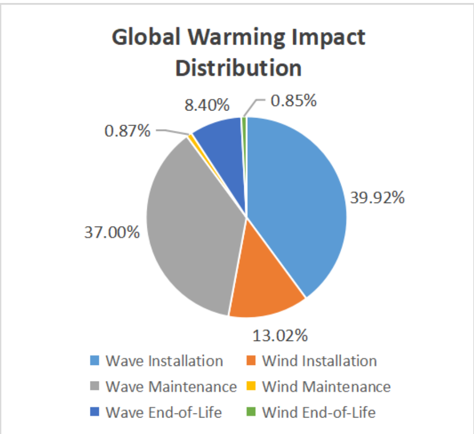


Figure 5.6: Global Warming Impact Distribution in 180 MW multi-source Wind-Wave Co-located Offshore Energy Park

By contrast, the end-of-life stage contributes 7.55% averagely across all impact categories, distributed across both wave (6.64%) and wind (0.90%). Although minor compared to installation and maintenance, this phase becomes more relevant in categories sensitive to waste and recycling processes, where assumptions regarding the recyclability of steel and aluminium reduce the modeled burden. Nonetheless, uncertainties remain high for composites and mooring materials with limited recycling pathways [95].

The climate change impact of the co-located park is calculated at 75.63 gCO_2-eq/kWh (Table 5.4). Of this, wave technology contributes 64.45 gCO_2-eq/kWh (85.32%), while wind accounts for 7.19 gCO_2-eq/kWh (9.3%). Within the wave share, the main installation hotspots are floater assembly (19.78 gCO_2-eq/kWh), mooring installation

(5.12 gCO_2-eq/kWh), and foundation installation (2.07 gCO_2-eq/kWh). Compared to the stand-alone WEC park, this contribution is proportionally lower, reflecting efficiency gains from shared infrastructure. Despite this, the largest single contributor on average is still the installation process, which is responsible for $\sim$45% of the burden across material usage categories.

On the other hand, for wind technology, the overall decrease compared to standalone wind with installed capacity of 180 MW is 12% with highest increment in end-of-life by 25.62%. However, wind energy contributes 9.13 gCO_2-eq/kWh with installation remains modest at 8.42% of the category share, with turbine assembly (5.61 gCO_2-eq/kWh) as the principal hotspot, alongside minor contributions from substation and cabling. On average, this contrast demonstrates that the environmental footprint of the multi-source park remains wave-driven, due to the higher number of WEC units and associated maintenance demand, while wind maintains a comparatively lower impact profile.

In conclusion, the life cycle GWP impact of wind energy in co-located system decreases from 18.30 gCO_2-eq/kWh in the stand-alone case to 7.19 gCO_2-eq/kWh when infrastructure is shared, representing a reduction of $\sim$34%. This reduction is primarily driven by decreases in installation from 8.58 to 5.89 gCO_2-eq/kWh) and maintenance burdens decrease from 1.06 to 0.66 gCO_2-eq/kWh, highlighting the efficiency gains achieved through shared substations and cabling systems.

For wave energy converter, the effect of co-location is even comparable, whereas the GWP impact falls from 98.65 gCO_2-eq/kWh to 68.44 gCO_2-eq/kWh, a reduction of around 31%. Installation burdens decline from 48.99 gCO_2-eq/kWh to 34.11 gCO_2-eq/kWh, and maintenance from 41.07 to 27.98 gCO_2-eq/kWh, reflecting both shared infrastructure and reduced per-device intervention requirements. Moreover, the end-of-life impact drops from 8.59 to 6.35 gCO_2-eq/kWh.

Overall, these findings confirm that co-location not only improves land- and sea-use efficiency but also provides measurable environmental benefits by lowering per-kWh impacts. The improvements are more significant for wave energy, reflecting its higher infrastructure intensity and sensitivity to shared systems. For wind, the reductions are smaller, particularly in maintenance and installation phases. These results reinforce the strategic value of multi-source offshore parks, where shared infrastructure and coordinated operations create clear synergies that enhance the sustainability profile of emerging marine renewable technologies. Thus, the reduction of impacts from wind energy is relatively modest, as the number of installed turbines only decreases from 12 to 10 units. By contrast, the reduction for wave energy is far more substantial, with the number of devices decreasing from 450 to 75 units. This highlights that the composition of installed units plays a decisive role in shaping the environmental profile of the combined renewable energy system. By carefully optimizing the installed capacity mix, a win–win solution can be achieved for both technologies while simultaneously maximizing the reduction in climate change impacts (GWP).

5.3.2. Cradle to Grave: Shared Infrastructure with LCIA Methodology IMPACTWorld+

IMPACT World+ is globally regionalized method for life cycle impact assessment (LCIA) by integrating multiple state-of-the-art developments as well as damages on water and carbon areas of concern. [20]. As IMPACTWorld+ have both midlevel and damage level indicators, this study focuses only on the midpoint level indicators, namely in table 5.1. The total impact of the functional unit for the midpoint impact categories using IMPACTWorld+ LCIA Methodology are represented in table 5.5.

Table 5.5: Total Impact Assessment Result with IMPACTWorld+

Impact Category	Unit	Value
GWP, LT	g CO2 eq (long)	72.28
GWP	g CO2 eq (short)	76.91
FD	MJ	1.00E+00
ADF	kg SO2 eq	6.56E-15
FET	CTUe	4.53E+03
FE	kg PO4 P-lim eq	3.76E-07
HTc	CTUh	2.44E-07
HTnc	CTUh	5.96E-08
IR	Bq C-14 eq	3.56E-01
LU	m2 arable land eq .yr	6.79E-04
LT	m2 arable land eq	1.18E-05
ME	kg N N-lim eq	3.91E-05
MD	kg deprived	3.73E-02
OD	kg CFC-11 eq	1.01E-09
PM	kg PM2.5 eq	6.81E-05
POF	kg NMVOC eq	1.07E-03
AD	kg SO2 eq	4.20E-09
WS	m3 world-eq	1.61E-01

Across categories, installation dominates material- and resource-related burdens, while maintenance drives emission-related impacts. For instance, the Climate Change impact amounts to 72.28 gCO_2-eq/kWh (long-term, >100 years) and 76.91 gCO_2-eq/kWh (short-term, 0–100 years). Both categories are strongly influenced by wave technology, which contributes nearly $\sim$90% of the total due to the high number of devices. The difference between short- and long-term GW reflects the time horizon of radiative forcing: the short-term emphasizes near-term climate responses (dominated by short-lived GHGs), whereas the long-term captures sustained temperature change from longer-lived gases [20]. The diversification lies on the characterization factor of methane, fossil as emission to air where it's 13 CO_2-eq/kg in long term and 31 CO_2-eq/kg in short term. This difference is due to the relatively low methane duration of ocupancy in the atmostphere.

Besides the GWP impact, Freshwater Ecotoxicity (FET) reaches a very high 3.67E+E02 CTUe for floater assembly and 4.53E+03 CTUe for tow operations, reflecting the metal-intensive character of floating wind-wave systems. This category is especially sensitive to copper, aluminium, and steel, which dominate mooring chains, cabling, and floater structures. As reported by [20] and [21], IMPACT-World+ employs older but more conservative USEtox v2.0 characterization factors, which strongly amplify ecotoxicity from metals compared to EF 3.1 (USEtox v2.1).

On the other hand, categories such as Acidification potential is calculated at 4.20E-09 kg SO_2-eq and photochemical oxidant formation at 1.07E-03 kg NMVOC-eq have more than 50% contribution from maintenance life stage. These categories are dominated by service vessel activity, where repeated sailing, maintenance duration, devices number, and part replacement over a 25-year lifetime translate into significant emissions of NO_x, SO_x, and primary particulates. These impacts are closely tied to service vessel operations, which release SO_x and NO_x, and particular matters during fuel combustion. This domination by vessel activity illustrates how renewable energy systems can have substantial indirect high emissions through their logistics chain.

At the component level, short term GWP impact lies in the installation, including floater assembly (20.10 gCO_2-eq/kWh), mooring systems (5.20 gCO_2-eq/kWh), and turbine assembly (5.07 gCO_2-eq/kWh). Substations and export cables, while essential, contribute only slightly, by less than 1 gCO_2-eq/kWh each. On the maintenance side, the wave share dominates with 28.47 gCO_2-eq/kWh, compared to only less than 1 gCO_2-eq/kWh for wind. This differences underscores the structural difference between many small wave devices and fewer large wind turbines, with the former requiring proportionally more inspection which leads to increasing fuel consumption.

End-of-life remains minor (<5% across all categories)under the current modelling assumptions. This is due to optimistic scenario assumed of recycling credits for materials used in both technologies. However, if less favourable end-of-life pathways were assumed (e.g., landfilling of blades), the contribution could increase significantly, leading to further attention in future assessments.

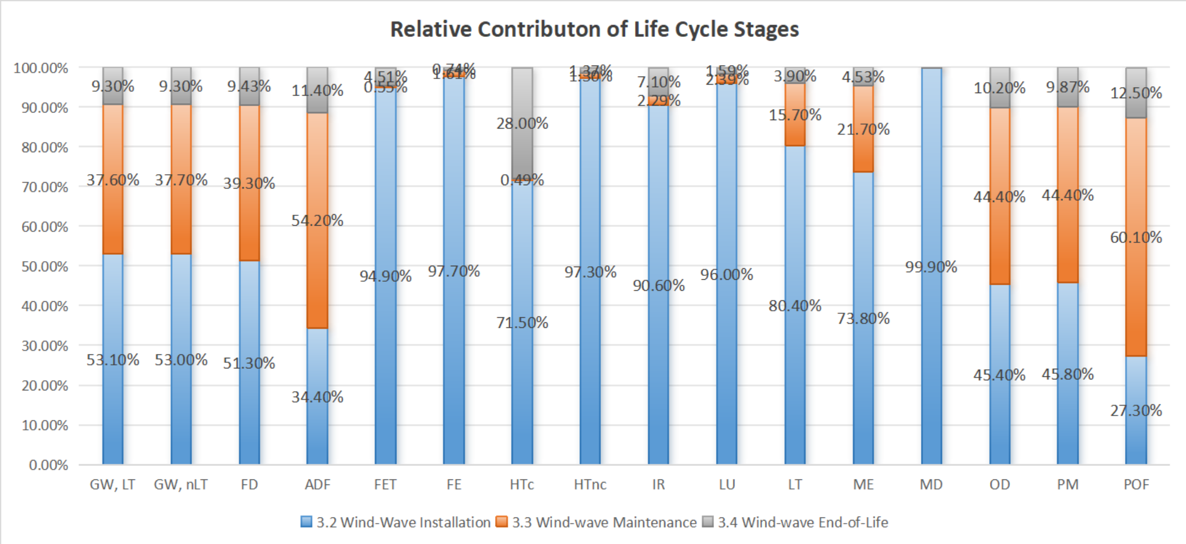


Figure 5.7: Contribution Analysis of the multi-source Wind and Wave Energy 180 MW, IMPACTWorld+ Methodology

5.3.3. Cradle to Grave: Separated Infrastructure with LCIA Method Environmental Footprint 3.1

The contribution of the 180 MW co-located offshore wind-wave park under the separated infrastructure for each technologies is presented in figure 5.8 with numerical values in table 5.6. The result shows that the separation of infrastructure increases installation driven impacts.

Table 5.6: 180 MW Co-located Wind and Wave Impact Assessment

Impact Category	Unit	Value
AC	mol H+-Eq	1.58E-03
GW	g CO2-Eq	7.93E+01
FET	CTUe	5.91E-01
FD	MJ, net calorific value	9.90E-01
FE	kg P-Eq	2.77E-05
ME	kg N-Eq	4.17E-04
TE	mol N-Eq	3.98E-03
HTc	CTUh	7.90E-11
HTnc	CTUh	1.77E-09
IR	kBq U235-Eq	4.13E-03
LU	dimensionless	2.62E-01
MD	kg Sb-Eq	1.79E-06
OD	kg CFC-11-Eq	1.00E-09
PM	disease incidence	1.30E-08
POF	kg NMVOC-Eq	1.12E-03
WU	m3 world Eq deprived	1.72E-02

Compared to the co-located energy park with shared infrastructure, using the same equation as in equation 4.3 to find the total mass of the offshore substation, the substation mass is found to increase from 3812 t in the shared scenario to a combined 6225 t when separated (2603 t for wave and 3622 t for wind). However, the main contribution for the midpoint impact still dominated by the installation process, particularly the wave energy floater assembly, with average of 28.84% across all categories, followed by turbine assembly with an average of 6.99% across all categories.

The second alteration compared to the shared infrastructure is in the offshore cable, to sufficiently transmits power with the minimized the power losses during the electricity transport. Therefore, four distinct systems are required: 33 kV inter-array and 66 kV export for wave, and 66 kV inter-array and 150 kV export for wind. This optimization thus creates a new approach for this system, which rather acts as a hybrid system, the wind and wave will act in paralel despite of the sharing of a location.

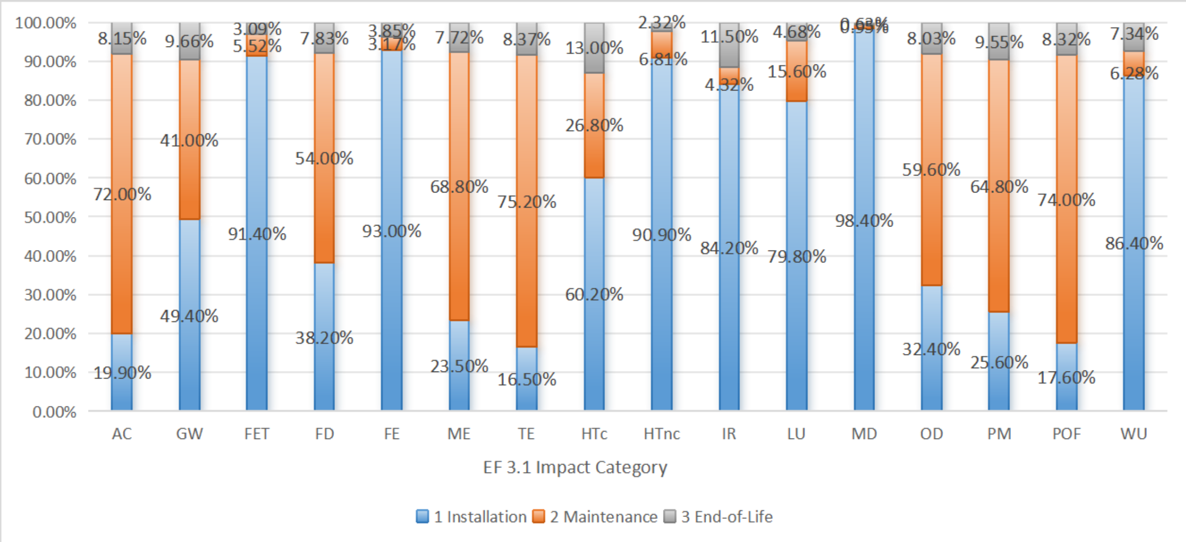


Figure 5.8: Contribution Analysis of the multi-source Wind and Wave Energy 180 MW

The figure above illustrates how the installation dominates material- and resource-intensive categories, including Freshwater Ecotoxicity (94.2%), Freshwater Eutrophication (94.70%), Human Toxicity carcinogenic and non-carcinogenic (94.00% and 67.80%), Ionising Radiation (86.00%), Land Use (86.50%), Material resources: metals/minerals (99.10%), and Water Use (89.60%), primarily due to the large steel and copper requirements of floaters, WEC foundations, mooring chains, and duplicated substations and cabling. By contrast, maintenance dominates air-quality categories such as Acidification (57.50%), Marine Eutrophication (53.00%), Terrestrial Eutrophication (53.30%), Particulate Matter Formation (53.50%), and Photochemical Oxidant Formation (59.70%). The ozone depletion category is more balanced, with near equivalence between installation ($\approx$ 46%) and maintenance ($\approx$ 43%).

At the component level, the wave floater assembly emerges as the single most impactful element. It contributes approximately 18.10% of climate change impacts (19.78 gCO_2-eq/kWh) and dominates several material-intensive categories, reaching up to 57.10% in freshwater ecotoxicity. Other significant contributors include WEC foundations, mooring systems, and, to a lesser extent, wind turbine assembly. The persistence of these hotspots across categories illustrates that the environmental profile of a co-located park is still fundamentally shaped by wave infrastructure, even when wind is present.

For GWP impact specifically (79.32 gCO_2-eq/kWh), the wind energy contributes 8.29% in 6.58 gCO_2-eq/kWh while the wave energy contributes 72.74 gCO_2-eq/kWh or 91.79% over the total GWP impact. Overall, installation contributes 53.62% (42.52 gCO_2-eq/kWh), dominated by floaters, wind turbine, and moorings, while maintenance accounts for 36.32% (28.82 gCO_2-eq/kWh), almost entirely from wave logistics, and the end-of-life still dominated by wave end-of-life, with 9.35% compared to wind in only 0.72%.

In conclusion, this distribution highlights that wave technology still determines the overall footprint due to its high unit count and structural requirements; and second, that maintenance strategies are nearly as consequential as installation, thus, operational decarbonisation (e.g., vessel electrification or alternative fuels) could have a more significant effects. Further discussion about the gains and losses of each changed component will be discussed in section 5.4.2

5.4. Results for Sensitivity Analysis

The sensitivity analysis in this chapter aims to study how the outputs of LCA in multi-source offshore are related and influenced by its inputs. In this case, the output changes are influenced by two causes, namely the LCIA methodology and the site arrangement. By doing the sensitivity analysis, therefore, the modification of which scenario that has the least global warming potential can be prioritized.

5.4.1. Sensitivity Analysis on LCIA Methodology (Cradle to Grave)

This sensitivity study assesses the impact of different methodologies in LCA impact the results of life cycle assessment. The aim is to illustrate how methodological choices can influence LCA outcomes and support the need for transparent and robust evaluation. The result of midpoint impact categories in both methodologies is pictured in the graph 5.9 using logarithmic scale. The log scale is chosen because the magnitudes of the impacts vary widely across categories (from very small to very large values). This ensures that both minor and dominant contributions are visible within a single graph. To handle categories with true zero results, a small value (epsilon) was introduced so they could still appear on the log scale, and these cases are annotated with "≈ 0". A dashed line at the bottom indicates the approximate zero baseline.

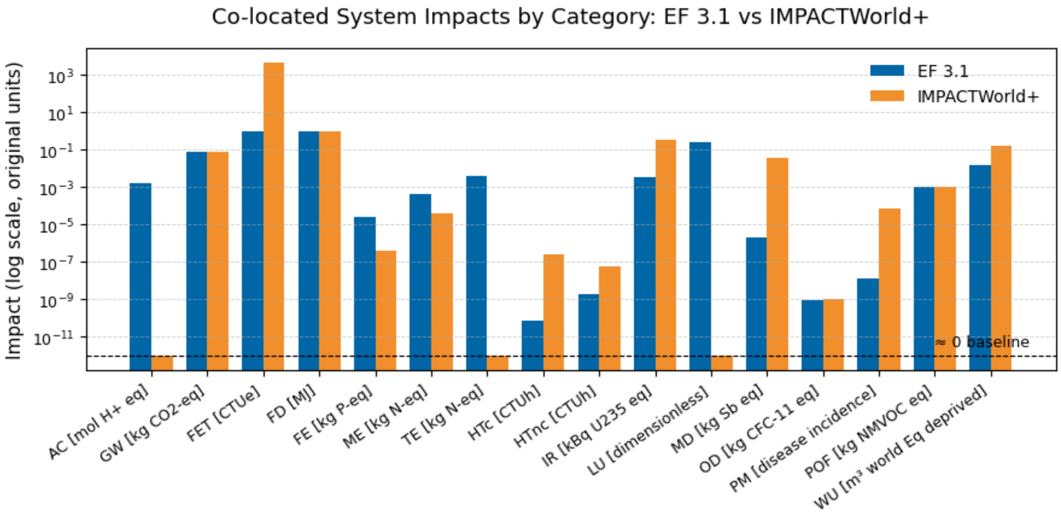


Figure 5.9: Life Cycle Impact Analysis Across IMPACTWorld+ and EF 3.1

In Figure 5.9, the midpoint results of EF 3.1 and IMPACTWorld+ (IW+) are compared. Some impact categories are not directly comparable between the two methods. For instance, Terrestrial Eutrophication (TE) and Acidification (AC) are only available in EF 3.1, since IW+ does not provide soil fate factors for a unified midpoint. Instead, IW+ divides acidification into terrestrial and freshwater, making one-to-one comparison with EF 3.1 impossible [61]. A similar situation occurs for Land Use (LU): EF 3.1 reports a single dimensionless score based on soil functions, while IW+ provides separate indicators for land occupation and land transformation, expressed in area·year equivalents [82]. The impact analysis from both categories in IW+ is thus merged in EF v3.1 with a dimensionless unit. However, LU cannot be directly compared with land occupation or transformation of biodiversity in IW+ because of the incomparable unit. Even though the impact is merged in EF v3.1, the characterization factor for each flow should also be adjusted accordingly

Where categories are available in both methods, some values are similar. Global Warming (GWP) impact is almost identical (EF 3.1: 75.63 gCO_2-eq/kWh; IW+: 76.91 gCO_2-eq/kWh; +1.67%). Energy resources: non-renewable (FD) is also comparable, with EF v3.1 slightly lower (EF 3.1: 9.39E-01 MJ; IW+: 1.00E+00 MJ; +6.45%). These small differences reflect varying background models but indicate overall consistency. Similarly, POF shows only a slight deviation, with EF 3.1 being 1.47

Other categories, however, diverge strongly. Freshwater Ecotoxicity (FET) is much higher in IW+ (EF 3.1: 5.91E-01 CTUe; IW+: 4.53E+03 CTUe). This is due to different metal characterization factors: EF 3.1 relies on USEtox v2.1, while IW+ uses v2.0, which applies far higher values for metals such as copper and aluminium [21, 20]. Since the system is highly metal-intensive (floaters, moorings, cables), IW+ magnifies this impact. Similarly, Human Toxicity, cancer (HTc) and non-cancer (HTnc) are 10–

100 times higher in IW+ (HTc: 7.41E-11 vs 2.44E-07 CTUh; HTnc: 1.84E-09 vs 5.96E-08 CTUh). This difference comes from IW+ including more exposure pathways (e.g., indoor emissions, pesticide residues) and using more spatially differentiated fate–effect factors, particularly for toxic metals.

Ionising Radiation (IR) also differs by two orders of magnitude (EF 3.1: 3.56E-03 kBq U235-eq; IW+: 3.56E-01 kBq C-14-eq; +9883.10%). The gap reflects the choice of reference isotope: EF 3.1 models U-235, while IW+ uses C-14 and broader chronic exposure factors. Additionally, the difference in characterization factor that shows higher in IW+ to the power of 10 resulting high value in IR impact of IW+ compared to EF v3.11. Mineral resources (MD) follow a similar trend, with IW+ much higher (EF 3.1: 1.92E-06 kg deprived; IW+: 3.73E-02 kg Sb-eq). IW+ uses the material competition scarcity concept, which describes the fraction of material required by future users who cannot adapt to full dissipation of easily accessible stocks [20]. In contrast, EF v3.1 applies the abiotic depletion potential (ADP), which focuses on nonrenewable resource use during energy production—mainly copper, silver, and other metalloid materials.

In some cases, IW+ yields much lower results. For example, Freshwater Eutrophication (FE) and Marine Eutrophication (ME) are both lower in IW+ (FE: −98.6%, ME: −90.43%) because of different nutrient fate modeling. These difference are caused by the background processes that is used in each technology, whereas a few of the emissions flow characterization factor in IW+ are rather smaller compared to EF v3.1., since the methodology takes into account more emission parameters, including oxygen demand, compared to EF v3.1. As for ME impact category, the flow impact analysis is similar (e.g. ammonium and NO_x), the characterization factors differ. These values largely arise from fuel and magnet use within the electrical systems.

Finally, some categories differ mainly because of the unit of expression. Particulate Matter (PM) is expressed in EF 3.1 as disease incidence (1.28E-08), while IW+ reports kg $PM_2.5$ (6.81E-05), leading to an apparent 0.5 million% increase. Besides, the difference in unit in measuring the particulate matter formation, the IW+ takes into account more flow parameter compared to the EF 3.1, sourcing from fuel and electricity use and iron production. Similarly, Water Use (WU/WS) is 9 times higher in IW+ (EF 3.1: 1.59E-02 vs IW+: 1.61E-01; +911%), since IW+ applies a “world-equivalent deprived” approach rather than EF 3.1’s scarcity indicator. In the WS impact category, IW+ not only take into account the emission to water, but rather also takes into account the usage of water as a resource to assess the water scarcity. The flows for the WS/WU itself arises mostly from metal production for the energy technology devices.

Regarding the impact of global warming (GWP), 5.10 sums the results of the global warming potential with different methodologies applied.

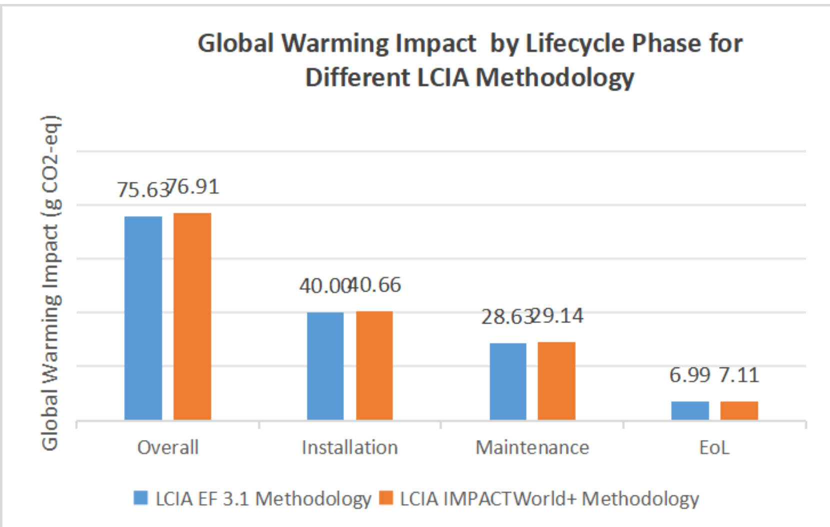


Figure 5.10: Global Warming Potential (g CO_2-eq/kWh) Sensitivity Analysis for Different LCIA Methodology

Based on figure 5.10 above, in the case of LCIA using IMPACTWorld+ the resulting values were 3%

higher than using the Environmental Footprint 3.1 methodology. When comparing between the contributors to GWP impact in both methodology, both methodology have peak in installation process, with value of 40.00 g CO_2eq/kWh and 40.66 g CO_2eq/kWh for EF 3.1 and IMPACTWorld+ respectively. This phase is dominated by material-intensive components and activities such as the floater assembly for WEC, turbine assembly for floating offshore wind, and mooring installation, which are consistently higher in IMPACTWorld+. The impact from floater assembly to the GWP centered in the steel production, either hot-rolled or cold-rolled. The similarity of this pattern reflects the shared reliance of both method on life cycle inventory flows for steel and copper.

Additionally, maintenance in IMPACTWorld+ shows higher value compared to the EF 3.1 methodology by $\sim$1.7% or 0.47 g CO_2eq/kWh. Giving a closer look to the contributors of GWP impact, this discrepancy lies in the ”emission to air” flow by ”methane, fossil”. In IMPACTWorld+, the Characterization Factor (CF) of the methane is 36 g CO_2eq/kg, whereas it's 29.8 in EF 3.1. These differences in the CF are due to the differences in baseline data, whereas the EF 3.1 refers to the research done by IPCC, which shows that methane from fossil fuel sources has slightly higher emissions metric values than methane from biogenic sources. Therefore, this leads to additional fossil CO_2 in the atmosphere [10]. On the other hand, IMPACTWorld+ reflects a midpoint climate change characterization factor that has been regionally weighted, based on the methane's impact in regions [20]. This reflects the methodological background processes can reduce the apparent contribution of vessel activity in IMPACTWorld+, even though the flows for the LCIA remains the same.

The end-of-life (EoL) stage is marginal in both methods (6.99 vs. 7.11 g CO_2eq/kWh), with differences of less than 5% and heavier in IW+. This consistency reflects the reliance on steel recycling credits, which are handled similarly across both LCIA methods.

Taken together, the results suggest that while GWP impacts are relatively stable across EF 3.1 and IW+, methodological choices do shape the attribution of burdens between life cycle stages. IW+ amplifies the global warming impact mainly driven by the burden from ”methane, fossil” as explained above because the other flow –carbon dioxide, fossil– CF is still comparable with EF 3.1. For offshore renewable energy systems, this implies that while conclusions about their low-carbon potential remain valid regardless of method, methodological transparency is critical when discussing hotspot stages and decarbonisation strategies.

The summary of results of comparison between both methodology is presented below:

Table 5.7: Co-located park: EF 3.1 vs IMPACTWorld+ (IW+)

Impact Category	Co-located EF 3.1	Co-located IW+	Δ (IW+ - EF 3.1)	Percent difference
AC	1.55E-03	N/A	N/A	N/A
GW	7.56E-02	7.69E-02	1.29E-03	1.70%
FET	5.91E-01	4.53E+03	4.53E+03	767810.80%
FD	9.39E-01	1.00E+00	6.06E-02	6.45%
FE	2.69E-05	3.76E-07	-2.65E-05	-98.60%
ME	4.09E-04	3.91E-05	-3.70E-04	-90.43%
TE	3.90E-03	N/A	N/A	N/A
HTc	7.41E-11	2.44E-07	2.44E-07	328706.06%
HTnc	1.84E-09	5.96E-08	5.78E-08	3148.04%
IR	3.56E-03	3.56E-01	3.52E-01	9883.10%
LU	2.47E-01	N/A	N/A	N/A
MD	1.92E-06	3.73E-02	3.73E-02	1945501.40%
OD	9.48E-10	1.01E-09	6.59E-11	6.96%
PM	1.28E-08	6.81E-05	6.80E-05	533456.13%
POF	1.09E-03	1.07E-03	-1.61E-05	-1.47%
WU	1.59E-02	1.61E-01	1.45E-01	911.63%

Overall, as shown in table 5.7, the comparison between IMPACTWorld+ and EF 3.1 shows that the characterization factor numbers in each number are shaped by methodological design as by the system itself. While global warming and fossil energy demand appear robust across methods, categories such as toxicity, ionising radiation, and particulate matter reveal how different assumptions, coverage, and modeling approaches can shift the scale of impacts by several orders of magnitude. This does not necessarily imply that one methodology is more “correct” than the other, but rather that each frames environmental mechanisms through its own point of view and is highly dependent on the purpose of the LCA itself.

5.4.2. Sensitivity Analysis on Infrastructure Arrangement (Cradle to Grave)

This section will discuss about how the difference of system operation in a co-located wind-wave energy park would influence the GWP impact —between hybrid and paralel system. Whereas in hybrid system all devices —wind and wave— would be connected by the same inter-array cable to the same substation, which ultimately connected to one export cable. On the other hand, paralel system will lead to different inter-array cable that connects wave array and wind array, to a different substation for each technology, and ultimately connected to different export cable for each technology. This arrangement certainly create disrepancy between the wind and wave share towards the BOP (Balance of Plant).

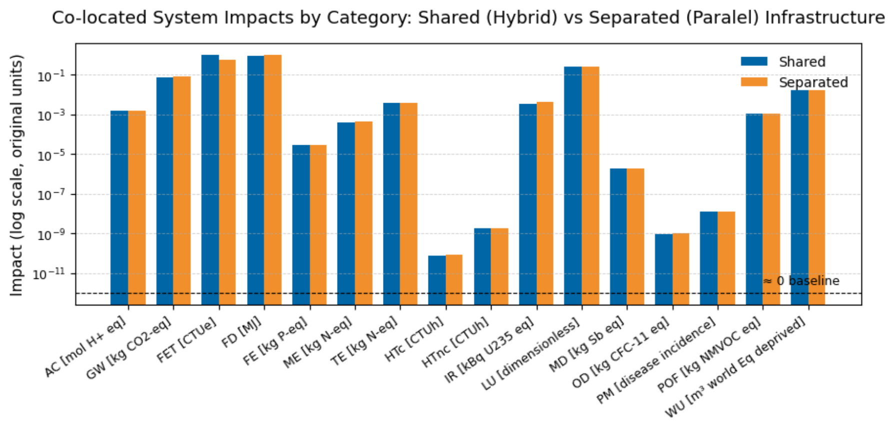


Figure 5.11: Global Warming Potential (g CO_2-eq/kWh) Sensitivity Analysis for Different Infrastructure Arrangement

The result shown in 5.11 shows the impact assessment result of co-located offshore energy parks in shared versus separated infrastructure arrangements, with GWP category dominates the impact with values of 75.63 g CO_2eq/kWh in shared infrastructure and 79.32 g CO_2eq/kWh when it’s separated. This difference is primarily attributed to the heavier steel demand for duplicate substations and jackets, which together grow from 3,812 tonnes in the shared design to 6,225 tonnes in the separated arrangement. This not only raises climate emissions through energy-intensive blast furnace routes but also amplifies Acidification (AC) and Particulate Matter (PM) categories.

Fossil usage (FD) rises moderately by 5.36%, consistent with the higher energy requirements for producing and transporting heavier components. Nutrient-related categories show relatively minor changes. Freshwater Eutrophication (FE) and Marine Eutrophication (ME) increase by 2.91% and 2.04% respectively, primarily due to additional NO_x emissions during transportation and installation of the extra substation. Similarly, Terrestrial Eutrophication (TE) rises by 2.18% as the larger volume of equipment requires longer installation time and heavier fuel use.

Human toxicity categories show mixed trends: carcinogenic toxicity (HTc) increases slightly by 6.65%, while non-carcinogenic toxicity (HTnc) decreases marginally by −3.39%. These variations reflect the interplay between increased metal content and updated emission profiles from component manufacturing. The persistence of non-zero toxicity values still indicates that alloying metals, smelting by-products, and polymer additives have measurable though limited effects. Ionising Radiation (IR) increases by 15.94%, linked indirectly to higher electricity use in the material supply chain and substation assembly. Land Use (LU) grows by 6.07%, associated with expanded mining and manufacturing operations to meet higher material demand. Conversely, Mineral Resources use (MD) shows a small reduction (−6.48%), led by the usage of less copper for dynamic cabling, as a result of power capacity adjustment in the paralel system.

Categories of smaller magnitude, such as Ozone Depletion (OD) and Particulate Matter (PM), remain relatively stable with slight increases of 5.75% and 1.89%, respectively, showing that the key differentiating processes (steel and cable production) are not the primary contributors under EF 3.1's characterization approach. Water Use (WU) increases by 8.11%, as manufacturing additional jackets and substations leads to greater indirect water consumption for steelmaking and cooling processes.

However, the results confirm that shared infrastructure generally yields lower impacts across nearly all categories, even if the relative differences (e.g., AC: 1.72%, PM: 1.89%) appear numerically small while the infrastructure shared. This indicates that while the substation sizing, export cable, and the inter-array cable have been adjusted following the relative power capacity carried by each technology —30 MW for wave and 150 MW for wind— infrastructure sharing still significantly reduces the embodied burdens per kWh of electricity delivered. From a methodological reflection, EF 3.1's midpoint set provides a view of how upstream metal and fossil inputs propagate across diverse categories, and the observed dominance of GW, AC, PM, and FD matches well with recent offshore renewable LCA literature, where heavy steel structures, vessel fuel use, and cabling are identified as main hotspots [74], [98]

As previously said, GWP category dominates the impact with values with detailed distribution as in the figure 5.12 and 5.13 below.

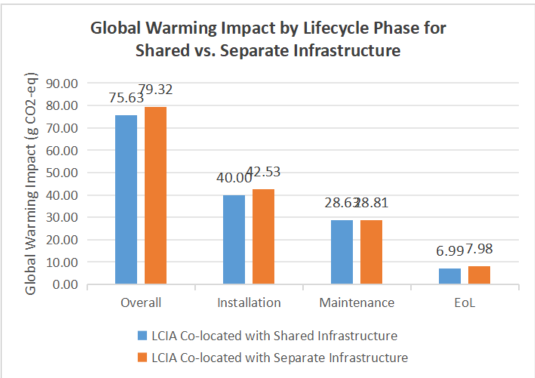


Figure 5.12: Global Warming Impact Across Infrastructure Arrangement

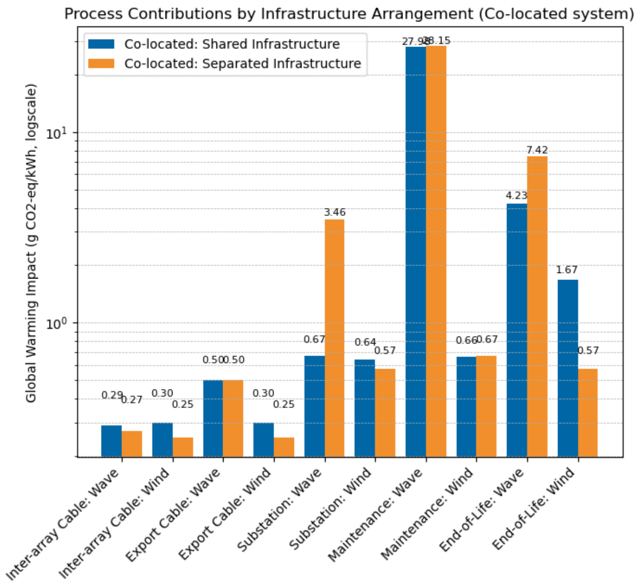


Figure 5.13: Process Contributions by Infrastructure Arrangement

Based on the figure above, global warming (GWP) impact across shared and separated infrastructure arrangements reveals that the overall carbon intensity of the co-located system increases from 75.63 g CO_2eq/kWh in the shared case to 79.32 g CO_2eq/kWh in the separated case. This divergence is mainly explained by the installation phase, which rises from 40.00 g CO_2eq/kWh to 42.53 g CO_2eq/kWh when additional substations and heavier jackets are required. This increase in steel demand when the substation is separated grows up to 2,421.82 tonne from the when both technology share the same infrastructure. However, the separation of inter-array cable by adjusting the power capacity and the power transmitted –WEC array uses 33 kV and FOWT array uses 66 kV– shows positive impact of dicreasing marginal GWP impact.

The maintenance phase contributes comparably in both scenarios (28.63 vs. 28.81 g CO_2eq/kWh), mainly because the additional component to have maintenance is subtle, the wave substation. This aligns with offshore wind literature, where O&M logistics especially fuel use in service operation vessels are consistently reported as lifecycle hotspots [36]. End-of-life (EoL) remains negligible in both cases $\sim$7 g CO_2eq/kWh, with increase by 1 g CO_2-eq/kWh when in paralel system, due to additional raw material usage.

Lastly, the findings indicate that shared infrastructure consistently reduces GWP impacts by lowering heavy steel and cable duplication, although O&M remains a dominant hotspot irrespective of design. The results highlight the importance of integrated system design: environmental gains from shared substations and export cabling could be offset if O&M logistics are not optimized.

The summary of impact categories difference between the two infrastructure arrangement is presented in the table below

Table 5.8: Shared vs Separated Infrastructure (co-located park)

Impact category	Shared Infrastructure	Separated Infrastructure	Δ (separated - shared)	Percent difference
AC	1.55E-03	1.58E-03	2.67E-05	1.72%
GW	75.63	79.32	3.70E+00	4.89%
FET	5.91E-01	5.91E-01	2.24E-05	0.00%
FD	9.39E-01	9.90E-01	5.03E-02	5.36%
FE	2.69E-05	2.77E-05	7.82E-07	2.91%
ME	4.09E-04	4.17E-04	8.32E-06	2.04%
TE	3.90E-03	3.98E-03	8.50E-05	2.18%
HTc	7.41E-11	7.90E-11	4.93E-12	6.65%
HTnc	1.84E-09	1.77E-09	-6.23E-11	-3.39%
IR	3.56E-03	4.13E-03	5.68E-04	15.94%
LU	2.47E-01	2.62E-01	1.50E-02	6.07%
MD	1.92E-06	1.79E-06	-1.24E-07	-6.48%
OD	9.48E-10	1.00E-09	5.45E-11	5.75%
PM	1.28E-08	1.30E-08	2.41E-10	1.89%
POF	1.09E-03	1.12E-03	2.52E-05	2.31%
WU	1.59E-02	1.72E-02	1.29E-03	8.11%

Overall, the results confirm that shared infrastructure consistently reduces life cycle impacts across most categories by avoiding duplication of steel- and copper-intensive components. The effect is most pronounced in climate change, acidification, particulate matter, and fossil depletion, where avoided emissions are equivalent to the upstream processing and transport of thousands of tonnes of raw materials. These findings align with recent literature emphasizing that substation sharing and hybrid cabling provide not only economic savings but also measurable environmental benefits [74, 98, 36]. From a methodological perspective, this sensitivity highlights that infrastructure configuration is not a significant detail but has a visible of environmental outcomes as it increases by 24.19% in GWP impact category. A shared arrangement frames the system as an integrated energy hub with optimized resource use, while a separated arrangement treats wind and wave as parallel projects with duplicated embodied burdens.

In conclusion, infrastructure sharing streamlines resource use and consistently lowers environmental burdens, whereas separated designs magnify hotspots through material duplication.

5.5. Results for Energy Payback Indexes

Using the resulting Cumulative Energy Demand (CED) for the whole lifecycle for the three baseline named 180 MW floating wind, wave energy, and multi-source offshore energy park, the primary energy consumption for each energy park can be concluded. Thus, this value can be used for the calculation for energy payback time (EPBT) as in equation 3.8 for an energy park with CFs of 38.1%, 30.3%, and 42.1% for 180 MW offshore wind, wave energy, and co-located offshore energy park.

The calculation for EPBT starts with applying CED Midpoint (H) using the ecoinvent library in openLCA, to asses the primary energy usage, to investigate the energy used throughout the life cycle of a system. It includes both direct and indirect grey consumption of energy due to usage. With such methodology, the energy used per kWh (MJ-eq/kWh) for the wind park is 0.16 MJ-eq/kWh, 1.58 MJ-eq/kWh for wave energy park, and multi-source wind and wave energy park needs about 0.78 MJ-eq/kWh of energy.

Following the CED per kWh, using the total energy used over lifetime (25 years) and the annual energy production, the EPBT can results below:

Table 5.9: Energy Payback Time per System

System	AEP [MWh/year]	EPBT [years]
180 MW Wind Energy Park	601,358.00	1.13
180 MW Wave Energy Park	561,340.80	9.41
180 MW multi-source Energy Park	849,546.00	7.28

Based on the table above, it is found that within a large capacity of energy park, WEC would have a longer duration of both energy and greenhouse payback period. However, looking into the detail distribution of the shared energy used and energy generated between wind and wave, this duration decreases by 15% when the WEC deployed in the same location with FOWT to achieve the same rated capacity. This is because the energy used for wave is 89.4% (1.19 MJ-eq/kWh) of total energy used. With wave contributes 16% to energy generation in the co-located energy park, therefore the EPBT for wave itself is 8.26 years, while wind take approximately 1 year.

The comparison with lower rated park capacity —10 MW array, [70]— shows the EPBT ranges between 2.6 to 5.2 years. Additionally, Thomson, et al. [87] shows that Pelamis WEC with 120 m long, 3.5 m in diameter and rated at 750 kW have 7.5 years of EPBT. This comparison implies that EPBT is highly influenced by both array capacity, capacity factor, and system configuration: while larger standalone WEC parks show much higher values, co-location with wind enables economies of scale that bring the EPBT closer to those reported for smaller arrays in earlier studies.

Along with the EPBT, it is also possible to calculate the time needed by the system to mitigate GHG emissions from the wind turbine. Prior to that, according to the emissions from 2022 data of power generation by source in Europe [47], the total emissions from coal, oil, and natural gas used for electricity generation amounted to 721.5, 49.3, 367.7 Mt CO_2 respectively, resulting in a combined total of 1,138.5 Mt CO_2. In the same year, European Union generated approximately 4,018,742 GWh of electricity. Furthermore, the value of emission intensity reported by the European Environment Agency excluding emissions from heat production is reported to be 288 g CO_2eq/kWh. Reflecting these values with the 3.9, the annual emission avoided and GPBT from each system are as below:

Table 5.10: Greenhouse Gas Payback Time per System

System	Annual Emission Avoided [g CO_2-eq]	GPBT [years]
180 MW Wind Energy Park	171,053,359,234.65	1.65
180 MW Wave Energy Park	110,384,102,508.17	12.54
180 MW multi-source Energy Park	186,618,579,171.64	8.61

It is important to note that the GPBT values reported here reflect a simplified assumption that all electricity demand originates from fossil-based generation. This represents a maximum-substitution scenario, in which each kilowatt-hour produced by the offshore energy park replaces a high-emission unit of electricity. Under this assumption, the avoided emissions per kWh are large, resulting in shorter GPBT values.

In reality, however, modern and future electricity grids increasingly rely on a mix of fossil and renewable energy sources. As the share of renewables increase, the emission intensity of the marginal electricity displaced by offshore renewable systems decreases. Since the annual avoided emissions decrease while the life-cycle emissions remain constant, the GPBT duration will therefore increase. This longer carbon payback periods in cleaner grids, not because they perform worse, but because each kWh of renewable electricity offsets fewer grams of CO_2-eq in a low-carbon energy system.

The results in table 5.9 and table 5.10 confirm the technological maturity gap between wind and wave energy. Offshore wind shows both rapid EPBT and GPBT, confirming its robustness as a decarbonization pathway. Wave energy, in its current state, is characterized by long payback times that undermine its carbon and energy efficiency. However, the co-located scenario illustrates that synergies in shared infrastructure can significantly reduce payback times for wave energy systems.

6
Discussion

6.1. Key Findings Interpretation

6.1.1. Influence of Device Composition on GWP impact

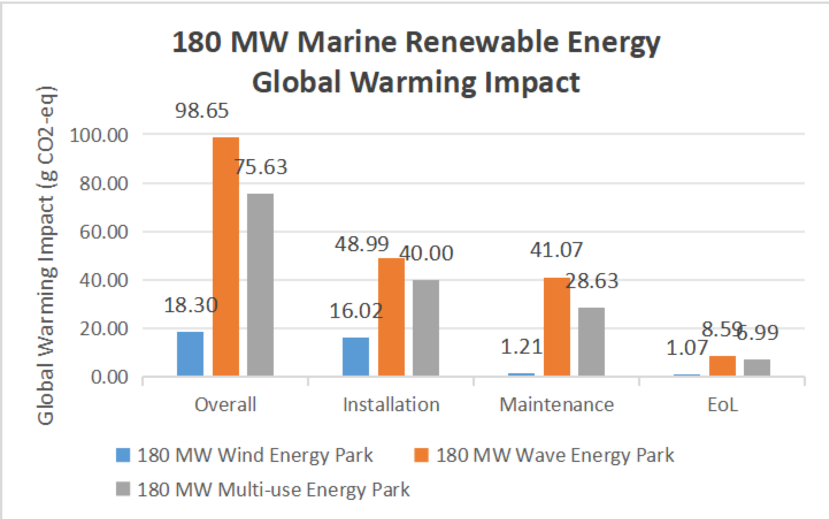


Figure 6.1: GW Emission Comparison of 180 MW Offshore Renewable Energy Park

Figure 6.1 shows the multi-source wind and wave energy systems emits GW lower than 180 MW wave energy park, yet, higher than 180 MW floating offshore wind energy park. The total GWP impact of the multi-source is 75.63 gCO_2-eq/kWh, indicating a reduction of 25% from wave energy park and $\sim 5\times$ higher than the wind alone. The co-located wind and wave have a major reduction compared to the wave technology alone is mainly because of the lower number of installed devices. Looking at the process contribution, installation and manufacturing which includes the material needed for each devices remain as the main contributor in all three scenarios, where the main contributor to the installation process GWP impact is the market for steel and its machinery for the manufacturing process.

To understand how standalone technology compares with co-located wind-wave offshore renewable energy, this study follows the framework in Figure 3.8 to analyze how the burden is distributed to each technology when it shares a co-located space. The comparison between a standalone technology and its contribution within a co-located space to produce 180 MW is shown in the figures below.

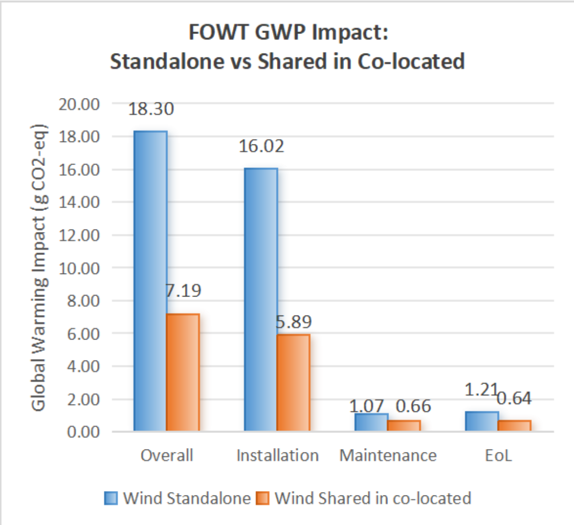


Figure 6.2: Wind GWP impact Share Comparison

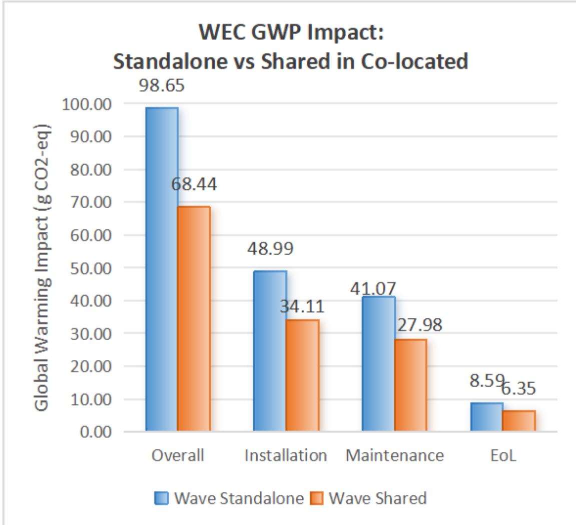


Figure 6.3: Wave GWP impact Share Comparison

Based on the figure 6.2 and 6.3, the effect of sharing is somewhat equal between the two technology –both as a standalone or its share in multi-source. When co-located, the share of each technology is around ~30% compared when it's in a standalone system.

When looking at the installation phase, the pattern persists: the co-located system (≈ 40.00 gCO_2-eq/kWh) lies close to the wave-only park (48.99 gCO_2-eq/kWh) and far above the wind-only park (16.02 gCO_2-eq/kWh). This phase reflects the material and manufacturing intensity of offshore infrastructure—particularly steel for floaters and mooring chains, and copper for subsea cabling and substations. Even when infrastructure is shared, these materials remain the largest source of embodied carbon. The slight increase in the co-located case over the wave-only case arises from the change in inter-array cable, whereas in the wave-only scenario, it uses a 33 kV cable to adjust for the power carried by the wind; therefore, the inter-array cable in the multi-source scenario uses 66 kV. This change of cable dimension lead to increasing GWP impact.

On the other hand, wind energy experience a comparable effect when it's being co-located. The wind share in co-located is 34% lower compared to standalone wind energy. Phase contributions somewhat noticable with falls from 16.02 to 5.89 gCO_2-eq/kWh and maintenance from 1.07 to 0.66 gCO_2-eq/kWh. These small reductions suggest that wind's carbon footprint is already efficient, and the benefits of sharing are limited by the small scale of infrastructure avoided relative to the turbine and substructure mass. The main contributor for GWP is the steel material that shaped the turbine, including the tower, blades, and semi-submersible structure.

Taken together, the three graphs show that infrastructure sharing have a comparable benefits for both system, where the cradle and maintenance life stage dominates the emissions. The hybrid system achieves a compromise profile: much lower than wave-only, but still higher than wind-only. This confirms that sharing can stabilize and reduce installation-phase emissions, but it does not neutralize installed number of devices hotspots, especially in wave technology. However, the analysis shows that other than GWP impact, multi-source co-located wind and wave have a significantly lower values across other midpoint impact categories.

From a societal perspective, these results underline a critical point. Although wave energy remains environmentally have higher GWP impact compared to mature technology such as offshore wind, it still gives relative gains compared to non-renewable technology, moreover when its co-located with offshore wind technology. In the broader energy mix of Europe, the continent still primarily uses non-renewable sources with highest percentage from natural gas (20.95%) and coal (17.10%) as per 2022, these energy resources have GWP impact of 820 gCO_2-eq/kWh that can rises up to 910 gCO_2-eq/kWh for coal and 434 gCO_2-eq/kWh for natural gas [94]. Even the least favorable case in this study —the wave-only park— remains substantially lower than fossil alternatives, reinforcing the strategic importance of marine renewables for climate mitigation. Nonetheless, the results also caution against overstating the short-term readiness of wave energy, as its material and maintenance intensity pose barriers to rapid deployment.

6.1.2. Emission Fluctuation due to Infrastructure Arrangement in Co-located Wind-Wave Energy Park

The fluctuation of the GWP emission in the three baseline scenarios has shown that the multi-source offshore energy park results in an amount of emission that falls between the standalone wind energy park and the standalone wave energy park. The differences lie mostly in the installation process and maintenance.

However, to add clarity about how shared infrastructure impacts the GWP emissions in the case of a multi-source offshore energy park, this research also conducted another scenario in which the offshore substation and cabling are separated to retrieve energy generated from the WECs and the FOWTs. The sizing of the topside mass of the offshore substation was conducted through interpolation for 30 MW WECs and 150 MW FOWTs, based on references from installed substations. Meanwhile, the sizing of the jacket was estimated using a linear regression of topside mass and water depth. Therefore, in the case of separated infrastructure in a multi-source offshore park, the topside masses are 187 tonnes and 933 tonnes for wave and wind, respectively, with jacket masses of 8,536 and 45,172 tonnes. This means that while the total topside mass of both structures is slightly higher than that in the shared infrastructure scenario, the total jacket mass is relatively lower.

In parallel with substation separation, the export cable design also required additional sizing adjustments. The 66 kV inter-array cables connect between the wind turbines, while the 33 kV cables connect the WECs. To minimize transmission losses, the wind substation is connected through a 150 kV export cable, whereas the WEC substation uses a 66 kV export cable to transmit generated power. These adjustments between the power ratings and the transmitted loads for each technology lead to a reduction in GWP from the dynamic cable processes. Specifically, the total inter-array cable weight for wave decreases by 154.20 tonnes (39%), resulting in a GWP reduction of 0.18 gCO_2-eq/kWh (−7%). A similar trend is seen in the inter-array cables for wind, where separation reduces GWP by 0.18 gCO_2-eq/kWh compared to the parallel system. However, the export cable for wind experiences a 15% increase in total mass and a 19.34% rise in GWP due to the larger conductor cross-section. These increases are mainly driven by the higher use of copper and lead, the principal materials acting as the conductor and protective sheath of the cables.

As shown in Figure 6.1, the separated-infrastructure scenario increases overall GWP emissions by 4.89%, from 75.63 gCO_2-eq/kWh(shared) to 79.32 gCO_2-eq/kWh. This clearly demonstrates that shared infrastructure substantially reduces emissions by avoiding duplication of heavy and carbon-intensive components such as substations, while separation of array cables can locally lower emissions due to optimized power flow distribution that eventually leads to decreasing total cable mass. The result aligns with Garcia-Teruel et al. [36], who emphasize that the design and deployment of auxiliary infrastructure are key drivers of lifecycle emissions in multi-technology offshore parks.

However, the fluctuations linked to O&M remain unchanged. Maintenance contributes $\sim$30 gCO_2-eq/kWh in both shared and separated scenarios, dominated by vessel fuel consumption for servicing WECs. These emissions are inherently variable, depending on weather windows, failure rates, and vessel deployment. Consequently, while sharing stabilizes structural emissions (construction-related), it does not address operational variability, which continues to drive the bulk of lifecycle fluctuations. This confirms findings from offshore O&M literature, which emphasize vessel logistics as a persistent hotspot irrespective of infrastructure design [36].

Overall, these findings suggest that shared infrastructure reduces GWP emissions primarily by avoiding duplication of heavy and carbon-intensive components, such as substations. Additionally, the separation of inter-array cable between wave- and wind- array can lower the GWP impact even better. The sharing infrastructure also limits emissions from fabrication and transport activities by consolidating installation processes. As a result, shared infrastructure helps stabilize and lower lifecycle emissions, particularly in components like substations and inter-array cabling, where material intensity and complexity tend to drive large fluctuations.

6.1.3. Impacted Lifecycle due to Shared Infrastructure

The comparison between standalone and co-located configurations shows that the installation phase is the lifecycle stage most affected by infrastructure sharing in multi-use offshore energy parks. This phase experiences the largest reduction in Global Warming Potential (GWP) for both wind and wave systems, primarily due to the avoidance of redundant heavy components and the consolidation of logistics-intensive activities.

For wave energy, installation emission decreases from 48.99 to 34.11 gCO_2-eq/kWh ($\sim$30%), representing the single largest contribution to overall GWP reduction. Similarly, the floating offshore wind system shows a decrease from 8.58 to 5.89 gCO_2-eq/kWh ($\sim$31%), confirming that infrastructure sharing strongly influences the construction and deployment stage. These reduction rooted from several factors. First, the maximization of devices number to achieve the same rated capacity can reduce the demand for structural steel and its manufacturing process (e.g. blast furnace-basic oxygen furnace). Additionally, the higher energy yield in the multi-source energy park leads to a lower value to share the burden between two technologies.

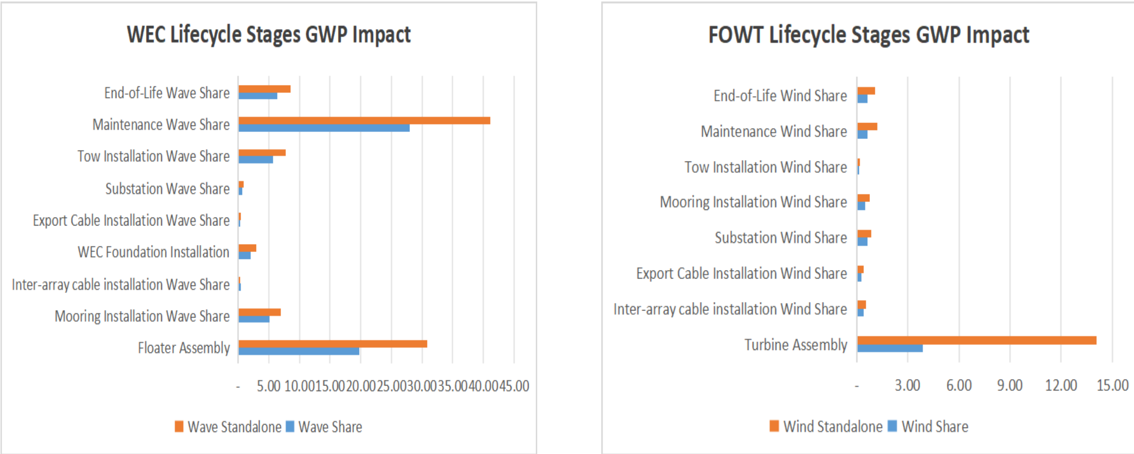
Second, the adjusted number of devices that eventually leads to adjusted occupied area, amplify the benefits. A less occupied sea area leads to reduction number of mobilizations and standby times, both of which are major contributors to marine fuel consumption. For instance, the floater assembly for the wave devices alone accounts for a difference of 11.02 gCO_2-eq/kWh between standalone and shared setups with reduction of 375 devices, while turbine assembly in the wind system is 2.78 gCO_2-eq/kWh lower when integrated into the shared operation plan. These findings are consistent with Raadal et al. [74], who identified the assembly and offshore installation of steel-intensive structures as the dominant hotspots in offshore renewable LCAs.

For wind energy, the overall GWP emissions decrease only from 18.30 to 7.19 gCO2-eq/kWh, with the biggest increment occurring in the installation phase, by 63.23%. However, in both systems, installation remains as the biggest contributor to GWP impact, while end-of-life contributions remains low. This reflects the maturity and material efficiency of floating wind systems, where structural steel and turbine components dominate emissions. On the other hand, the adjustment of the End-of-Life strategy may fluctuate the GWP impact.

While installation that includes raw materials and manufacturing processes shows the strongest sensitivity, maintenance also exhibits reductions under shared infrastructure. The GWP contribution from maintenance drops by 13.09 gCO_2-eq/kWh (wave) and 0.41 gCO_2-eq/kWh (wind) in co-located operation. This is primarily because vessel operations –which dominate O&M emissions– is optimized due to installed device reduction and shared maintenance frequencies. However, because O&M emissions depend heavily on external factors such as weather windows, failure rates, and downtime constraints, the variability of this phase remains high, as also emphasized in Garcia-Teruel et al. [36]. Thus, while sharing reduces the average emissions, it does not entirely stabilize the uncertainty associated with operational phases.

The end-of-life (EoL) stage, although the least dominant contributor in absolute magnitude, also benefits from infrastructure sharing, with GWP reductions of 2.24 gCO_2-eq/kWh for wave and 0.42 gCO_2-eq/kWh for wind. This improvement primarily results from the reduced scale of dismantling activities, which lowers vessel fuel consumption and decreases the volume of materials requiring recycling or disposal. Consequently, less energy is expended in cutting, transport, and reprocessing of structural steel and cabling, leading to fewer emissions from downstream recycling and waste treatment processes.

For a visual comparison of each lifecycle phase—standalone (180 MW) versus its allocation within the multi-source energy park discussed above—see below:



(a) Comparison between WEC Life Cycle Stages GWP Impact in Standalone and Multi-source Energy Park

(b) Comparison between FOWT Life Cycle Stages GWP Impact in Standalone and Multi-source Energy Park

Figure 6.4: Comparison between Technology Life Cycle Stages GWP Impact in Standalone and Multi-source Energy Park

When comparing the co-located offshore wind–wave system under shared and separated configurations, the global warming (GWP) impact contribution of the installation stage increases from 40.00 gCO_2-eq/kWh in the shared case to 42.53 gCO_2-eq/kWh in the separated case, representing an $\sim 15\%$ rise. This difference accounts for nearly the entire increase in total lifecycle emissions between the two scenarios.

The primary driver of this increase lies in the duplication of high-mass components, particularly substations and export cable. Inventory data confirm that the separated scenario requires substantially larger material inputs: the wave substation jacket mass increases by approximately 1,968 tonnes of steel. These materials are associated with high embodied carbon intensities due to their energy-intensive extraction and processing routes (e.g., blast furnace steel production, copper smelting, and lead refining). This correlation between material demand and GW outcomes is further illustrated in the process-level contribution analysis, where the substation (wave) contribution rises from 0.67 to 3.46 gCO2-eq/kWh and the export cable for both wave and wind increases from 0.38 to 0.64 gCO2-eq/kWh and 0.46 to 0.45 gCO2-eq/kWh.

In contrast, inter-array cable have a decreasing GWP impact by up to 30%. This increment is specifically caused by the adjustment of power rating dimension in wave energy array and adjustment of the length for the same power rating in wind energy array. In the shared infrastructure scenario, as the wave and wind energy device works in hybrid configuration, therefore it adjusted to the wind's cable rating. However, in the separated scenario, the system acts as a paralel to be connected to different substation that eventually connected to the onshore transmission system.

The maintenance and end-of-life phases are largely unaffected by infrastructure sharing. Maintenance for wave share contributes almost equally in both configurations lower in hybrid system (27.98 vs 28.15 gCO2-eq/kWh), as it is governed by vessel fuel consumption and operational intensity rather than the layout of shared or separated assets. This highlights that while infrastructure design influences the structural emissions tied to upfront construction, it does not significantly alter the operational emissions, which remain dominated by O&M logistics throughout the 25-year lifetime.

Therefore, infrastructure sharing can be interpreted as a structural efficiency, as it reduces the material- and resource-intensive impacts of the installation stage by avoiding duplication of substations, jackets, and cables. Maintenance and end-of-life phases, however, remain invariant under this design choice. This finding aligns with broader offshore renewable energy literature [74], which consistently identifies construction-phase steel and cabling as the largest contributors to installation impacts, while O&M logistics remain the persistent hotspot across scenarios.

In conclusion, the three comparisons demonstrate that installation is the lifecycle phase most strongly influenced by infrastructure sharing, as it directly reduces the material and resource intensity of substations, cabling, and support structures. Maintenance highly dependent on the total occupied area and number of devices installed, because they are driven by vessel fuel consumption and operational logistics, and end-of-life are marginal, as it can varies dependng on the recyclability assumptions.

6.1.4. Influence of LCIA Method Choice

Life cycle impact assessment (LCIA) methodology holds a fundamental aspect to evaluate the environmental performance of offshore renewable energy system. To answer about *"How do LCIA method choices (e.g., IMPACTWorld+ vs EF3.1) influence the assessment of GW emissions in offshore renewable energy systems?"*, an LCA with configuration of multi-source offshore energy park with shared infrastructure was conducted.

Using the same baseline and life cycle inventory (LCI), the total climate change impact assessed using IMPACT World+ results in 76.91 gCO_2-eq/kWh, while EF 3.1 yields 75.63 gCO_2-eq/kWh. At first glance, the overall climate change results are numerically consistent. Looking at the individual lifecycle stages, the largest difference occurs in WEC floater assembly, which includes PTO manufacturing and towing installation. The total contribution of floater assembly is $\sim$25 gCO_2-eq/kWh using both LCIA methodologies. The close alignment suggests that both methodologies apply robust characterization factors for carbon dioxide, methane, and nitrous oxide, which dominate climate forcing.

However, the stability observed in GWP impact outcomes masks substantial divergences in other midpoint categories, which reveals methodological sensitivities. Figure 5.10 shows that freshwater ecotoxicity (FET), human toxicity (HTc, HTnc), and ionising radiation (IR) differ by one to three orders of magnitude depending on the method applied.

This comparison illustrates that LCIA method is not a neutral decision, but requires a justification for methodology selection based on the goal and scope of the study. For example, in addition to the characterization factors, it is also important to recognize the assessment indicator of the LCA, whereas EF 3.1 offers only midpoint and IMPACTWorld+ could provide both midpoint and endpoint. Additionally, few of midpoint indicators are different between the two methodologies (e.g. water use vs water scarcity and the absence of short term climate change in EF 3.1). Therefore, for robust and credible LCA, method transparency, consistent reporting, and a clear understanding of methodological assumptions are essential. Without this clarity, two assessments using different methods may not be fully comparable, even if they appear similar on the surface.

In conclusion, LCIA method choices influence GHG assessment outcomes subtly at the aggregate level but significantly at the flow-specific and category-specific levels. EF 3.1 offers EU-aligned, conservative climate factors, while IMPACTWorld+ provides globally differentiated, more ecologically explicit modeling. Both perspectives are valid, and their triangulation strengthens the robustness of this study's findings.

6.1.5. Validation Against Literature

The calculated results show that the wind energy has the lowest specific emission (18.03 gCO_2-eq/kWh), followed by the multi-source offshore renewable energy (75.63 gCO_2-eq/kWh), while wave energy shows the highest emissions for the full system with 98.65 gCO_2-eq/kWh. These results are validated against ranges in the literature.

System	**This Study (gCO_2-eq/kWh)**	**Literature Range (gCO_2-eq/kWh)**	**Literature**
Wind (180 MW)	18.03	6–31	[101], [22], [91], [95], [19]
Wave (180 MW)	98.65	80–300	[103], [28], [18]
Multi-source (180 MW)	75.63	N/A	N/A

Table 6.1: Validation of climate change impact category against literature.

The wind energy result falls well within the established range for offshore wind LCAs, confirming a strong alignment. The wave energy findings also align with prior studies, though they leave some room for interpretation. Pennock et al. [70] reported greenhouse gas emissions of 25.1–46.0 gCO_2-eq/kWh for a wave energy park, while Engelfried [28] estimated 52–77 gCO_2-eq/kWh for technology without peripheral components and 300–325 gCO_2-eq/kWh when including full periphery. The results of this study fall above the "no periphery" scenarios but remain well below the full-periphery cases. This suggests that the modeling assumptions adopted here account for partial, though not extreme, peripheral contributions.

In the case of wave energy, several factors can explain this deviation, such as:

- Operations and maintenance frequency assumption, whereas this study assumed semi-annual O&M interventions, resulting in higher vessel and fuel contributions, while some studies assume less frequent interventions (every 2–5 years).
- Corrective maintenance approach assumption, whereas this study assumed corrective maintenance frequency for each component using the multiplication of failure rate, number of devices, and total lifetime duration for the technology device. Moreover, this study took into account the frequency of components maintenance frequency.
- System boundaries: The inclusion of export cables and scaled jacket structures for substation in this study increases embodied impacts compared with studies that disregard these components.

6.2. Study Implications

6.2.1. Implications for Offshore Park Design

The result shows that the multi-source offshore wind and wave energy park can create a solid greenhouse gas (GHG) savings, particularly when the key infrastructure (offshore substation and offshore cable) is shared. With the emission reduction up to 50% compared to the stand-alone WEC energy park, a multi-source offshore energy park can achieve the same rated capacity. While not all component and activities of the manufacturing to the end-of-life within the multi-source offshore park have the same carbon intensity, therefore, the efficiency gains from a multi-source offshore energy park should be balanced with the design choices and configuration such as the energy park layout and amount of each devices.

As described in section 5.4.2, the dominance of maintenance-related impacts points to the need for operational strategies that minimise vessel movements, such as shared service crews, hybrid-powered vessels, and coordinated maintenance schedules across multiple technologies. These measures can reduce environmental burdens while also shrinking the spatial footprint of recurring marine traffic.

6.2.2. Implications for LCA Practitioners

The comparison between IMPACTWorld+ and EF3.1 methodologies illustrates that while the direction of the result remains consistent, the increment of the result in EF3.1 methodology shows higher GW results mainly due to its higher characterization factor, which in this study was visible in the flow of methane (fossil) greenhouse gas impact.

For the practitioners, this emphasizes several points such as:

- Method selection is important depending on the end goal of the study. This include parameters to look out, characterization factors, midpoint/endpoint indicator availability, and category definitions that can shift both results and importance of each lifecycle stages.
- Transparency in reporting including its key characterization factor differences, method choice considerations, and any exclusion categories or indicators.
- Realistic and thorough modeling since emission outcomes are sensitive to physical configuration decisions and the processes that acts as predecent or dependent in the lifecycle. The LCA model thus should reflect feasible and corresponding designs.

6.2.3. Implications of Technology Choice on Energy and Carbon Payback

As described in section 5.5, the energy payback time (EPBT) and greenhouse gas payback time (GPBT) results reveal clear differences between technologies: the 180 MW floating wind park achieves the shortest payback (EPBT of 1.13 years, GPBT of 1.65 years), while the wave energy park exhibits significantly longer payback periods (EPBT of 9.41 years, GPBT of 12.54 years). The co-located case falls between these extremes (EPBT of 7.28 years, GPBT of 8.61 years).

These differences highlight that while wave energy currently lags behind in terms of EPBT and GPBT compared to floating offshore wind, the co-located offshore wind and wave energy park offers a strategic compromise with the same rated capacity. This suggests that intergrating marine renewables with smaller occupied of sea area can act as a pathway for marine renewable energy without delaying overall climate benefits.

6.3. Study Limitations

6.3.1. Technological Assumptions

Excluded Substation Electrical Model

Offshore substations consist of a main electrical power system, auxiliary systems, a topside structure to house the systems, and a foundation. Offshore substation can either be HVAC or HVDC depending on the energy park capacity and the distance from the shore. In this study, the electrical component design and calculation is disregarded. This is because the whole design of an offshore substation include a detailed single-line-diagram (SLD) and ratings calculation, complete electrical studies (e.g. load flow & losses, protection and coordinatioin, switchgear selection), primary equipment selection, and miscellaneous that requires interdisciplinary studies between electrical engineering and civil engineering. Therefore, the substation topside mass used in this study is based on extrapolation from installed substation with its respective rated park capacity.

Excluded Detailed Wake Effects Modeling

Wind turbine wakes are regions downwind of the rotor, where wind speed is reduced and turbulence is increased due to energy extraction. This can significantly lower the performance of downstream turbines, especially in closely packed offshore wind farms. Wake losses and added turbulence persist over large distances and can impact power generation and turbine fatigue life [26]. Currently, several approaches used for wake effects modeling are analytical and semi-empirical models to predict wind speed deficits and turbulence using simplified formulations [89], numerical simulations which incorporated combination of large eddy simulations (LES) including near-wake dynamics [85], and CFD-Based Methods that can resolve fine-scale features of turbine wakes up to its atmospheric stability effects. With a detailed wake effects modeling, performance prediction, layout optimization, and commercial viabilty for future large-scale offshore wind developments can be maximized. Wake effects can reduce farm output by 5–15% depending on layout density [89]. Not including this effect may therefore underestimate LCA intensity values by a comparable margin.

Excluded Hydrodynamic and Mechanical System Optimization for WECs

Detailed WEC park modeling involves simulation of hydrodynamics interactions between multiple devices, optimization of array layout, and modeling power take-off (PTO) using control strategies to maximize energy extraction and reduce losses from device interactions. Raghavan et al. (2025) [75] demonstrated that mixed array layouts achieved q-factor —the ratio of the power absorbed by the farm to the devices in isolation— up to 5.7. Additionally, Bozzi et al. (2017) [17] found that for a separation distance of 5-20 device diameters, power output can increase up to 12% relative to isolated devices. Thus, optimizing the placement and orientation of WECs is crucial for maximizing total park output. Genetic algorithms and parametric studies can be utilized to find layouts that minimize hydrodynamic losses and extreme mooring loads [102]. Moreover, since point absorbers are circulars, the directionality of incoming waves can be disregarded.

6.3.2. Modeling Scope

Excluded Scouring and Bed Protection

This study does not account for the potential impacts of seabed scouring and the associated bed protection measures for both the floating offshore wind turbine (FOWT) and wave energy converter (WEC) mooring systems, as well as for the offshore substation foundation. Scouring can significantly influence both structural stability and environmental impacts over the project lifetime. However, for floating systems such as FOWTs, the influence of scouring is relatively minor because the anchors and moorings exert limited direct seabed loading compared to fixed-bottom structures. To prevent this from happening, bed protection such as rock dumping or concrete mattresses are often used to stabilise the seabed in practice.

However, incorporating bed protection could increase the material inputs and vessel usage thus eventually contribute to the GW emissions during the installation and maintenance phase. This exclusion from the current model means the installation-phase emissions presented here may underestimate real-world values, especially for sites with erodible sediments or high tidal currents.

Furthermore, the physical presence of scour protection structures has ecological implications, as they may alter local hydrodynamics, sediment transport patterns, and benthic habitat composition. While such effects fall outside the direct scope of the LCA, they are relevant in multi-source marine space planning and could influence the long-term environmental footprint of the project.

Excluded Hydrodynamics for Substation Substructure Model

The offshore substation jacket mass in this study was estimated using a simplified linear regression approach, based solely on topside weight and water depth relationships derived from existing installations. This approach does not explicitly model hydrodynamic loading factors such as wave forces, current velocities, and extreme storm conditions, which are critical determinants of jacket member sizing and reinforcement requirements [24].

In reality, jacket structures for offshore substations are designed to withstand site-specific metocean conditions, which can result in substantial variations in steel mass and welding requirements. This requires in-depth calculation with Morison's equation of the tubular members, bracing configurations, and joint stress analysis, which increase both material quantities and manufacturing complexity. This exclusion may underestimate or overestimate the actual substation jacket mass and its lifecycle impacts.

7
Conclusion and Recommendation

7.1. Conclusion

This study set out to evaluate the environmental performance of a 180 MW co-located offshore wind–wave energy park, with particular focus on the Global Warming (GWP) impact and its sensitivity to infrastructure design and methodological choices. Using a cradle-to-grave life cycle assessment (LCA) approach, three key aspects were investigated: the overall GWPP intensity of the co-located system, the process hotspots driving these emissions, and the influence of Life Cycle Impact Assessment (LCIA) methodology on the results. By comparing shared versus separated infrastructure configurations and applying both EF$\sim$3.1 and IMPACTWorld+ methods, the analysis reveals how design integration and methodological assumptions can significantly alter the environmental profile of multi-source offshore energy systems. The following subsections summarize the main findings, providing insights into both the technical drivers of emissions and the interpretative challenges of LCA modelling.

7.1.1. Impact of multi-source Co-located Wind-wave Energy Park to GWP impact Emission

The assessment of the 180 MW co-located offshore wind–wave park demonstrates that while offshore renewables substantially reduce greenhouse gas (GHG) emissions compared to fossil-based energy, their environmental performance is still strongly shaped by design choices. The calculated Global Warming (GWP) intensity of the co-located system under shared infrastructure is 75.63 gCO_2-eq/kWh in EF 3.1 and 76.91 gCO_2-eq/kWh in IMPACTWorld+, positioning the system at the lower-to-mid range of published offshore renewable LCAs. When infrastructure is separated, however, the carbon intensity rises to 79.32 gCO_2-eq/kWh, a 14% increase over the shared scenario. This demonstrates that the environmental benefit of multi-source energy parks depends not only on the integration of multiple technologies but also on the degree to which infrastructure is shared. In other words, co-location is not inherently beneficial unless accompanied by design integration, as duplication of substations and cabling amplifies embodied burdens.

7.1.2. Process Hotspots of GWP impact Emission

Across all scenarios and methodologies, the hotspots of GWP impact are consistently found in the installation and maintenance phases. Installation dominates due to the high material intensity of floaters, foundations, mooring chains, and export cabling. In the paralel (separated infrastructure) case, installation related GWP emissions increase from 42.53 gCO_2-eq/kWh in the shared system to 40.00 gCO_2-eq/kWh, directly linked to additional steel demand for substations and jackets. This confirms that heavy structural components are the primary drivers of embodied emissions. Maintenance contributes nearly as much as installation ($\approx$28 gCO_2-eq/kWh) in both infrastructure cases, reflecting the fuel consumption of service vessels over a 25-year lifetime. The persistence of maintenance as a hotspot highlights that operational decarbonisation, through vessel electrification, biofuels, or optimized maintenance strategies, is equally as important as material efficiency in reducing lifecycle emissions. End-of-life processes remain comparatively minor (≈1–2 gCO_2-eq/kWh), although their true contribution is sensitive to assumptions about recycling credits and decommissioning practices.

7.1.3. Impact of LCIA Methodology Choice

The sensitivity analysis comparing EF 3.1 and IMPACTWorld+ illustrates that methodological choices can alter both the magnitude and interpretation of LCA results. For GWP, both methods yield closely aligned results (differences below 5%), reflecting the harmonization of climate change factors with IPCC guidelines. However, attribution across life cycle stages shifts: IW+ assigns a larger share of

GWP impact to maintenance due to higher characterization factors for fossil methane (29.8 vs. 31 in IW+), while IMPACTWorld+ emphasizes installation through its regionally weighted treatment of industrial processes. Beyond climate change, categories diverge substantially. Freshwater ecotoxicity, human toxicity, mineral depletion, and particulate matter show differences of several orders of magnitude, arising from the use of different USEtox versions, exposure pathways, and resource depletion metrics. This confirms that while climate and energy-related indicators are robust across methods, toxicity and resource categories are highly method-dependent. For interpretation, this means that conclusions about carbon intensity can be made with confidence, whereas conclusions about toxicity or depletion require caution, transparent reporting of methodological assumptions.

Overall, the results highlight two key aspects of sensitivity: infrastructure configuration and LCIA methodology. Shared infrastructure consistently reduces GWP emissions and most midpoint categories, with further consideration of embodying the paralel system of array cable to prevent over-design to carry power by the WEC array. On the other hand, methodological choice shapes the attribution and magnitude of non-climate and biodiversity categories. Together, these findings confirm that LCA outcomes in offshore renewable energy are not purely reflections of the physical system but also of the design boundaries and modelling perspectives applied.

7.2. Direction for Future Study

This research has provided insights into the environmental performance of co-located offshore wind–wave energy parks, but it also highlights several areas where further work is needed to deepen understanding and to support decision-making for industry and policy. The following subsections outline key directions for future study.

7.2.1. Expand to Techno-economic Dimension

While this study focused on life cycle environmental impacts, future assessments would benefit from integrating techno-economic indicators such as the Levelised Cost of Energy (LCOE) and cost per tonne of CO_2 avoided. This would allow a more holistic approach to multi-source offshore systems, balancing environmental burdens with economic feasibility. This integration will incorporate assumptions as the input for CLCA, whereas the output (e.g. emissions and avoided emission) will be linked with techno-economic models (e.g. CAPEX, OPEX, and investments returns). For investors and policymakers, this integration would make results more actionable by providing insights into both cost-effectiveness and decarbonisation potential. Scenario-based approaches that link life cycle emissions with financial performance could also quantify trade-offs between infrastructure sharing, O&M strategies, and long-term financial performance.

7.2.2. Expand to Spatial Planning and Ecosystem Dimension

The co-location of offshore wind and wave energy inevitably interacts with marine spatial planning and ecosystem services. Future studies should extend beyond carbon metrics to assess biodiversity impacts, competition with fisheries, and potential synergies with other marine uses such as aquaculture or shipping. Incorporating ecosystem service modelling and geospatial planning tools would improve the capacity of LCA to capture cumulative impacts at sea-basin scale. This dimension is particularly relevant for policymakers and regulators, as offshore energy hubs are increasingly considered not only as energy projects but as multi-functional nodes in marine spatial planning.

7.2.3. Circularity and Recycling Studies

The results of this study confirm that material production, particularly steel, copper, and other metal materials is a critical driver of life cycle impacts. Future research should therefore focus on exploring alternative materials such as low-carbon steel or concrete, as has been done in [28].

At the same time, future studies should look at how materials from offshore systems can be recycled or reused after decommissioning. This would help reduce the need for new raw materials and lower overall impacts. Because the current end-of-life stage is often based on general assumptions in which as a high uncertainty, especially for heavy components such as mooring chains, using data from real recycling projects could make future assessments more accurate and realistic.

7.2.4. Sensitivity to Site Location

The present study was based on a representative offshore site, but the environmental profile of multi-source wind–wave systems will vary significantly depending on geographic context. Differences in wind and wave regimes directly affect capacity factors and energy yields, regional electricity grid intensities influence upstream burdens of material and manufacturing, and water depth can influence the structure type for either technology devices or its infrastructures.

In addition, site location determines installation and maintenance logistics: greater distance from shore or harsher metocean conditions can increase vessel requirements, fuel use, and ultimately lifecycle emissions. Beyond technical performance, site-specific sensitivity also extends to ecological and socio-economic dimensions, as some locations overlap with sensitive habitats or competing marine uses. Incorporating multi-site comparisons with regionally differentiated datasets would therefore improve the robustness of LCA results, allowing more nuanced conclusions about where co-located offshore systems deliver the greatest sustainability benefits.

A recent study by Engelfried, et al. (2026) [29] combines a detailed representative LCA model of two WEC types, FPV, and FOWT with spatial resource and bathymetry data, to obtain impact maps for the studied devices. The study then identified the distribution of GWP impact and associated payback periods across the studied area with respective identified devices, creating map for MREs' GWP impact and carbon payback period. Similar approach then could be applied to multi-source offshore energy farm, to help identify the most sustainable locations for multi-source offshore energy farm.

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Appendix A.1: 180 MW Floating Offshore Wind Life Cycle Inventory

Please see next page.

Turbine General Information		
Rated capacity	180	MW
AEP	601,358	MWh/year
	601.36	GWh/year
Total 25 year	15.03	TWh
Turbines per PP	12	turbines
N Turbines benchmark	66	turbines
Hub height	138	m
Tower base diameter	9	m
Grid distance	25	km

Manufacturing & Assembly

Unit Process: Turbine manufacturing

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
11751454.55	kg	7.82E-04	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
1781090.91	kg	1.18E-04	kg	Steel, high alloyed	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
2588909.09	kg	1.72E-04	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
162727.27	kg	1.08E-05	kg	Aluminium & Al alloys	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
195272.73	kg	1.30E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
8545.45	kg	5.68E-07	kg	Copper alloys	market for brass | brass | Cutoff, U - RoW
0.00	kg	0.00E+00	kg	Lead	market for lead | lead | Cutoff, U - GLO
826181.82	kg	5.50E-05	kg	Polymer materials	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
3090.91	kg	2.06E-07	kg	Modified organic natural materials	glass fibre reinforced plastic production, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - RER
1736545.45	kg	1.16E-04	kg	Ceramic / glass	market for glass fibre | glass fibre | Cutoff, U - GLO
576.00	kg	3.83E-08	kg	SF6 gas	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
10909.09	kg	7.26E-07	kg	Magnets	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
30000.00	kg	2.00E-06	kg	Electronics	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
36545.45	kg	2.43E-06	kg	Lubricants	market for lubricating oil | lubricating oil | Cutoff, U - RER
18000.00	kg	1.20E-06	kg	Coolant / other glycols	market for ethylene glycol | ethylene glycol | Cutoff, U - RER
729818.18	kg	4.85E-05	kg	steel, low-alloyed, hot rolled	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, U - GLO
373454.55	kg	2.48E-05	kg	iron ore concentrate	market for iron ore concentrate | iron ore concentrate | Cutoff, U - GLO
10618.17	kg	7.06E-07	kg	sheet rolling, steel	sheet rolling, steel | sheet rolling, steel | Cutoff, U - RER
4377.95	kg	2.91E-07	kg	Average metal working, steel	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
162.73	kg	1.08E-08	kg	Sheet rolling, aluminium	sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, U - RER
172.62	kg	1.15E-08	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
495.27	m	3.29E-08	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
tdistRoad*40%*(turbine)	t*km	8.43E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(turbine)	t*km	1.26E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	1.42E-03	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
595449.09	kg	3.96E-05	kg	steel removed by milling, average	steel milling, average | steel removed by milling, average | Cutoff, U - RER
11751454.55	kg	7.82E-04	kg	sheet rolling copper	sheet rolling, copper | sheet rolling, copper | Cutoff, U - RER
180000	hr	1.20E-05	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	15 MW Wind Turbine	FOWT manufacturing
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Substation low-medium voltage

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
76,240	kg	5.07E-06	kg	Sand	market for sand | sand | Cutoff, U - RoW
9,553	kg	6.35E-07	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
101,421	kg	6.75E-06	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
41,757	kg	2.78E-06	kg	Aluminium	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
11	kg	7.61E-10	kg	Nickel	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
202	kg	1.34E-08	kg	Alkyd paint	market for alkyd paint, white, without water, in 60% solution state | alkyd paint, white, without water, in 60% solution state | Cutoff, U - RER
412	kg	2.74E-08	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
1,658	kg	1.10E-07	kg	Chromium steel	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
55,823	kg	3.71E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
2,356	kg	1.57E-07	kg	Glass fibre	market for glass fibre | glass fibre | Cutoff, U - GLO
38	kg	2.54E-09	kg	Kraft paper	market for kraft paper | kraft paper | Cutoff, U - RER
101,933	kg	6.78E-06	kg	Lubricating oil	market for lubricating oil | lubricating oil | Cutoff, U - RER
19	kg	1.27E-09	kg	Polycarbonate	market for polycarbonate | polycarbonate | Cutoff, U - RER
305	kg	2.03E-08	kg	Polyester resin	market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER
84	kg	5.58E-09	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
10	m3	6.82E-10	m3	Sawn timber	market for sawnwood, board, hardwood, dried (u=10%), planed | sawnwood, board, hardwood, dried (u=10%), planed | Cutoff, U - Europe without Switzerland
4	kg	2.54E-10	kg	Silver	market for silver | silver | Cutoff, U - GLO
11,245	kg	7.48E-07	kg	Sulphate pulp	market for sulfate pulp, bleached | sulfate pulp, bleached | Cutoff, U - RER
2,036	kg	1.35E-07	kg	Sulphur hexafluoride	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
248	kg	1.65E-08	kg	Synthetic rubber	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
2,204,856	kg	1.47E-04	kg	Gravel	gravel production, crushed | gravel, crushed | Cutoff, U - RoW
tdistRoad*40%*(mSubstation)	t*km	1.01E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mSubstation)	t*km	1.52E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	2.39E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
7,219,726	kg	4.80E-04	kg	steel, low alloyed	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
5,636	m	3.75E-07	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Substation for WP	Substation low-medium voltage
Environmental flows, in					

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Turbine Assembly (Steel)					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Turbine	units	1.00E+00	kWh	Wind turbine	Turbine Manufacturing
5943.2	m	3.95E-07	m	welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
5280	kg	3.51E-07	kg	Electronics, For Control Units	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
13536045.45	kg	9.00E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
12087.28	m2	8.04E-07	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
1	unit	1.00E+00	kWh	substation for FOWT	Substation for WP
1.15	m2	7.65E-11	m2	building, hall, steel construction	market for building, hall, steel construction | building, hall, steel construction | Cutoff, U - GLO
180000	hr	1.20E-07	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	assembled OFWT for Installation	
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Installation

Unit process: Mooring					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
3427.2	kg	2.28E-04	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
mChains	kg	1.80E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
fuelPrelay*9.96	kWh	0.00E+00	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
tdistRoad*40%*(mChains+mAnchors)	t*km	9.12E-06	t.km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mChains+mAnchors)	t*km	1.37E-05	t.km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.05*(mChains+mAnchors))*0.942	t*km	2.15E-04	t.km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1		1	kWh	mooring for FOWT	Mooring
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 66 kV					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1098065.47	kg	7.30E-05	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
732132.10	kg	4.87E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
549032.74	kg	3.65E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
183099.37	kg	1.22E-05	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
91549.68	kg	6.09E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
549032.74	kg	3.65E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	1.06E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	1.59E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mCable)*0.942	t*km	1.66E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	inter-array subsea cable 66 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Unit process: electrical connection 220 kV					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
730170.56	kg	4.86E-05	kg	Steel, unalloyed low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
277787.28	kg	1.85E-05	kg	Copper	market for lead | lead | Cutoff, U - GLO
565248.75	kg	3.76E-05	kg	Lead	market for copper, cathode | copper, cathode | Cutoff, U - GLO
229672.50	kg	1.53E-05	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
229672.50	kg	1.53E-05	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
277787.28	kg	1.85E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	8.11E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	1.22E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mCable))*0.942	t*km	1.27E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea export cable 220 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
0.5*dist*1000	m2*yr			Occupation, seabed, natural (non-use)	Resource/ Land
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Towing Installation

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
(fuelTow+fuelHookMoorings)*9.96	kWh	5.56E-04	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	Tow Installation	installation (steel)
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Installation

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1.00	kWh	Turbine	Assembled OFWT for Installation
mooringIO	items	1.00	kWh	mooring for wind turbine	Mooring
dist	km	1.00	kWh	subsea cable 66 kV	Electrical Connection
dist	km	1.00	kWh	export cable 220 kV	Electrical Connection
(fuelTow+fuelHookFoudnation + fuelHookMoorings)	L	1.00	kWh	Tow Installation	market for diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	Installation process per kWh	installation (steel)
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Use Phase

Unit process: Maintenance

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
FuelScheduledMaintenance*9.96	kWh	3.20E-03	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
FuelCorrectiveMaintenance*9.96	kWh	2.82E-04	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	year	1	kWh	maintenance for FOWT	maintenance
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
End-of-Life					
Unit process: Dismantling (steel)					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1.15	m2	1.14818E-08	m2	building, hall, steel construction	market for building, hall, steel construction | building, hall, steel construction | Cutoff, U - GLO
900	hr	5.99E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
16,197,105.67	kg	9.70E-04	kg	steel production, electric, low-alloyed – RER	steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria
2,962,775.33	kg	1.77E-04	kg	iron production, electric, low-alloyed – RER	iron scrap, unsorted, Recycled Content cut-off | iron scrap, unsorted | Cutoff, U - GLO
1,086,461.02	kg	6.50E-05	kg	treatment of copper scrap by electrolytic refining	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, U - GLO
412,855.73	kg	1.10E-05	kg	polyethylene terephthalate, granulate, amorphous, recycled	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, U - RoW
321,222.18	kg	8.55E-06	kg	polypropylene terephthalate, granulate, amorphous, recycled	treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U - RER
204,483.83	kg	1.22E-05	kg	treatment of aluminium scrap, postconsumer, prepared for recycling, at remelter	aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
16,197,105.67	kg	1.08E-04	kg	Treatment of scrap steel, inert material landfill - EU w/o CH	treatment of waste steel, inert material landfill | waste steel | Cutoff, U
2,962,775.33	kg	1.97E-05	kg	Treatment of scrap iron, inert material landfill - EU w/o CH	treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | Cutoff, U - Europe without Switzerland
1,086,461.02	kg	7.23E-06	kg	treatment of scrap copper, municipal incineration - Eu w/o CH	treatment of waste copper, municipal incineration | waste copper | Cutoff, U - Europe without Switzerland
412,855.73	kg	1.65E-05	kg	market group for waste plastic,mixture - IT	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
321,222.18	kg	1.28E-05	kg	market group for waste plastic,mixture - IT	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
10,909.09	kg	7.26E-07	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
30,000.00	kg	2.00E-06	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
204,483.83	kg	1.36E-06	kg	waste aluminium	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
9,552.85	kg	6.35E-07	kg	inert waste, for final disposal	treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U - RoW
101,932.67	kg	6.10E-06	kg	waste mineral oil	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - Europe without Switzerland
101,932.67	kg	6.78E-07	kg	waste mineral oil	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
2,653,879.36	kg	1.77E-04	kg	used cable	treatment of used cable | used cable | Cutoff, U - GLO
2,032,551.60	kg	1.35E-04	kg	used cable	treatment of used cable | used cable | Cutoff, U - GLO
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Appendix A.2: 180 MW Wave Energy Converter Life Cycle Inventory

Please see next page.

WEC General Information		
Rated capacity	180	MW
AEP	561340.8	MWh/year
	561.34	GWh/year
Total 25 year	14.03	TWh
WECs per PP	450	turbines
Diameter	9	m
Grid distance	25	km

Manufacturing & Assembly

Unit Process: PTO manufacturing

Amount	Unit	Amount per kWh	unit	Product	Processes (database: ecoinvent 3.11, allocation, cut-off by classification)
Economic flows, in:					
675,000.00	kg	4.81E-05	kg	cast iron	market for cast iron | cast iron | Cutoff, U - GLO
648,000.00	kg	4.62E-05	kg	copper, cathode	market for copper, cathode | copper, cathode | Cutoff, U - GLO
405,000.00	kg	2.89E-05	kg	Permanent magnet, for electric motor	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
360,000.00	kg	2.57E-05	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
572,555.26	kg	4.08E-05	kg	epoxy resin, liquid	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
155,250.00	kg	1.11E-05	kg	cast iron removed by milling, large parts	cast iron milling, average | cast iron removed by milling, average | Cutoff, U - RER
tdistRoad*40%	t*km	5.21E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%	t*km	8.08E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore 0.942	t*km	9.06E-03	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
82800	kg	5.90E-06	kg	steel removed by milling, average	steel milling, average | steel removed by milling, average | Cutoff, U - RER
648000	kg	4.62E-05	kg	sheet rolling copper	sheet rolling, copper | sheet rolling, copper | Cutoff, U - RER
1800	hr	1.28E-07	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Linear generator PTO for WEC	PTO manufacturing
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Substation low-medium voltage

Amount	Unit	Amount per kWh	unit	Product	Processes (database: ecoinvent 3.11, allocation, cut-off by classification)
Economic flows, in:					
76,240	kg	5.43E-06	kg	Sand	market for sand | sand | Cutoff, U - RoW
9,553	kg	6.81E-07	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
101,421	kg	7.23E-06	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
41,757	kg	2.98E-06	kg	Aluminium	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
11	kg	8.15E-10	kg	Nickel	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
202	kg	1.44E-08	kg	Alkyd paint	market for alkyd paint, white, without water, in 60% solution state | alkyd paint, white, without water, in 60% solution state | Cutoff, U - RER
412	kg	2.93E-08	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
1,658	kg	1.18E-07	kg	Chromium steel	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
55,823	kg	3.98E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
2,356	kg	1.68E-07	kg	Glass fibre	market for glass fibre | glass fibre | Cutoff, U - GLO
38	kg	2.72E-09	kg	Kraft paper	market for kraft paper | kraft paper | Cutoff, U - RER
101,933	kg	7.26E-06	kg	Lubricating oil	market for lubricating oil | lubricating oil | Cutoff, U - RER
19	kg	1.36E-09	kg	Polycarbonate	market for polycarbonate | polycarbonate | Cutoff, U - RER
305	kg	2.17E-08	kg	Polyester resin	market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER
84	kg	5.98E-09	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
10	m3	7.31E-10	m3	Sawn timber	market for sawnwood, board, hardwood, dried (u=10%), planed | sawnwood, board, hardwood, dried (u=10%), planed | Cutoff, U - Europe without Switzerland
4	kg	2.72E-10	kg	Silver	market for silver | silver | Cutoff, U - GLO
11,245	kg	8.01E-07	kg	Sulphate pulp	market for sulfate pulp, bleached | sulfate pulp, bleached | Cutoff, U - RER
2,036	kg	1.45E-07	kg	Sulphur hexafluoride	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
248	kg	1.77E-08	kg	Synthetic rubber	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
2,204,856	kg	1.57E-04	kg	Gravel	gravel production, crushed | gravel, crushed | Cutoff, U - RoW
tdistRoad*40%*(mSubstation)	t*km	1.52E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mSubstation)	t*km	2.28E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	2.56E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
7,219,726	kg	5.14E-04	kg	steel, low alloyed	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
5,636	m	4.02E-07	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Substation for WEC	Substation low-medium voltage
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Unit process: Floater Assembly (Steel)					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
PTO	units	1.00E+00	kWh	lin. Gen. PTO for WEC	PTO manufacturing
132706219.99	kg	9.46E-03	kg	steel, low-alloyed, hot rolled	market for steel, low-alloyed
Iweld	m	2.7302E-06	m	welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
35000+mRod	kg	1.83E-03	kg	steel, low alloyed	market for steel, low-alloyed
198000.00	kg	1.41E-05	kg	Electronics, For Control Units	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
35000+mRod	kg	1.83E-03	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
1	unit	1.00E+00	kWh	Substation for WEC	Substation low-medium voltage
1.15	m2	8.19E-11	m2	building, hall, steel construction	building construction, hall, steel construction
10	hr	3.21E-07	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
1	unit	1.00E+00	kWh	Pre-defined painting inventory	Painting
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	assembled WEC for Installation	
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: paint					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
43.36524	kg	3.09E-09	kg	xylene	market for xylene, mixed | xylene, mixed | Cutoff, U - RER
22.996773	kg	1.64E-09	kg	n-butanol	market for n-butanol | n-butanol | Cutoff, U - GLO
5.910975	kg	4.21E-10	kg	Phenol	market for phenol | phenol | Cutoff, U - RER
1.57626	kg	1.12E-10	kg	p-phenylen diamine	market for p-phenylene diamine | p-phenylene diamine | Cutoff, U - GLO
1.57626	kg	1.12E-10	kg	o-phenylen diamine	market for o-phenylene diamine | o-phenylene diamine | Cutoff, U - GLO
2.36439	kg	1.68E-10	kg	Ethanol, without water, in 99,7% solution state, from ethylene	market for ethanol, without water, in 99.7% solution state, from ethylene | ethanol, without water, in 99.7% solution state, from ethylene | Cutoff, U - RER
0.071359339	kg	5.08E-12	kg	Ethyl benzene	market for ethyl benzene | ethyl benzene | Cutoff, U - RER
1.87180875	kg	1.33E-10	kg	Ethylene diamine	market for ethylene diamine | ethylene diamine | Cutoff, U - RER
1.57626	kg	1.12E-10	kg	O-aminophenol	market for o-aminophenol | o-aminophenol | Cutoff, U - GLO
377.6481855	kg	2.69E-08	kg	epoxy resin, liquid	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
7.13022975	kg	5.08E-10	kg	naphtha	market for naphtha | naphtha | Cutoff, U - RER
8.148834	kg	5.81E-10	kg	Dimethenamide	market for dimethenamide | dimethenamide | Cutoff, U - GLO
432.2835	kg	3.08E-08	kg	flat glass, uncoated	market for flat glass, uncoated | flat glass, uncoated | Cutoff, U - RER
12.8	m3	9.12E-10	m3	Compressed air, 700kPa gauge	market for compressed air, 700 kPa gauge | compressed air, 700 kPa gauge | Cutoff, U - RER
tdistRoad*40%	t*km	2.28E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*0.77*0.002	t*km	3.43E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore *0.05*0.002*0.942	t*km	2.15E-06	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	kWh			glass flake epoxy paint for WEC (applied)	painting
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Installation

Unit process: Mooring

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
mChains+mAnchors	kg	2.79E-03	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
mChains	kg	8.66E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
fuelPrelay*9.96	kWh	1.42E-05	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel
tdistRoad*0.77*40%	t*km	1.56E-04	t.km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*0.77*60%	t*km	2.34E-04	t.km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
('tdistoffshore*0.05*(mChains+mAnchors)/1000)*0.942	t*km	2.63E-03	t.km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1		1	kWh	mooring for WEC	Mooring
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Amount	Unit	Amount per kWh	unit	Product	Processes (database: ecoinvent 3.11, allocation, cut-off by classification)

Unit process: electrical connection 33 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
173,752.82	kg	1.24E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
222,702.06	kg	1.59E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
52,453.68	kg	3.74E-06	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
34,422.73	kg	2.45E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
33,772.71	kg	2.41E-06	kg	Steel, low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
173,752.82	kg	1.24E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*0.77*40%*(mCable)/1000	t*km	6.76E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*0.77*60%*(mCable)/1000	t*km	1.01E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore *0.05*0.002*0.942*n route*mCable	t*km	4.83E-05	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 33kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 132 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
409261.55	kg	2.92E-05	kg	Steel, low-alloyed	market for copper, cathode | copper, cathode | Cutoff, U - GLO
411303.22	kg	2.93E-05	kg	Copper	market for lead | lead | Cutoff, U - GLO
145700.83	kg	1.04E-05	kg	Lead	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
81332.61	kg	5.80E-06	kg	Polyethylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
585401.79	kg	4.17E-05	kg	Polypropylene	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
411303.22	kg	2.93E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*0.77*40%*(mCable)/1000	t*km	8.30E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*0.77*60%*(mCable)/1000	t*km	1.25E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore *0.05*0.002*0.942*n route*mCable	t*km	1.40E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 33kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Foundation (steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
19350000.00	kg	1.38E-03	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
tdistRoad*40%*(mFoundation)/1000	t*km	7.72E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mFoundation)/1000	t*km	1.16E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore *0.942*n route*mFoundation	t*km	1.30E-03	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
40000	kg	1.28E-03	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
Economic flows, out:					
Ftow	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items			Foundation for WEC (steel)	Foundation (steel)
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Unit process: Installation (Steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	Floater (Steel)	Flaoter Assembly (steel)
1	items	1	kWh	Foundation for WEC (steel)	Foundation (steel)
mooringIO	items	1	kWh	mooring for WEC	Mooring
dist	km	1	kWh	subsea cable 33kV	Electrical Connection
(fuelTow+fuelHookFoudnation + fuelHookMoorings)/0.029516912	L	2.27E-02	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	operational WEC (steel)	installation (steel)
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Use-phase					
Unit process: Maintenance					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
FuelScheduledMaintenance*9.96	kWh	1.07E-01	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
FuelCorrective*9.96	kWh	1.38E-02	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	year	1	kWh	maintenance for WEC	maintenance
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
End-of-Life					
Unit process: Dismantling (steel)					
Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	EOL WEC (steel)	Use Phase (steel)
1.15	m2	8.19467E-11	m2	building, hall, steel construction	market for building, hall, steel construction | building, hall, steel construction | Cutoff, U - GLO
900	hr	6.41E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
20338913.06	kg	1.30E-03	kg	steel production, electric, low-alloyed – RER	steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria
830661.6952	kg	5.33E-05	kg	iron production, electric, low-alloyed – RER	iron scrap, unsorted, Recycled Content cut-off | iron scrap, unsorted | Cutoff, U - GLO
1936878.856	kg	1.24E-04	kg	treatment of copper scrap by electrolytic refining	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, U - GLO
133870.1596	kg	5.72E-06	kg	polyethylene terephthalate, granulate, amorphous, recycled	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, U - RoW
619824.5157	kg	2.65E-05	kg	polypropylene terephthalate, granulate, amorphous, recycled	treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U - RER
41756.56189	kg	2.68E-06	kg	treatment of aluminium scrap, postconsumer, prepared for recycling, at remelter	aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
20338913.06	kg	1.45E-04	kg	Treatment of scrap steel, inert material landfill	treatment of waste steel, inert material landfill | waste steel | Cutoff, U
830661.6952	kg	5.92E-06	kg	Treatment of scrap iron, inert material landfill	treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | Cutoff, U - Europe without Switzerland
1936878.856	kg	1.38E-05	kg	treatment of scrap copper, municipal incineration	treatment of waste copper, municipal incineration | waste copper | Cutoff, U - Europe without Switzerland
133870.1596	kg	3.82E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
619824.5157	kg	1.77E-05	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
405000	kg	2.89E-05	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
198000	kg	1.41E-05	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
41756.56189	kg	2.98E-07	kg	treatment of scrap aluminium, municipal incineration	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
582108.1134	kg	4.15E-05	kg	treatment of inert waste, inert material landfill	treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U - RoW
101932.6698	kg	6.54E-06	kg	Mineral oil regeneration	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - Europe without Switzerland
101932.6698	kg	7.26E-07	kg	Market for waste mineral oil EU	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
1633000	kg	1.16E-04	kg	Used 220 kV cable incineration	treatment of used cable | used cable | Cutoff, U - GLO
517104.00	kg	3.68E-05	kg	Used 33 kV cable incineration	treatment of used cable | used cable | Cutoff, U - GLO
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Appendix A.3: 180 MW Multi-source Hybrid Energy Park Life Cycle Inventory

Please see next page.

Turbine General Information		
Rated capacity	180	MW
AEP	849,546.00	MWh/year
	849.55	GWh/year
Total 25 year	21.24	TWh
Turbines per PP	10	turbines
Installed wind turbine	150	MW
WEC per park	75	devices
Installed WEC	30	MW
Grid distance	25	km
Tower base diameter	9	m
Grid distance	25	km

Manufacturing & Assembly Wind Energy

Unit Process: Turbine manufacturing

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
9792878.79	kg	5.49E-04	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
1484242.42	kg	8.32E-05	kg	Steel, high alloyed	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
2157424.24	kg	1.21E-04	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
135606.06	kg	7.60E-06	kg	Aluminium & Al alloys	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
162727.27	kg	9.12E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
7121.21	kg	3.99E-07	kg	Copper alloys	market for brass | brass | Cutoff, U - RoW
0.00	kg	0.00E+00	kg	Lead	market for lead | lead | Cutoff, U - GLO
688484.85	kg	3.86E-05	kg	Polymer materials	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
2575.76	kg	1.44E-07	kg	Modified organic natural materials	glass fibre reinforced plastic production, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - RER
1447121.21	kg	8.11E-05	kg	Ceramic / glass	market for glass fibre | glass fibre | Cutoff, U - GLO
480.00	kg	2.69E-08	kg	SF6 gas	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
9090.91	kg	5.10E-07	kg	Magnets	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
25000.00	kg	1.40E-06	kg	Electronics	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
30454.55	kg	1.71E-06	kg	Lubricants	market for lubricating oil | lubricating oil | Cutoff, U - RER
15000.00	kg	8.41E-07	kg	Coolant / other glycols	market for ethylene glycol | ethylene glycol | Cutoff, U - RER
608181.82	kg	4.96E-07	kg	steel, low-alloyed, hot rolled	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, U - GLO
311212.12	kg	2.04E-07	kg	iron ore concentrate	market for iron ore concentrate | iron ore concentrate | Cutoff, U - GLO
8848474.32	kg	7.60E-09	kg	sheet rolling, steel	sheet rolling, steel | sheet rolling, steel | Cutoff, U - RER
3648294.03	kg	8.06E-09	kg	Average metal working, steel	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
135606.06	kg	2.31E-08	kg	Sheet rolling, aluminium	sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, U - RER
143847.31	kg	3.41E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
412.72	m	1.74E-05	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
tdistRoad*40%*(turbine)	t*km	5.92E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(turbine)	t*km	8.88E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	9.95E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
496207.58	kg	2.78E-05	kg	steel removed by milling, average	steel milling, average | steel removed by milling, average | Cutoff, U - RER
9792878.79	kg	5.49E-04	kg	sheet rolling copper	sheet rolling, copper | sheet rolling, copper | Cutoff, U - RER
1500	hr	4.20E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Turbine Manufacturing	PTO manufacturing
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Substation low-medium voltage

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
72,442	kg	3.56E-06	kg	Sand	market for sand | sand | Cutoff, U - RoW
9,077	kg	4.46E-07	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
96,369	kg	4.74E-06	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
39,677	kg	1.95E-06	kg	Aluminium	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
11	kg	5.34E-10	kg	Nickel	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
192	kg	9.44E-09	kg	Alkyd paint	market for alkyd paint, white, without water, in 60% solution state | alkyd paint, white, without water, in 60% solution state | Cutoff, U - RER
391	kg	1.92E-08	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
1,576	kg	7.75E-08	kg	Chromium steel	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
53,042	kg	2.61E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
2,238	kg	1.10E-07	kg	Glass fibre	market for glass fibre | glass fibre | Cutoff, U - GLO
36	kg	1.78E-09	kg	Kraft paper	market for kraft paper | kraft paper | Cutoff, U - RER
96,855	kg	4.76E-06	kg	Lubricating oil	market for lubricating oil | lubricating oil | Cutoff, U - RER
18	kg	8.90E-10	kg	Polycarbonate	market for polycarbonate | polycarbonate | Cutoff, U - RER
290	kg	1.42E-08	kg	Polyester resin	market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER
80	kg	3.92E-09	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
10	m3	4.79E-10	m3	Sawn timber	market for sawnwood, board, hardwood, dried (u=10%), planed | sawnwood, board, hardwood, dried (u=10%), planed | Cutoff, U - Europe without Switzerland
4	kg	1.78E-10	kg	Silver	market for silver | silver | Cutoff, U - GLO
10,685	kg	5.25E-07	kg	Sulphate pulp	market for sulfate pulp, bleached | sulfate pulp, bleached | Cutoff, U - RER
1,934	kg	9.51E-08	kg	Sulphur hexafluoride	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER

Amount	Unit	Amount per kWh	unit	Product	Processes
235	kg	1.16E-08	kg	Synthetic rubber	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
2,095,030	kg	1.03E-04	kg	Gravel	gravel production, crushed | gravel, crushed | Cutoff, U - RoW
tdistRoad*40%*(mSubstation)	t*km	9.97E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mSubstation)	t*km	1.50E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	1.68E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
5,175,276	kg	3.37E-04	kg	steel, low alloyed	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
4,040	m	2.63E-07	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER

Economic flows, out:

Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Substation for multi-use energy park	Substation low-medium voltage

Environmental flows, in

Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Flow Name*	*Compartment*

Manufacturing & Assembly Wave Energy

Unit Process: PTO manufacturing

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
112,500.00	kg	3.31E-05	kg	cast iron	market for cast iron | cast iron | Cutoff, U - GLO
108,000.00	kg	3.18E-05	kg	copper, cathode	market for copper, cathode | copper, cathode | Cutoff, U - GLO
67,500.00	kg	1.99E-05	kg	Permanent magnet, for electric motor	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
60,000.00	kg	1.77E-05	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
6,000.00	kg	2.81E-05	kg	epoxy resin, liquid	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
25,875.00	kg	7.61E-06	kg	cast iron removed by milling, large parts	cast iron milling, average | cast iron removed by milling, average | Cutoff, U - RER
tdistRoad*40%*mPTO	t*km	3.71E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*mPTO	t*km	5.56E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942*mPTO	t*km	6.62E-03	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
13800	kg	4.06E-06	kg	steel removed by milling, average	steel milling, average | steel removed by milling, average | Cutoff, U - RER
108000	kg	3.18E-05	kg	sheet rolling copper	sheet rolling, copper | sheet rolling, copper | Cutoff, U - RER
300	hr	4.41E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO

Economic flows, out:

Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Linear generator PTO for WEC	PTO manufacturing

Environmental flows, in

Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Flow Name*	*Compartment*

Unit process: Substation low-medium voltage

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
52,054	kg	3.74E-06	kg	Sand	market for sand | sand | Cutoff, U - RoW
6,522	kg	4.69E-07	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
69,246	kg	4.97E-06	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
28,510	kg	2.05E-06	kg	Aluminium	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
8	kg	5.61E-10	kg	Nickel	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
138	kg	9.91E-09	kg	Alkyd paint	market for alkyd paint, white, without water, in 60% solution state | alkyd paint, white, without water, in 60% solution state | Cutoff, U - RER
281	kg	2.02E-08	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
1,132	kg	8.13E-08	kg	Chromium steel	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
38,114	kg	2.74E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
1,608	kg	1.16E-07	kg	Glass fibre	market for glass fibre | glass fibre | Cutoff, U - GLO
26	kg	1.87E-09	kg	Kraft paper	market for kraft paper | kraft paper | Cutoff, U - RER
69,596	kg	5.00E-06	kg	Lubricating oil	market for lubricating oil | lubricating oil | Cutoff, U - RER
13	kg	9.35E-10	kg	Polycarbonate	market for polycarbonate | polycarbonate | Cutoff, U - RER
208	kg	1.50E-08	kg	Polyester resin	market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER
57	kg	4.11E-09	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
7	m3	5.03E-10	m3	Sawn timber	market for sawnwood, board, hardwood, dried (u=10%), planed | sawnwood, board, hardwood, dried (u=10%), planed | Cutoff, U - Europe without Switzerland
3	kg	1.87E-10	kg	Silver	market for silver | silver | Cutoff, U - GLO
7,678	kg	5.52E-07	kg	Sulphate pulp	market for sulfate pulp, bleached | sulfate pulp, bleached | Cutoff, U - RER
1,390	kg	9.98E-08	kg	Sulphur hexafluoride	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
169	kg	1.22E-08	kg	Synthetic rubber	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
1,505,400	kg	1.08E-04	kg	Gravel	gravel production, crushed | gravel, crushed | Cutoff, U - RoW
tdistRoad*40%*(mSubstation)	t*km	1.05E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mSubstation)	t*km	1.57E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	1.76E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
5,175,276	kg	3.54E-04	kg	steel, low alloyed	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
4,040	m	2.76E-07	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER

Economic flows, out:

Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Substation for multi-use energy park	Substation low-medium voltage

Environmental flows, in

Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out			
Amount	*Unit*	*Flow Name*	*Compartment*

Unit process: Devices Assembly (Steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Turbine					
Turbine	units	1.00E+00	kWh	Turbine Manufacture	Turbine Manufacturing
4952.67	m3	2.78E-07	m3	welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
440	kg	2.47E-08	kg	Electronics, For Control Units	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
11280621.21	kg	6.32E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
4221.515128	kg	2.37E-07	kg	Epoxy Resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
1.15	m2	6.45E-11	m2	building, hall, steel construction	market for building, hall, steel construction | building, hall, steel construction | Cutoff, U - GLO
1500	hr	4.20E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
WEC					
#REF!	units	1.00E+00	kWh	lin. Gen. PTO for WEC	PTO manufacturing
18727328.33	kg	5.51E-03	kg	steel, low-alloyed, hot rolled	market for steel, low-alloyed
17161.72512	m	5.05E-06	m	welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
4273065	kg	1.26E-03	kg	steel, low alloyed	market for steel, low-alloyed
33000	kg	9.71E-06	kg	Electronics, For Control Units	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
#REF!	kg	1.26E-03	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
1	kWh	1.00E+00	kWh	glass flake epoxy paint for WEC (applied)	Substation low-medium voltage
#REF!	m2	3.38E-10	m2	building, hall, steel construction	building construction, hall, steel construction
300	hr	4.41E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO

Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	assembled WEC for Installation	

Environmental flows, in			
Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out			
Amount	*Unit*	*Flow Name*	*Compartment*

Installation

Wave Share

Unit process: Mooring and Anchor

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
6,525,000.00	kg	1.92E-03	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
2,025,000.00	kg	5.96E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
3.48E+04	kWh	1.08E-04	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel
tdistRoad*40%*(mMooring)	t*km	1.61E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mMooring)	t*km	1.81E-03	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER

Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1		1	kWh	mooring for WEC	Mooring

Environmental flows, in			
Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out			
Amount	*Unit*	*Flow Name*	*Compartment*

Unit process: electrical connection 33 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
80927.12	kg	3.91E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
103725.72	kg	5.01E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
24430.83	kg	1.18E-05	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
16032.73	kg	7.74E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
15729.98	kg	7.59E-06	kg	Steel, low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
80927.12	kg	3.91E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	6.51E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	9.77E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mCable)*0.942	t*km	1.10E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO

Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 33 kV	electrical connection

Environmental flows, in			
Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out			
Amount	*Unit*	*Flow Name*	*Compartment*

Unit process: electrical connection 66 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
193993.65	kg	3.58E-05	kg	Steel, unalloyed low alloyed	market for copper, cathode | copper, cathode | Cutoff, U - GLO
73803.26	kg	1.36E-05	kg	Copper	market for lead | lead | Cutoff, U - GLO
150176.79	kg	2.77E-05	kg	Lead	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
61020.00	kg	1.13E-05	kg	Polyethylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
61020.00	kg	1.13E-05	kg	Polypropylene	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
277787.28	kg	1.36E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	5.58E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	8.37E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942*mCable	t*km	9.39E-05	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 66 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Foundation (steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
3225000.00	kg	9.49E-04	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
tdistRoad*40%*(mFoundation)/1000	t*km	5.31E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mFoundation)/1000	t*km	7.97E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore *0.942*n route*mFoundation	t*km	8.94E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
40000	kg	1.18E-05	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items			Foundation for WEC (steel)	Foundation (steel)
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Wind Share

Unit process: Mooring and Anchor

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
2,630,400.00	kg	1.47E-04	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
2,030,400.00	kg	1.14E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
tdistRoad*40%*(mMooring)	t*km	8.26E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mMooring)	t*km	1.24E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mMooring)*0.942	t*km	1.39E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1		1	kWh	mooring for WEC	Mooring
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 66 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
380905.09	kg	3.72E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
488212.77	kg	4.77E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
114990.22	kg	1.12E-05	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
75462.33	kg	7.37E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
74037.34	kg	7.23E-06	kg	Steel, low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
380905.09	kg	3.72E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	6.20E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	9.30E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mCable)*0.942	t*km	1.11E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 66 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*

Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 220 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
514622.05	kg	3.41E-05	kg	Steel, unalloyed low alloyed	market for copper, cathode | copper, cathode | Cutoff, U - GLO
195783.66	kg	1.30E-05	kg	Copper	market for lead | lead | Cutoff, U - GLO
398385.65	kg	2.64E-05	kg	Lead	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
161872.50	kg	1.07E-05	kg	Polyethylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
161872.50	kg	1.07E-05	kg	Polypropylene	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
514622.05	kg	1.30E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	5.32E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	7.98E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942*mCable	t*km	8.94E-05	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 220 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Towing Installation (Steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items			Floater (Steel)	Flaoter Assembly (steel)
1	items			Foundation for WEC (steel)	Foundation (steel)
mooringIO	items			mooring for WEC	Mooring
dist	km			subsea cable 33kV	Electrical Connection
(fuelTow+fuelDeviceHook)*9.96	kWh	1.00E+00	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
(fuelTow+fuelDeviceHook+fuelFoundation)*9.96	items	2.69E-03	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Installation (Steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	WEC Floater (Steel)	Flaoter Assembly (steel)
1	items	1	kWh	Foundation for WEC (steel)	Foundation (steel)
1	items	1	kWh	Wind Turbine	Wind Turbine
mooringIO	items	1	kWh	Mooring	Mooring
dist	km	1	kWh	subsea cable 66kV	Electrical Connection
		1	kWh	Subsea cable 220 kV	Electrical Connection
(fuelTow+fuelHookFoudnation + fuelHookMoorings)	t*km	1.00E+00	kWh	Tow Installation	Tow Installation
1	items	1.00E+00	kWh	Substation module	Substation low-medium voltage
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	Installation per kWh	installation (steel)
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Unit process: Maintenance Wave Share

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
FuelScheduledMaintenance*9.96	kWh	1.20E-02	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
FuelCorrective*9.96	kWh	1.24E-03	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	year	1	kWh	maintenance of multi-use offshore park	maintenance
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Unit process: Maintenance Wind Share

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
FuelScheduledMaintenance*9.96	kWh	1.84E-03	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
FuelCorrective*9.96	kWh	8.84E-05	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	year	1	kWh	maintenance of multi-use offshore park	maintenance
Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Unit process: End-of-Life (Wind)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1.15	m2	5.37E-11	m2	building, hall, steel construction	building construction, hall, steel construction
750	hr	4.20E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state
310,888.75	kg	8.60E-06	kg	treatment of aluminium scrap, postconsumer, prepared for recycling, at remelter	aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | Cutoff, U - GLO
943,426.78	kg	5.40E-04	kg	treatment of copper scrap by electrolytic refining	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, U - GLO
2,469,027.55	kg	1.25E-04	kg	iron production, electric, low-alloyed – RER	iron scrap, unsorted, Recycled Content cut-off | iron scrap, unsorted | Cutoff, U - GLO
237,334.83	kg	1.16E-05	kg	polypropylene terephthalate, granulate, amorphous, recycled	treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U - RER
276,942.40	kg	9.00E-06	kg	polyethylene terephthalate, granulate, amorphous, recycled	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, U - RoW
13,718,064.35	kg	7.07E-04	kg	steel production, electric, low-alloyed – RER	steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
13,718,064.35	kg	7.85E-05	kg	Treatment of scrap steel, inert material landfill	treatment of waste steel, inert material landfill | waste steel | Cutoff, U
2,469,027.55	kg	1.38E-05	kg	Treatment of scrap iron, inert material landfill	treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | Cutoff, U - Europe without Switzerland
943,426.78	kg	6.00E-05	kg	treatment of scrap copper, municipal incineration	treatment of waste copper, municipal incineration | waste copper | Cutoff, U - Europe without Switzerland
276,942.40	kg	7.71E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
237,334.83	kg	6.00E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
25,440.00	kg	5.10E-07	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
310,888.75	kg	1.18E-06	kg	treatment of scrap aluminium, municipal incineration	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
13,298.53	kg	9.56E-07	kg	treatment of inert waste, inert material landfill - CH	treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U - RoW
96,855.31	kg	4.46E-07	kg	Mineral oil regeneration	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - Europe without Switzerland
96,855.31	kg	4.29E-06	kg	Market for waste mineral oil EU	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
1,133,607.75	kg	4.76E-07	kg	Used inter-array cable incineration	treatment of used cable | used cable | Cutoff, U - GLO
1,432,536.36	kg	1.03E-04	kg	Used export cable incineration	treatment of used cable | used cable | Cutoff, U - GLO
Environmental flows, in		**7.91176E-05**			
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Unit process: End-of-Life (Wave)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1.15	m2	5.06E-22	m2	building, hall, steel construction	building construction, hall, steel construction
150	hr	3.46E-19	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state
9894178.658	kg	4.19E-04	kg	steel production, electric, low-alloyed – RER	steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria
138656.0913	kg	5.88E-06	kg	iron production, electric, low-alloyed – RER	iron scrap, unsorted, Recycled Content cut-off | iron scrap, unsorted | Cutoff, U - GLO
254113.8967	kg	1.08E-05	kg	treatment of copper scrap by electrolytic refining	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, U - GLO
57.25933673	kg	1.62E-09	kg	polyethylene terephthalate, granulate, amorphous, recycled	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, U - RoW
77052.73	kg	2.18E-06	kg	polypropylene terephthalate, granulate, amorphous, recycled	treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U - RER
28509.9443	kg	1.21E-06	kg	treatment of aluminium scrap, postconsumer, prepared for recycling, at remelter	aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
9894178.658	kg	4.66E-05	kg	Treatment of scrap steel, inert material landfill	treatment of waste steel, inert material landfill | waste steel | Cutoff, U
138656.0913	kg	6.53E-07	kg	Treatment of scrap iron, inert material landfill	treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | Cutoff, U - Europe without Switzerland
254113.8967	kg	1.20E-06	kg	treatment of scrap copper, municipal incineration	treatment of waste copper, municipal incineration | waste copper | Cutoff, U - Europe without Switzerland
57.25933673	kg	1.08E-09	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
77052.73131	kg	1.45E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
33000	kg	1.55E-06	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
67500	kg	3.18E-06	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
28509.9443	kg	1.34E-07	kg	treatment of scrap aluminium, municipal incineration	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
12523.35899	kg	5.90E-07	kg	treatment of inert waste, inert material landfill	treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U - RoW
69596.1211	kg	2.95E-06	kg	Mineral oil regeneration	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - Europe without Switzerland
69596.1211	kg	3.28E-07	kg	Market for waste mineral oil EU	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
240846.38	kg	1.13E-05	kg	Used inter-array cable incineration	treatment of used cable | used cable | Cutoff, U - GLO
540013.71	kg	2.54E-05	kg	Used export cable incineration	treatment of used cable | used cable | Cutoff, U - GLO

Environmental flows, in				
Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out				
Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Appendix A.4: 180 MW Multi-source Paralel Energy Park Life Cycle Inventory

Please see next page.

Turbine General Information		
Rated capacity	180	MW
AEP	849,546.00	MWh/year
	849.55	GWh/year
Total 25 year	21.24	TWh
Turbines per PP	10	turbines
Installed wind turbine	150	MW
WEC per park	75	devices
Installed WEC	30	MW
Grid distance	25	km
Tower base diameter	9	m
Grid distance	25	km

Manufacturing & Assembly Wind Energy

Unit Process: Turbine manufacturing

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
9792878.79	kg	5.49E-04	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
1484242.42	kg	8.32E-05	kg	Steel, high alloyed	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
2157424.24	kg	1.21E-04	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
135606.06	kg	7.60E-06	kg	Aluminium & Al alloys	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
162727.27	kg	9.12E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
7121.21	kg	3.99E-07	kg	Copper alloys	market for brass | brass | Cutoff, U - RoW
0.00	kg	0.00E+00	kg	Lead	market for lead | lead | Cutoff, U - GLO
688484.85	kg	3.86E-05	kg	Polymer materials	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
2575.76	kg	1.44E-07	kg	Modified organic natural materials	glass fibre reinforced plastic production, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - RER
1447121.21	kg	8.11E-05	kg	Ceramic / glass	market for glass fibre | glass fibre | Cutoff, U - GLO
480.00	kg	2.69E-08	kg	SF6 gas	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
9090.91	kg	5.10E-07	kg	Magnets	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
25000.00	kg	1.40E-06	kg	Electronics	market for electronics, for control units | electronics, for control units | Cutoff, U - GLO
30454.55	kg	1.71E-06	kg	Lubricants	market for lubricating oil | lubricating oil | Cutoff, U - RER
15000.00	kg	8.41E-07	kg	Coolant / other glycols	market for ethylene glycol | ethylene glycol | Cutoff, U - RER
608181.82	kg	3.41E-05	kg	steel, low-alloyed, hot rolled	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, U - GLO
311212.12	kg	1.74E-05	kg	iron ore concentrate	market for iron ore concentrate | iron ore concentrate | Cutoff, U - GLO
8848474.32	kg	4.96E-04	kg	sheet rolling, steel	sheet rolling, steel | sheet rolling, steel | Cutoff, U - RER
3648294.03	kg	2.04E-04	kg	Average metal working, steel	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
135606.06	kg	7.60E-06	kg	Sheet rolling, aluminium	sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, U - RER
143847.31	kg	8.06E-06	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
412.72	m	2.31E-08	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER
tdistRoad*40%*(turbine)	t*km	5.92E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(turbine)	t*km	8.88E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	9.95E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
496207.58	kg	2.78E-05	kg	steel removed by milling, average	steel milling, average | steel removed by milling, average | Cutoff, U - RER
9792878.79	kg	5.49E-04	kg	sheet rolling copper	sheet rolling, copper | sheet rolling, copper | Cutoff, U - RER
1500	hr	8.41E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Turbine Manufacturing	PTO manufacturing
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Substation low-medium voltage

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
72,442	kg	4.06E-06	kg	Sand	market for sand | sand | Cutoff, U - RoW
9,077	kg	5.09E-07	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
96,369	kg	5.40E-06	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
39,677	kg	2.22E-06	kg	Aluminium	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
11	kg	6.09E-10	kg	Nickel	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
192	kg	1.08E-08	kg	Alkyd paint	market for alkyd paint, white, without water, in 60% solution state | alkyd paint, white, without water, in 60% solution state | Cutoff, U - RER
391	kg	2.19E-08	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
1,576	kg	8.83E-08	kg	Chromium steel	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
53,042	kg	2.97E-06	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
2,238	kg	1.25E-07	kg	Glass fibre	market for glass fibre | glass fibre | Cutoff, U - GLO
36	kg	2.03E-09	kg	Kraft paper	market for kraft paper | kraft paper | Cutoff, U - RER
96,855	kg	5.43E-06	kg	Lubricating oil	market for lubricating oil | lubricating oil | Cutoff, U - RER
18	kg	1.02E-09	kg	Polycarbonate	market for polycarbonate | polycarbonate | Cutoff, U - RER
290	kg	1.62E-08	kg	Polyester resin	market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER
80	kg	4.47E-09	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
10	m3	5.46E-10	m3	Sawn timber	market for sawnwood, board, hardwood, dried (u=10%), planed | sawnwood, board, hardwood, dried (u=10%), planed | Cutoff, U - Europe without Switzerland
4	kg	2.03E-10	kg	Silver	market for silver | silver | Cutoff, U - GLO
10,685	kg	5.99E-07	kg	Sulphate pulp	market for sulfate pulp, bleached | sulfate pulp, bleached | Cutoff, U - RER
1,934	kg	1.08E-07	kg	Sulphur hexafluoride	market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER
235	kg	1.32E-08	kg	Synthetic rubber	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
2,095,030	kg	1.17E-04	kg	Gravel	gravel production, crushed | gravel, crushed | Cutoff, U - RoW
tdistRoad*40%*(mSubstation)	t*km	1.14E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mSubstation)	t*km	1.71E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942	t*km	1.91E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
5,175,276	kg	2.90E-04	kg	steel, low alloyed	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
4,040	m	2.26E-07	m	Welding, arc, steel	welding, arc, steel | welding, arc, steel | Cutoff, U - RER

Economic flows, out:

Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Substation for multi-use energy park	Substation low-medium voltage

Environmental flows, in

Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Flow Name*	*Compartment*

Manufacturing & Assembly Wave Energy

Unit Process: PTO manufacturing

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
112,500.00	kg	3.31E-05	kg	cast iron	market for cast iron | cast iron | Cutoff, U - GLO
108,000.00	kg	3.18E-05	kg	copper, cathode	market for copper, cathode | copper, cathode | Cutoff, U - GLO
67,500.00	kg	1.99E-05	kg	Permanent magnet, for electric motor	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
60,000.00	kg	1.77E-05	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
6,000.00	kg	1.77E-06	kg	epoxy resin, liquid	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
25,875.00	kg	7.61E-06	kg	cast iron removed by milling, large parts	cast iron milling, average | cast iron removed by milling, average | Cutoff, U - RER
tdistRoad*40%*mPTO	t*km	3.71E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*mPTO	t*km	5.56E-04	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942*mPTO	t*km	6.62E-03	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
13800	kg	4.06E-06	kg	steel removed by milling, average	steel milling, average | steel removed by milling, average | Cutoff, U - RER
108000	kg	3.18E-05	kg	sheet rolling copper	sheet rolling, copper | sheet rolling, copper | Cutoff, U - RER
300	hr	8.83E-08	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO

Economic flows, out:

Amount	*Unit*			*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	unit	1	kWh	Linear generator PTO for WEC	PTO manufacturing

Environmental flows, in

Amount	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Flow Name*	*Compartment*

Unit process: Substation low-medium voltage

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
52,054	kg	1.53E-05	kg	Sand	market for sand | sand | Cutoff, U - RoW
6,522	kg	1.92E-06	kg	Epoxy resin	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
69,246	kg	2.04E-05	kg	Steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
28,510	kg	8.39E-06	kg	Aluminium	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
8	kg	2.30E-09	kg	Nickel	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
138	kg	4.06E-08	kg	Alkyd paint	market for alkyd paint, white, without water, in 60% solution state | alkyd paint, white, without water, in 60% solution state | Cutoff, U - RER
281	kg	8.27E-08	kg	Cast iron	market for cast iron | cast iron | Cutoff, U - GLO
1,132	kg	3.33E-07	kg	Chromium steel	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
38,114	kg	1.12E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO

<table>
<tr><td>1,608</td><td>kg</td><td>4.73E-07</td><td>kg</td><td>Glass fibre</td><td>market for glass fibre | glass fibre | Cutoff, U - GLO</td></tr>
<tr><td>26</td><td>kg</td><td>7.66E-09</td><td>kg</td><td>Kraft paper</td><td>market for kraft paper | kraft paper | Cutoff, U - RER</td></tr>
<tr><td>69,596</td><td>kg</td><td>2.05E-05</td><td>kg</td><td>Lubricating oil</td><td>market for lubricating oil | lubricating oil | Cutoff, U - RER</td></tr>
<tr><td>13</td><td>kg</td><td>3.83E-09</td><td>kg</td><td>Polycarbonate</td><td>market for polycarbonate | polycarbonate | Cutoff, U - RER</td></tr>
<tr><td>208</td><td>kg</td><td>6.13E-08</td><td>kg</td><td>Polyester resin</td><td>market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER</td></tr>
<tr><td>57</td><td>kg</td><td>1.68E-08</td><td>kg</td><td>Polyethylene</td><td>market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO</td></tr>
<tr><td>7</td><td>m3</td><td>2.06E-09</td><td>m3</td><td>Sawn timber</td><td>market for sawnwood, board, hardwood, dried (u=10%), planed | sawnwood, board, hardwood, dried (u=10%), planed | Cutoff, U - Europe without Switzerland</td></tr>
<tr><td>3</td><td>kg</td><td>7.66E-10</td><td>kg</td><td>Silver</td><td>market for silver | silver | Cutoff, U - GLO</td></tr>
<tr><td>7,678</td><td>kg</td><td>2.26E-06</td><td>kg</td><td>Sulphate pulp</td><td>market for sulfate pulp, bleached | sulfate pulp, bleached | Cutoff, U - RER</td></tr>
<tr><td>1,390</td><td>kg</td><td>4.09E-07</td><td>kg</td><td>Sulphur hexafluoride</td><td>market for sulfur hexafluoride, liquid | sulfur hexafluoride, liquid | Cutoff, U - RER</td></tr>
<tr><td>169</td><td>kg</td><td>4.98E-08</td><td>kg</td><td>Synthetic rubber</td><td>market for synthetic rubber | synthetic rubber | Cutoff, U - GLO</td></tr>
<tr><td>1,505,400</td><td>kg</td><td>4.43E-04</td><td>kg</td><td>Gravel</td><td>gravel production, crushed | gravel, crushed | Cutoff, U - RoW</td></tr>
<tr><td>tdistRoad*40%*(mSubstation)</td><td>t*km</td><td>3.11E-04</td><td>t*km</td><td>transport, freight, lorry, >32 metric ton, diesel, EURO 4</td><td>market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER</td></tr>
<tr><td>tdistRoad*60%*(mSubstation)</td><td>t*km</td><td>4.66E-04</td><td>t*km</td><td>transport, freight, lorry, >32 metric ton, diesel, EURO 6</td><td>market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER</td></tr>
<tr><td>tdistoffshore*0.942</td><td>t*km</td><td>5.23E-03</td><td>t*km</td><td>transport, freight, sea, ferry, heavy fuel oil</td><td>market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO</td></tr>
<tr><td>5,175,276</td><td>kg</td><td>1.52E-03</td><td>kg</td><td>steel, low alloyed</td><td>metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER</td></tr>
<tr><td>4,040</td><td>m</td><td>1.19E-06</td><td>m</td><td>Welding, arc, steel</td><td>welding, arc, steel | welding, arc, steel | Cutoff, U - RER</td></tr>
<tr><td colspan="6">Economic flows, out:</td></tr>
<tr><td>Amount</td><td>Unit</td><td></td><td></td><td>Product</td><td>Processes (database: ecoinvent 3.11, allocation, cut-off by classification)</td></tr>
<tr><td>1</td><td>unit</td><td>1</td><td>kWh</td><td>Substation for multi-use energy park</td><td>Substation low-medium voltage</td></tr>
<tr><td colspan="6">Environmental flows, in</td></tr>
<tr><td>Amount</td><td>Unit</td><td></td><td></td><td>Flow Name</td><td>Compartment</td></tr>
<tr><td colspan="6">Environmental flows, out</td></tr>
<tr><td>Amount</td><td>Unit</td><td></td><td></td><td>Flow Name</td><td>Compartment</td></tr>
</table>

Unit process: Devices Assembly (Steel)

<table>
<tr><td colspan="6">Economic flows, in:</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Amount per kWh</td><td>Unit</td><td>Product</td><td>Processes (database: ecoinvent 3.11, allocation, cut-off by classification)</td></tr>
<tr><td colspan="6">Turbine</td></tr>
<tr><td>Turbine</td><td>units</td><td>1.00E+00</td><td>kWh</td><td>Turbine Manufacture</td><td>Turbine Manufacturing</td></tr>
<tr><td>4952.67</td><td>m3</td><td>2.78E-07</td><td>m3</td><td>welding, arc, steel</td><td>welding, arc, steel | welding, arc, steel | Cutoff, U - RER</td></tr>
<tr><td>440</td><td>kg</td><td>2.47E-08</td><td>kg</td><td>Electronics, For Control Units</td><td>market for electronics, for control units | electronics, for control units | Cutoff, U - GLO</td></tr>
<tr><td>11280621.21</td><td>kg</td><td>6.32E-04</td><td>kg</td><td>metal working, average for steel product manufacturing</td><td>metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER</td></tr>
<tr><td>4221.515128</td><td>kg</td><td>2.37E-07</td><td>kg</td><td>Epoxy Resin</td><td>market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER</td></tr>
<tr><td>1.15</td><td>m2</td><td>6.45E-11</td><td>m2</td><td>building, hall, steel construction</td><td>market for building, hall, steel construction | building, hall, steel construction | Cutoff, U - GLO</td></tr>
<tr><td>1500</td><td>hr</td><td>8.41E-08</td><td>hr</td><td>machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state</td><td>market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO</td></tr>
<tr><td colspan="6">WEC</td></tr>
<tr><td>PTO</td><td>units</td><td>1.00E+00</td><td>kWh</td><td>lin. Gen. PTO for WEC</td><td>PTO manufacturing</td></tr>
<tr><td>18727328.33</td><td>kg</td><td>5.51E-03</td><td>kg</td><td>steel, low-alloyed, hot rolled</td><td>market for steel, low-alloyed</td></tr>
<tr><td>17161.72512</td><td>m</td><td>5.05E-06</td><td>m</td><td>welding, arc, steel</td><td>welding, arc, steel | welding, arc, steel | Cutoff, U - RER</td></tr>
<tr><td>4273065</td><td>kg</td><td>1.26E-03</td><td>kg</td><td>steel, low alloyed</td><td>market for steel, low-alloyed</td></tr>
<tr><td>33000</td><td>kg</td><td>9.71E-06</td><td>kg</td><td>Electronics, For Control Units</td><td>market for electronics, for control units | electronics, for control units | Cutoff, U - GLO</td></tr>
<tr><td>35000+mRod</td><td>kg</td><td>1.26E-03</td><td>kg</td><td>metal working, average for steel product manufacturing</td><td>metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER</td></tr>
<tr><td>1</td><td>kWh</td><td>1.00E+00</td><td>kWh</td><td>glass flake epoxy paint for WEC (applied)</td><td>Substation low-medium voltage</td></tr>
<tr><td>1.15</td><td>m2</td><td>3.38E-10</td><td>m2</td><td>building, hall, steel construction</td><td>building construction, hall, steel construction</td></tr>
<tr><td>300</td><td>hr</td><td>8.83E-08</td><td>hr</td><td>machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state</td><td>market for machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | machine operation, diesel, >= 18.64 kW and < 74.57 kW, generators | Cutoff, U - GLO</td></tr>
<tr><td colspan="6">Economic flows, out:</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Amount</td><td>Unit</td><td>Product</td><td>Processes (database: ecoinvent 3.11, allocation, cut-off by classification)</td></tr>
<tr><td>1</td><td>unit</td><td>1</td><td>kWh</td><td>assembled WEC for Installation</td><td></td></tr>
<tr><td colspan="6">Environmental flows, in</td></tr>
<tr><td>Amount</td><td>Unit</td><td></td><td></td><td>Flow Name</td><td>Compartment</td></tr>
<tr><td colspan="6">Environmental flows, out</td></tr>
<tr><td>Amount</td><td>Unit</td><td></td><td></td><td>Flow Name</td><td>Compartment</td></tr>
</table>

Installation

Wave Share

Unit process: Mooring and Anchor

<table>
<tr><td colspan="6">Economic flows, in:</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Amount per kWh</td><td>Unit</td><td>Product</td><td>Processes (database: ecoinvent 3.11, allocation, cut-off by classification)</td></tr>
<tr><td>6,525,000.00</td><td>kg</td><td>1.92E-03</td><td>kg</td><td>steel, low-alloyed</td><td>market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO</td></tr>
<tr><td>2,025,000.00</td><td>kg</td><td>5.96E-04</td><td>kg</td><td>metal working, average for steel product manufacturing</td><td>metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER</td></tr>
<tr><td>3.48E+04</td><td>kWh</td><td>1.02E-05</td><td>kWh</td><td>diesel, burned in fishing vessel</td><td>market for diesel, burned in fishing vessel</td></tr>
<tr><td>tdistRoad*40%*(mMooring)</td><td>t*km</td><td>1.08E-07</td><td>t*km</td><td>transport, freight, lorry, >32 metric ton, diesel, EURO 4</td><td>market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER</td></tr>
<tr><td>tdistRoad*60%*(mMooring)</td><td>t*km</td><td>1.61E-07</td><td>t*km</td><td>transport, freight, lorry, >32 metric ton, diesel, EURO 6</td><td>market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER</td></tr>
<tr><td>tdistoffshore*(mMooring)*0.942</td><td>t*km</td><td>1.81E-06</td><td>t*km</td><td>transport, freight, sea, ferry, heavy fuel oil</td><td>market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO</td></tr>
<tr><td colspan="6">Economic flows, out:</td></tr>
<tr><td>Amount</td><td>Unit</td><td>Amount</td><td>Unit</td><td>Product</td><td>Processes (database: ecoinvent 3.11, allocation, cut-off by classification)</td></tr>
<tr><td>1</td><td></td><td>1</td><td>kWh</td><td>mooring for WEC</td><td>Mooring</td></tr>
<tr><td colspan="6">Environmental flows, in</td></tr>
<tr><td>Amount</td><td>Unit</td><td></td><td></td><td>Flow Name</td><td>Compartment</td></tr>
</table>

Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 33 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
80927.12	kg	2.38E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
103725.72	kg	3.05E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
24430.83	kg	7.19E-06	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
16032.73	kg	4.72E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
15729.98	kg	4.63E-06	kg	Steel, low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
80927.12	kg	2.38E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	3.97E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	5.95E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mCable)*0.942	t*km	6.68E-05	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 33 kV	electrical connection

Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

0.39431

Unit process: electrical connection 66 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
193993.65	kg	5.71E-05	kg	Steel, unalloyed low alloyed	market for copper, cathode | copper, cathode | Cutoff, U - GLO
73803.26	kg	2.17E-05	kg	Copper	market for lead | lead | Cutoff, U - GLO
150176.79	kg	4.42E-05	kg	Lead	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
61020.00	kg	1.80E-05	kg	Polyethylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
61020.00	kg	1.80E-05	kg	Polypropylene	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
277787.28	kg	8.17E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	8.90E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	1.33E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942*mCable	t*km	1.50E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 66 kV	electrical connection

Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Foundation (steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
3225000.00	kg	9.49E-04	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
tdistRoad*40%*(mFoundation)/1000	t*km	5.31E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mFoundation)/1000	t*km	7.97E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore *0.942*n route*mFoundation	t*km	8.94E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
40000	kg	1.18E-05	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
Economic flows, out:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items			Foundation for WEC (steel)	Foundation (steel)

Environmental flows, in					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Wind Share

Unit process: Mooring and Anchor

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
2,630,400.00	kg	1.47E-04	kg	steel, low-alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
2,030,400.00	kg	1.14E-04	kg	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - RER
1.74E+05	kWh	9.75E-06	kWh	diesel, burned in fishing vessel	market for diesel, burned in fishing vessel
tdistRoad*40%*(mMooring)	t*km	8.26E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mMooring)	t*km	1.24E-05	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mMooring)*0.942	t*km	1.39E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO

Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1		1	kWh	mooring for WEC	Mooring
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 66 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
380905.09	kg	2.14E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
488212.77	kg	2.74E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
114990.22	kg	6.45E-06	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
75462.33	kg	4.23E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
74037.34	kg	4.15E-06	kg	Steel, low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
380905.09	kg	2.14E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	3.56E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	5.34E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*(mCable)*0.942	t*km	6.35E-05	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 66 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: electrical connection 220 kV

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
514622.05	kg	2.88E-05	kg	Steel, unalloyed low alloyed	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
195783.66	kg	1.10E-05	kg	Copper	market for copper, cathode | copper, cathode | Cutoff, U - GLO
398385.65	kg	2.23E-05	kg	Lead	market for lead | lead | Cutoff, U - GLO
161872.50	kg	9.07E-06	kg	Polyethylene	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
161872.50	kg	9.07E-06	kg	Polypropylene	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
514622.05	kg	2.88E-05	kg	Wire drawing, copper	wire drawing, copper | wire drawing, copper | Cutoff, U - RER
tdistRoad*40%*(mCable)	t*km	6.38E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 4	market for transport, freight, lorry, >32 metric ton, diesel, EURO 4 | transport, freight, lorry, >32 metric ton, diesel, EURO 4 | Cutoff, U - RER
tdistRoad*60%*(mCable)	t*km	9.57E-06	t*km	transport, freight, lorry, >32 metric ton, diesel, EURO 6	market for transport, freight, lorry, >32 metric ton, diesel, EURO 6 | transport, freight, lorry, >32 metric ton, diesel, EURO 6 | Cutoff, U - RER
tdistoffshore*0.942*mCable	t*km	1.07E-04	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	km	1	kWh	subsea cable 220 kV	electrical connection
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Towing Installation (Steel)

Economic flows, in:					
Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items			Floater (Steel)	Flaoter Assembly (steel)
1	items			Foundation for WEC (steel)	Foundation (steel)
mooringIO	items			mooring for WEC	Mooring
dist	km			subsea cable 33kV	Electrical Connection
(fuelTow+fuelDeviceHook)*9.96	kWh	4.08E-04	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
(fuelTow+fuelDeviceHook+fuelFoundation)*9.96	items	1.68E-02	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
Economic flows, out:					
Amount	*Unit*	*Amount*	*Unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
Environmental flows, in					
Amount	*Unit*			*Flow Name*	*Compartment*
Environmental flows, out					
Amount	*Unit*			*Flow Name*	*Compartment*

Unit process: Installation (Steel)

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	WEC Floater (Steel)	Flaoter Assembly (steel)
1	items	1	kWh	Foundation for WEC (steel)	Foundation (steel)
1	items	1	kWh	Wind Turbine	Wind turbine
mooringIO	items	1	kWh	Mooring	Mooring
dist	km	1	kWh	Inter-array Cable	Electrical Connection
		1	kWh	Export Cable	Electrical Connection
(fuelTow+fuelHookFoudnation + fuelHookMoorings)	t*km	1.00E+00	kWh	Tow Installation	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
1	items	1.00E+00	kWh	Substation module	Substation low-medium voltage

Economic flows, out:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	items	1	kWh	Installation per kWh	installation (steel)

Environmental flows, in

Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Use Phase

Unit process: Maintenance Wave Share

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
FuelScheduledMaintenance*9.96	kWh	7.50E-02	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
FuelCorrective*9.96	kWh	7.78E-03	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO

Economic flows, out:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	year	1	kWh	maintenance of multi-use offshore park	maintenance

Environmental flows, in

Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Unit process: Maintenance Wind Share

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
FuelScheduledMaintenance*9.96	kWh	1.85E-03	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
FuelCorrective*9.96	kWh	1.08E-04	kWh	diesel, burned in fishing vessel	diesel, burned in fishing vessel | diesel, burned in fishing vessel | Cutoff, U - GLO
(MajorInterval*d)*0.942	t*km	7.54E-05	t*km	transport, freight, sea, ferry, heavy fuel oil	market for transport, freight, sea, ferry, heavy fuel oil | transport, freight, sea, ferry, heavy fuel oil | Cutoff, U - GLO

Economic flows, out:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1	year	1	kWh	maintenance of multi-use offshore park	maintenance

Environmental flows, in

Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*	*Unit*	*Flow Name*	*Compartment*

End-of-Life

Unit process: End-of-Life (Wind)

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1.15	m2	3.01E-21	m2	building, hall, steel construction	building construction, hall, steel construction
750	hr	4.12E-18	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state
310,888.75	kg	1.57E-05	kg	treatment of aluminium scrap, postconsumer, prepared for recycling, at remelter	aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | Cutoff, U - GLO
943,426.78	kg	4.76E-05	kg	treatment of copper scrap by electrolytic refining	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, U - GLO
2,469,027.55	kg	1.25E-04	kg	iron production, electric, low-alloyed – RER	iron scrap, unsorted, Recycled Content cut-off | iron scrap, unsorted | Cutoff, U - GLO
237,334.83	kg	7.98E-06	kg	polypropylene terephthalate, granulate, amorphous, recycled	treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U - RER
276,942.40	kg	9.31E-06	kg	polyethylene terephthalate, granulate, amorphous, recycled	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, U - RoW
13,718,064.35	kg	6.92E-04	kg	steel production, electric, low-alloyed – RER	steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria

Economic flows, out:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
13,718,064.35	kg	7.69E-05	kg	Treatment of scrap steel, inert material landfill	treatment of waste steel, inert material landfill | waste steel | Cutoff, U
2,469,027.55	kg	1.38E-05	kg	Treatment of scrap iron, inert material landfill	treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | Cutoff, U - Europe without Switzerland
943,426.78	kg	5.29E-06	kg	treatment of scrap copper, municipal incineration	treatment of waste copper, municipal incineration | waste copper | Cutoff, U - Europe without Switzerland
276,942.40	kg	6.21E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
237,334.83	kg	5.32E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
25,440.00	kg	1.43E-06	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
310,888.75	kg	1.74E-06	kg	treatment of scrap aluminium, municipal incineration	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
13,298.53	kg	7.45E-07	kg	treatment of inert waste, inert material landfill - CH	treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U - RoW
96,855.31	kg	4.89E-06	kg	Mineral oil regeneration	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - Europe without Switzerland
96,855.31	kg	5.43E-07	kg	Market for waste mineral oil EU	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
1,133,607.75	kg	5.30E-05	kg	Used inter-array cable incineration	treatment of used cable | used cable | Cutoff, U - GLO

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1,432,536.36	kg	6.69E-05	kg	Used export cable incineration	treatment of used cable | used cable | Cutoff, U - GLO

Environmental flows, in

Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Unit process: End-of-Life (Wave)

Economic flows, in:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
1.15	m2	3.16E-21	m2	building, hall, steel construction	building construction, hall, steel construction
150	hr	4.33E-18	hr	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state	machine operation, diesel, >= 18.64 kW and < 74.57 kW, steady-state
9894178.658	kg	2.62E-03	kg	steel production, electric, low-alloyed – RER	steel production, electric, low-alloyed | steel, low-alloyed | Cutoff, U - Europe without Switzerland and Austria
138656.0913	kg	3.67E-05	kg	iron production, electric, low-alloyed – RER	iron scrap, unsorted, Recycled Content cut-off | iron scrap, unsorted | Cutoff, U - GLO
254113.8967	kg	6.73E-05	kg	treatment of copper scrap by electrolytic refining	copper scrap, sorted, pressed, Recycled Content cut-off | copper scrap, sorted, pressed | Cutoff, U - GLO
57.25933673	kg	1.01E-08	kg	polyethylene terephthalate, granulate, amorphous, recycled	polyethylene terephthalate production, granulate, amorphous, recycled | polyethylene terephthalate, granulate, amorphous, recycled | Cutoff, U - RoW
77052.73	kg	1.36E-05	kg	polypropylene terephthalate, granulate, amorphous, recycled	treatment of waste plastic, mixed, recycling | polypropylene, flakes, recycled | Cutoff, U - RER
28509.9443	kg	7.55E-06	kg	treatment of aluminium scrap, postconsumer, prepared for recycling, at remelter	aluminium scrap, post-consumer, Recycled Content cut-off | aluminium scrap, post-consumer | Cutoff, U - GLO

Economic flows, out:

Amount	*Unit*	*Amount per kWh*	*unit*	*Product*	*Processes (database: ecoinvent 3.11, allocation, cut-off by classification)*
9894178.658		4.66E-05	kg	Treatment of scrap steel, inert material landfill	treatment of waste steel, inert material landfill | waste steel | Cutoff, U
138656.0913		6.53E-07	kg	Treatment of scrap iron, inert material landfill	treatment of waste bulk iron, excluding reinforcement, sorting plant | waste bulk iron, excluding reinforcement | Cutoff, U - Europe without Switzerland
254113.8967		1.20E-06	kg	treatment of scrap copper, municipal incineration	treatment of waste copper, municipal incineration | waste copper | Cutoff, U - Europe without Switzerland
57.25933673		6.74E-09	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
77052.73131		9.07E-06	kg	market group for waste plastic,mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, U
33000	kg	9.71E-06	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
67500	kg	1.99E-05	kg	market for waste electric and electronic equipment	treatment of waste electric and electronic equipment, shredding | waste electric and electronic equipment | Cutoff, U - GLO
28509.9443		1.34E-07	kg	treatment of scrap aluminium, municipal incineration	treatment of waste aluminium, municipal incineration | waste aluminium | Cutoff, U - Europe without Switzerland
12523.35899	kg	3.69E-06	kg	treatment of inert waste, inert material landfill	treatment of inert waste, inert material landfill | inert waste, for final disposal | Cutoff, U - RoW
69596.1211	kg	1.84E-05	kg	Mineral oil regeneration	treatment of waste mineral oil, hazardous waste incineration | waste mineral oil | Cutoff, U - Europe without Switzerland
69596.1211		3.28E-07	kg	Market for waste mineral oil EU	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
240846.38	kg	7.09E-05	kg	Used inter-array cable incineration	treatment of used cable | used cable | Cutoff, U - GLO
540013.71	kg	1.59E-04	kg	Used export cable incineration	treatment of used cable | used cable | Cutoff, U - GLO

Environmental flows, in

Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*

Environmental flows, out

Amount	*Unit*		*Unit*	*Flow Name*	*Compartment*