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Life cycle assessment and productivity analysis of a point absorber wave energy converter

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Abstract

The global energy transition, indispensable to gradually reduce the carbon intensity of many energy sources, is determining a significant development in offshore renewable technologies. However, when considering their entire life cycle, it is not completely environmentally friendly, and, as for the fossil fuels, some are more impactful than others.

The evaluation of these impacts is, therefore, fundamental and can be used to optimize manufacturing processes to reduce the quantity of carbon dioxide emitted into the atmosphere and related energy consumption.

The dissertation focuses on the complete life cycle assessment analysis of a wave energy converter, specifically a point absorber, starting from the goal and scope definition and following with the life cycle inventory of all the materials and processes used to build, install and decommission the device. Subsequently, through a life cycle impact assessment, the different impacts of the wave energy converter on the environment are investigated and compared with other ocean energy technologies. A sensitivity analysis is also performed, considering various key performance parameters. The work also involves the productivity estimation of the point absorber, including the solar panels and wind turbine placed on its top. While the latter is computed by elaborating data from PVGIS and Global Wind Atlas, the former is obtained by implementing the different input parameters, such as the device hydrodynamic and geometric information together with the metocean data from the installation site, in a specific Matlab-Simulink model.

Finally, the productivity analysis is performed on other installation sites, and the resulting changes in the impact assessment parameters are estimated and compared with the original values.

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Acronyms

AC Alternated Current (p. 29).

CFC Chlorofluorocarbon (pp. 36,37,38).

COP26 The 26th Climate Change Conference (p. 10).

CTU Comparative Toxic Unit (pp. 36,37,38).

DCB Dichlorobenzene (pp. 36,37,38).

FKM American standard name for Fluro-Elastomer (pp. 30,33).

GHG Greenhouse Gas (pp. 11,39,41).

ISO International Organization for Standardization (pp. 21,23).

LiNMC Lithium nickel manganese cobalt oxides (p. 31).

NMVOC Non-methane volatile organic compounds (pp. 36,37,38).

PTO Power Take-Off (pp. 13,14,15,30,31,51,58).

VRLA Valve Regulated Lead Acid (pp. 31,32).

Chapter 1

1 Introduction

1.1 Environmental challenges and goals

One of the main challenges that humanity has to face in the near future is the reduction of worldwide carbon emissions and a consequent transformation of the energy production sector. In 2020 indeed, fossil fuels still supplied around 80% of the global primary energy demand (1). Their combustion have caused through the years a significant growth in the amount of greenhouse gasses in our atmosphere which consequently determined an increase of the average global temperature (+1.1°C in the last 150 years) (2). However, traditional energy production mechanisms should not be dismantled for this reason only, but also for a sustainability perspective. Fossil fuels are indeed limited resources and the only way to fulfill long term energy needs is to invest in the renewable energies. According to the most recent studies indeed, oil, gas and coal will run out respectively in 50.7, 52.8, 114 years. However, it has to be taken into account that these estimations are formulated following the reserve-to-product ratio of 2015 and could therefore change if new reserves were found or if there was a variation in the annual production (3).

To cope with this challenge, Europe has speeded up the adoption of renewables, especially wind and solar, with the target of reaching a 32% energy production share by 2030 in order to decrease net greenhouse gas emissions by at least 55% compared to the values of 1990 (4). These goals are in line with those set by COP26, which included reaching net zero emissions within 2050 and limiting the temperature increase to 1.5°C (5).

For these purposes the different types of renewable energies that could be exploited are wind, solar, hydropower, geothermal, biomass and ocean energy.

Nevertheless, during their life cycle, not even renewable sources are completely environmentally friendly and, as for fossil fuels, some are more impactful than others. For example, considering the grams of CO_2 equivalent emitted for each kWh produced by the different technologies, a great variability in values is present among the different types of renewables (6,7).

Table 1.1: Life cycle GHG emissions of renewable technologies (6,7)

GHG emissions [g-CO_2eq/kWh]	Minimum	Average	Maximum
PV	50	99	160
Wind onshore	4	17	40
Wind offshore	9	13	17
Biomass	2	66	122
Geothermal	7	39	90
Big hydro	2	16	43
Small hydro	10	14	18
Ocean	10	37	126

As shown in the table above, the less impactful technologies are wind turbines and hydropower plants. Ocean energy technologies also show low average values and considering their low technology readiness level with respect to the other renewables, their potential of improvement is great.

1.2 Ocean Energy

Ocean energy represents the Earth's largest untapped source of clean energy and could probably play an important part in the future energy scenarios. Furthermore, it could determine huge benefits especially for the coastal areas and islands in terms of economic growth, energy availability and pollution reduction.

Ocean energy can be divided in five different sources, each with different origin and technology for conversion (8).

- Waves: determined by the transfer of wind's energy to the water surface. Their theoretical potential is 29500 TWh/year.
- Tides: determined by the Moon gravitational forces on Earth which cause both the tidal range and the tidal currents. Their theoretical potential is 7800 TWh/year.
- Ocean currents: determined by the combination of wind forces and thermohaline circulation. Their potential has not been globally estimated.
- Ocean thermal energy conversion (OTEC): determined by the temperature differences between the ocean surface and its deep layers below 1000 m. Its theoretical potential is 44000 TWh/year.

- Salinity Gradients: determined by the difference in salinity gradients between specific locations, for example river mouths and the surrounding marine water. Their theoretical potential is 1650 TWh/year (8).

In Europe, the most promising technologies in this field are those exploiting the waves and the tides. Norther-Europe presents indeed some of the world's highest tides, up to 13 meters, and being surrounded by the Atlantic Ocean, has also a great wave potential. OTEC potential is instead limited due to the low annual average sea surface temperatures of the waters surrounding Europe.
The European target is to install up to 100 GW of ocean energy technologies before 2050, which could provide up to 10% of the current electricity needs by the same year (9).

1.3 Wave energy

As described before, wave energy has an enormous potential and could theoretically fulfill the whole world energy demand. Furthermore, waves are considered a reliable source of energy and can be well forecasted even though, as most renewable energies, are intermittent and widely vary both in the short and long term.
Their worldwide distribution is presented in figure 1.1, that shows how the most powerful waves can be found in the mid-latitude regions, especially in the southern hemisphere. Closed basis at any latitude present instead very low values of mean power density due to their non-sufficient fetch which does not allow a proper wave formation. For example, while Northern-Europe values can reach 80 kW/m, the maximum power density in the Mediterranean Sea is only 15 kW/m (8).

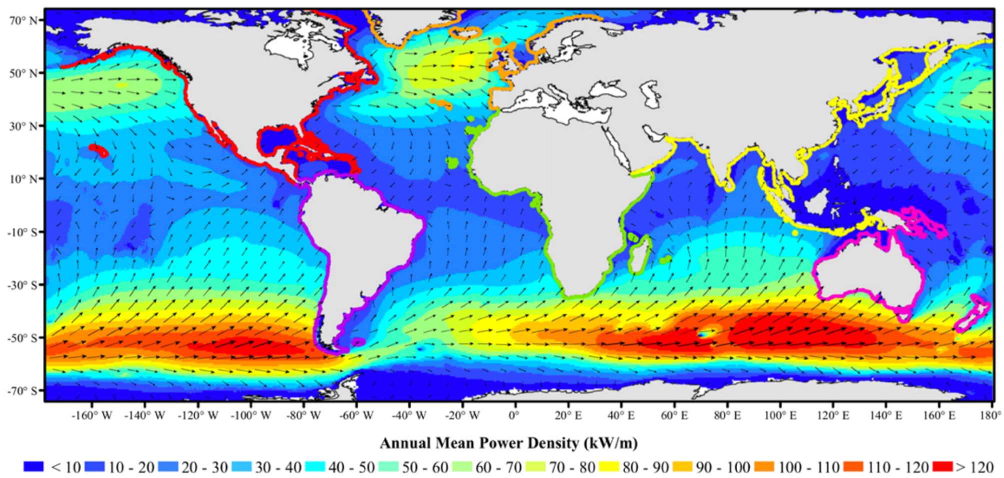


Figure 1.1: Global wave power potential (10)

1.4 Wave energy converters

In the latest years, many different types of technologies able to extract power from the waves have emerged and can be mainly divided in five categories:

- Attenuators: characterized by multiple interconnected segments disposed in parallel to the direction of the waves and able to extract energy from the segments relative motion. The PTO is usually made of hydraulic motors through which high pressured oil is pumped using hydraulic rams that resist the wave-induced motion of the hinged joints. Their technology readiness level is one of the highest among the marine technologies together with the following one (8).

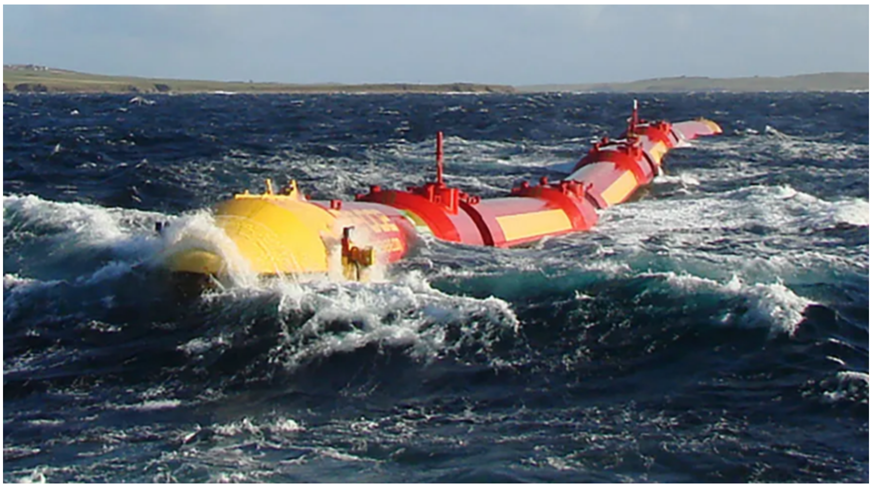


Figure 1.2 The Pelamis, example of attenuator (11)

- Oscillating water column: characterized by a hollow semi-submerged structure in which the passing of the wave determines the activation of the PTO due to the alternate stream of air which is pushed towards the external atmosphere when the water level rises while is pulled inside when the water level falls. The PTO is usually composed of a Wells turbine due to its capability to rotate continuously in the same direction despite the air flow motion (12).

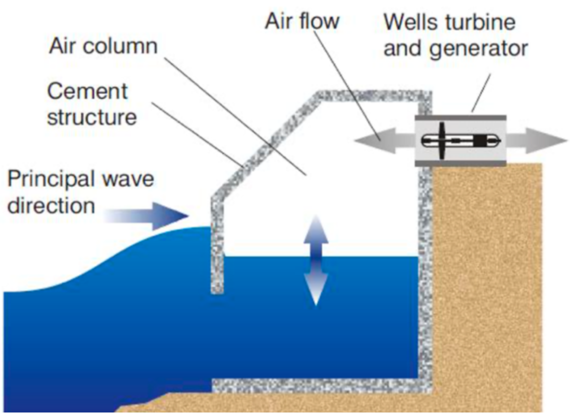


Figure 1.3: Oscillating water column scheme (12)

- Point absorber: characterized by a buoyant body that produces energy through its relative motion with the base connection located on the seabed. The PTO can be placed inside the floating device and is usually composed by a rotating electric generator or positioned at the base connection in the form of a linear generator.

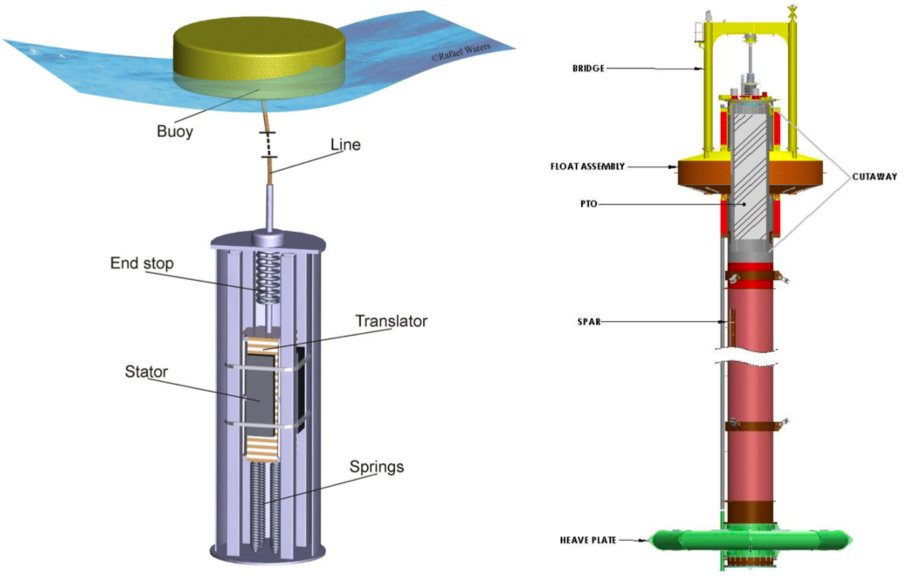


Figure 1.4 Linear point absorber (left), PowerBuoy (right) (13,14)

In the case of deep water, the technology can be modified so that there is no more need of a connection to the seabed. The so called PowerBuoy is composed by a float, a spar and a heave plate and in this case the relative motion between the float and the spar is exploited to produce energy.

- Rotating mass: is characterized by a floating device in which one or more rotating objects can be found. The wave-induced movement of the hull causes the internal mass to spin generating a gyroscopic torque. The latter is used by a rotating PTO to produce electricity.

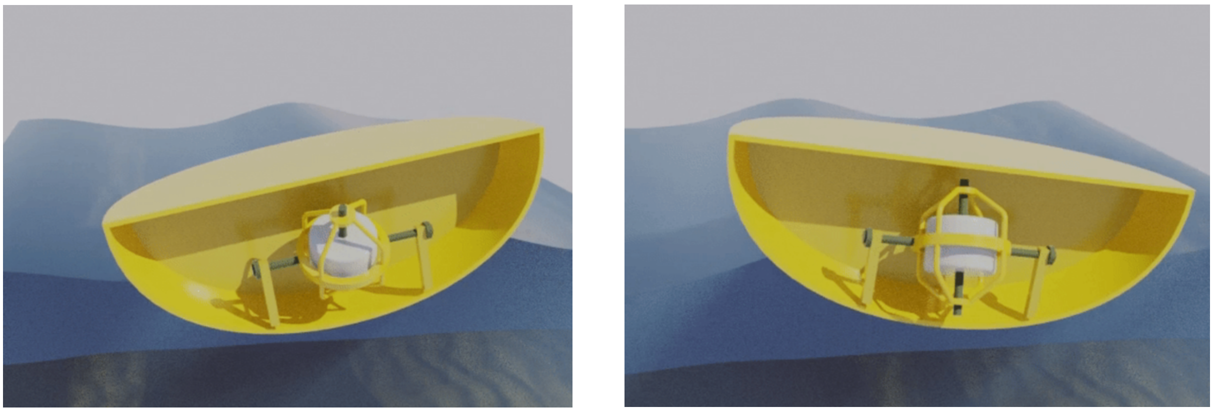


Figure 1.5: Schematics of a rotating mass wave energy converter (15)

- Overtopping device: collects the breaking waves in a reservoir positioned at a higher altitude with respect to the sea level and uses their potential energy to produce energy through a low-head turbine (8).

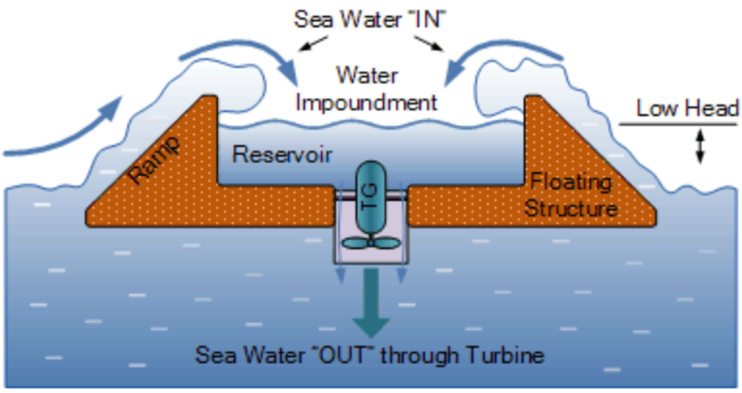


Figure 1.6: Schematics of a overtopping device (13)

1.5 Wave energy converters – WEPA concept

The device developed by Wave For Energy S.r.l. is a Water Energy Point Absorber (WEPA) and is based on a system able to use the heaving motion of the waves in order to extract energy. A central rope is attached to one end at the gravity anchor located on the seabed and to the other end is wound around a drum placed inside the buoy hull and connected, through a shaft, to an electric generator on one side and to a spiral spring on the other one. The generator applied to the device is a synchronous machine characterized by a permanent magnet rotor and a high number of poles able to provide high torque at low rpm values. The assembly of generator, drum and spring form the PTO, is shown in figure 1.7.

To enhance the efficiency of energy conversion, PTO control strategies such as PTO damping calibration are implemented, while its stiffness remains constant. In this way, WEPA will be able to adapt to the specific sea state (14).

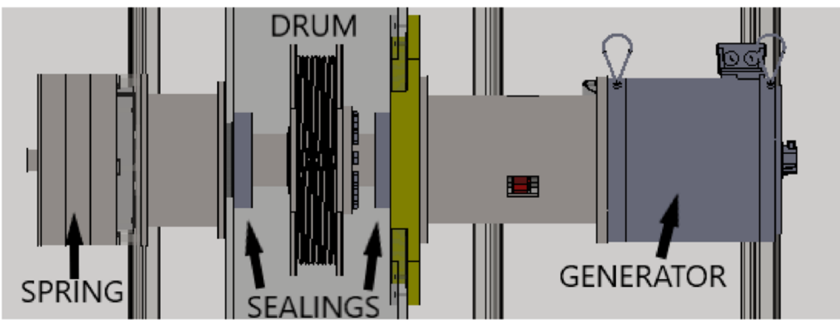


Figure 1.7: WEPA PTO (14)

The working principle, as shown in figure 1.8, is the following: when the device heaves upwards, the unwinding motion of the rope puts the drum into rotation and the generator starts producing electricity. When instead the buoy heaves downwards, the rope is rewound thanks to the spring or by using the generator as a motor.
The electrical generation is further improved by the placement of three photovoltaic panels and a wind turbine on the top of the device.
However, the purpose of this prototype is not only the generation of electricity, but also the production and collection of freshwater thanks to a reverse osmosis desalination device (14).

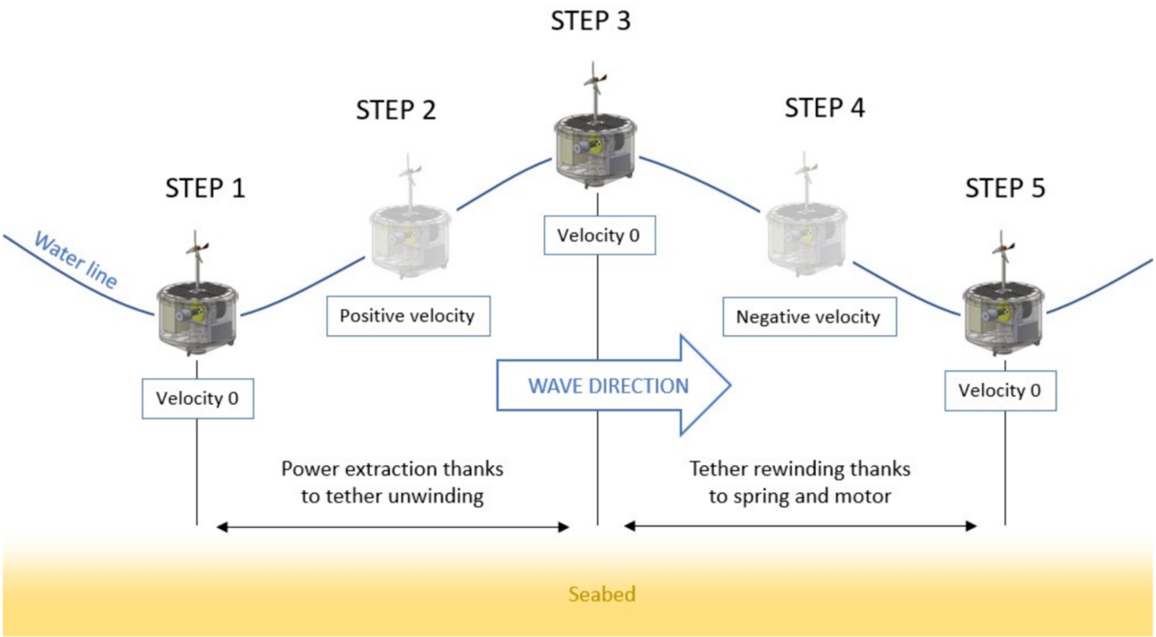


Figure 1.8: WEPA energy production mechanism (14)

1.6 WEPA installation site

As shown in figure 1.9, in the Mediterranean Sea, the highest values of wave energy flux are reached between the Balearic Islands and Sardinia because of the larger fetch. The west cost of the latter represents therefore a good spot to place a wave energy converter (15).

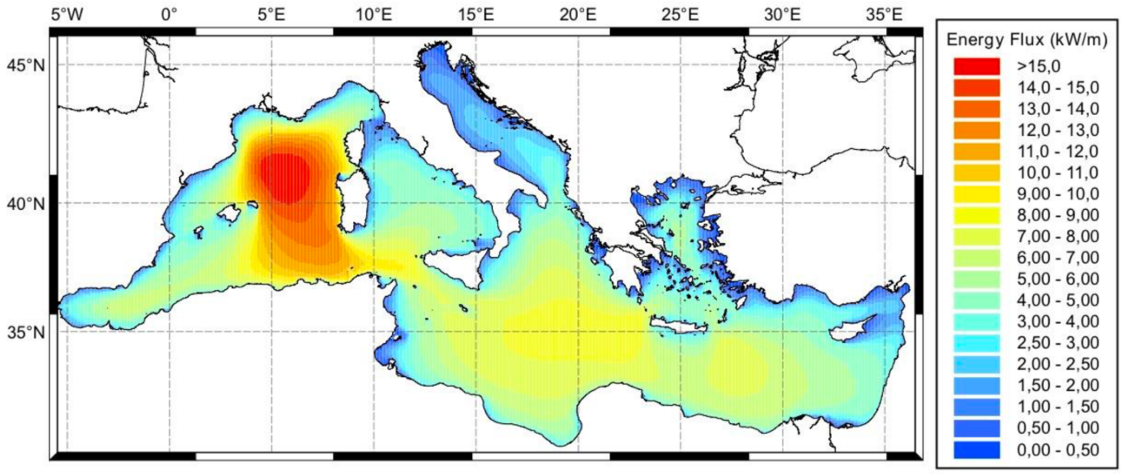
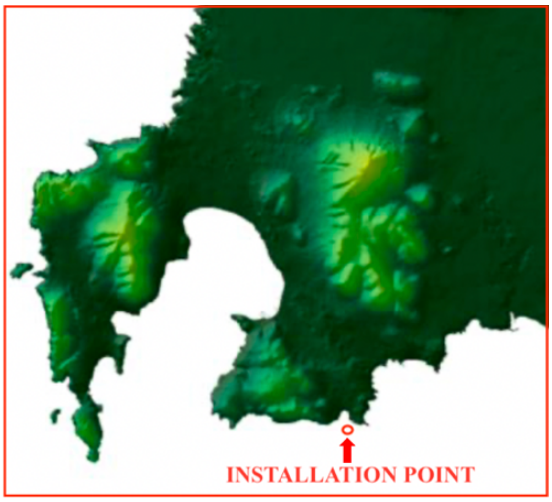


Figure 1.9: Mediterranean wave energy flux (15)

In particular, the coastal region of Porto Conte near Alghero was selected to test WEPA, figure 1.10. Its exact location was chosen following the criteria of visual impact minimization and preservation of the seabed. Therefore, the installation point is placed at more than 200 meters from the cost, so that the device is barely visible to the naked eye, and above a 6500 m^2 sand bank, avoiding damaging the surrounding poseidonia (16).



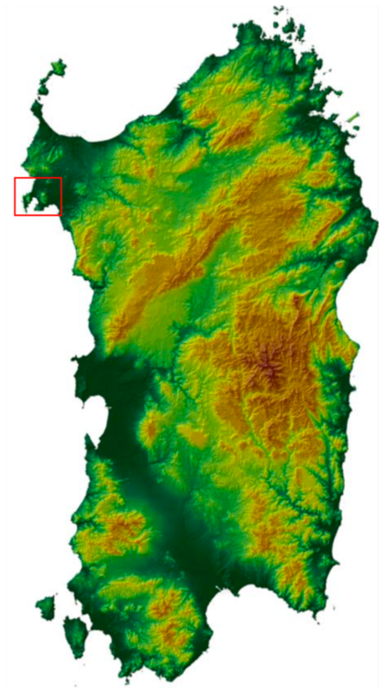


Figure 1.10: WEPA installation point (19)

However, being the location very close to the land and sheltered from the dominant north-west wind, the wave energy density shows really low values, around 2 kW/m. A detailed energy scatter is presented in the picture below. The parameters H_s and T_p respectively indicate the significant wave height and its peak period and are better explained in chapter 6 (17).

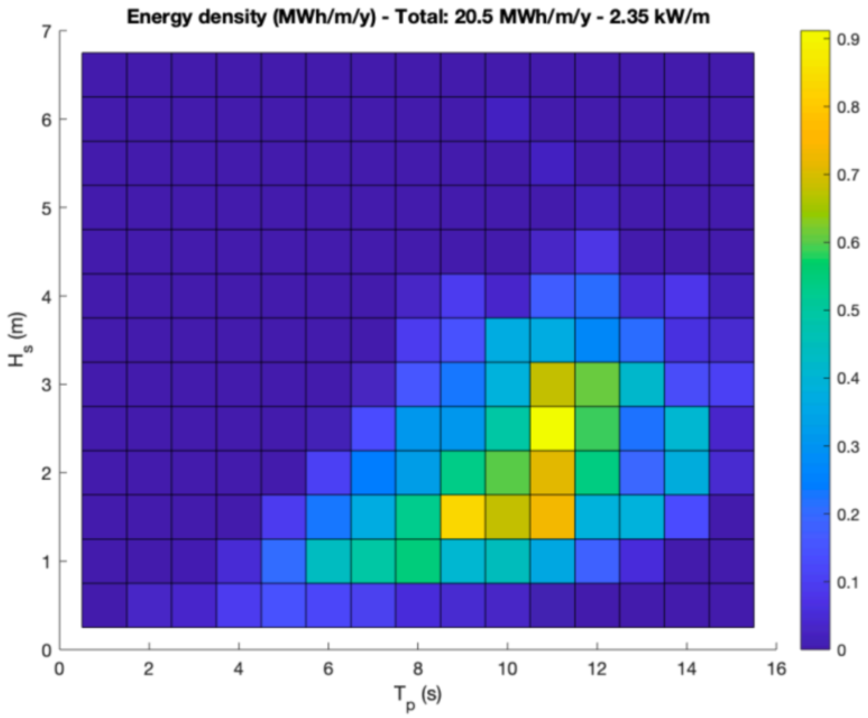


Figure 1.11: Energy scatter of the installation point (17)

1.7 Objectives

The purpose of this thesis is to perform a life cycle assessment and a productivity analysis of WEPA. The former will be carried out using an open-source software named openLCA (version 1.11.0). The database installed is Environmental footprint and the impact assessment method utilized is Environmental Footprint (Mid-point indicator).

The latter will be done applying an already developed MATLAB-Simulink model which will be modified in order to fulfill the needed requirements.

In detail, for the first part the objectives are:

- Perform a literature review on standardized life cycle assessment methodologies and guidelines.
- Conduct an inventory of all the materials and processes needed for WEPA realization.
- Implement these data on openLCA and perform the impact assessment analysis.
- Analyze the outputs preforming uncertainty and sensitivity analysis and comparing them with already existing studies.
- Provide an optimized solution.

For the second part, the objectives are:

- Analyze the parameters determining the wave energy.
- Compute WEPA annual productivity in the assigned location.
- Compute the productivity in other locations and compare the results.

1.8 Document outline

The document is organized as follows

Chapter 2

In this chapter the LCA concepts and methodology are analyzed. The phases of goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation are described according to the ISO standards.

Chapter 3

In this chapter the goal and scope of this specific project are described, addressing the motivation of the study and the application of interest together with all the starting parameters necessary to conduct the research such as functional unit and reference flow, system boundary and assessment parameters.

Chapter 4

In this chapter the life cycle inventory analysis is performed. For all the cradle-to-crave stages, the materials and processes needed are described. The initial data were mostly taken from the tables provided by the company and from the expertise of the engineers working at the project. Secondary data were instead given by the software.

Chapter 5

In this chapter the life cycle impact assessment is analyzed. Firstly, the Environmental Footprints methodology is investigated and compared with the Recipe method, commonly used in other studies.

Secondly, the most important impact factors are studied and a sensitivity analysis is performed. Finally a comparison with other studies regarding ocean energy technologies is carried out.

Chapter 6

In this chapter the parameters needed to estimate the potential of a wave are analyzed. Firstly, the hypothetical case of regular waves is presented, then, by using the latter as a starting point, the more complex case of irregular waves is investigated.

Chapter 7

In this chapter the WEPA productivity model is described. The different stages followed in order to obtain the annual energy produced by the device are analyzed, starting from its geometry definition through Solidworks and ending with the implementation of the hydrodynamic parameters, obtained from Ansys Aqua, in the Matlab-Simulink model.

Chapter 8

In this chapter the productivity of the photovoltaic panels and of the wind turbine installed at the top of the device are estimated. For the former, the data needed were taken from PVGIS, which provides the monthly average solar radiation. For the latter instead, wind data were taken from Windnavigator, which provides the Weibull parameters. Furthermore, the PV efficiency and rated power and the wind power curve were taken from the datasheets of the respective constructors.

Chapter 9

In this chapter, different wave scatters of sites located in the Mediterranean and North Seas are implemented in the Matlab-Simulink model and the results are compared. Furthermore, the relevant life cycle impact parameters are computed again, together with the energy and carbon payback time.

Chapter 10

In this chapter, all the work results are summarized and possible future improvements are described.

Chapter 2

2 LCA concepts and methodology

Life cycle assessment (LCA) is a worldwide standardized approach having the purpose of quantifying the potential repercussions on human well-being and on the environment associated with a specific good or service. The LCA analysis considers indeed the whole life cycle of the system under inspection, starting from the extraction of raw materials to the end-of-life management which comprehends decommissioning and recycling. The approach is therefore defined as "cradle to grave". Life cycle assessment is frequently used as a decision support tool to provide a valid contribution towards greater sustainability of commodities and services (18).

The life cycle assessment methodological framework was firstly developed in the early 1990s and was then standardized, resulting in the adoption of four standards (19):

- ISO 14040 (Principles and frameworks)
- ISO 14041 (Goal and scope definition)
- ISO 14042 (Life cycle impact assessment)
- ISO 14043 (Life cycle interpretation)

As a result of a 2006 revision, the latter three ISOs were then collected into ISO 14044 concerning the requirements and guidelines.

According to the standards just mentioned, the life cycle assessment analysis is divided into four main steps (19):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

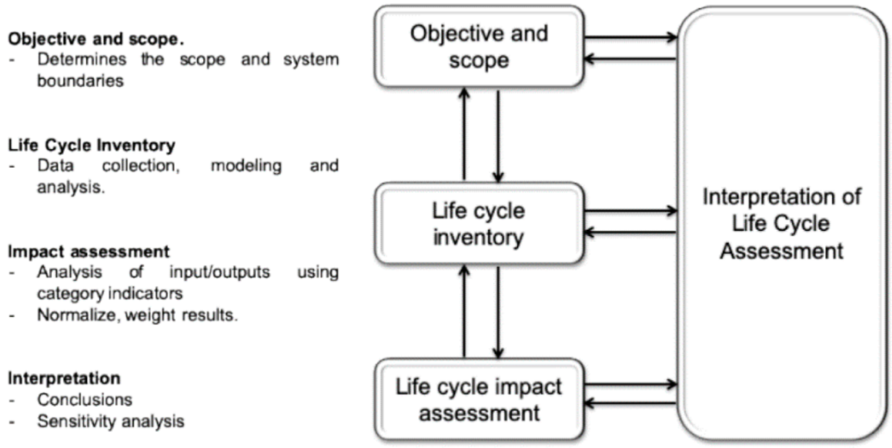


Figure 2.1: Life cycle assessment (LCA) framework. Adapted from ISO 14040 (18)

2.1 Goal and scope definition

Concerning the definition of the goal, it is necessary to address the motivation and context of the study, the type of audience the analysis is intended for, and which is the application of interest (analyses can be monitoring studies as well as decision support tools). These aspects set the foundations of the LCA study and influence the subsequent phase of scope definition, in which the procedure is framed primarily in terms of:

- Defining the functional unit and reference flows: the functional unit represents the reference unit for all entry and exit data between the environment and the product system and defines the qualitative and quantitative aspects of the function. The reference flow is the quantity of product needed to achieve the functional unit.
- Scoping the product system, determining the processes and procedures to be considered in the life cycle assessment under analysis and defining the system boundaries, both temporal and geographical. The purpose is therefore to identify which stages and processes should be taken into account during the analysis. Traditionally a lifecycle analysis includes all stages from raw material extraction to end-of-life processing (approach called: cradle-to-grave), but, according to the purpose of the study, the boundary choice could vary. Some examples are the cradle-to-gate analysis, which end with obtaining a product, and the gate-to-gate analysis which only focuses on the production processes.
- Appointing the assessment parameters to be considered. Their choice should be in line with the objective of the study and should be made to best represent all the potential effects of the analyzed system on the biosphere. The various parameters may refer to the effect of the

discharge of substances in the environment (such as climate change, ozone depletion, human toxicity, ecotoxicity, photochemical ozone formation, acidification, and eutrophication) or refer to the resources utilized by the system itself (such as depletion of mineral, fossil, or water resources and land consumption).

- Choosing whether the analysis should be attributional, i.e. evaluating the impacts relative to the studied work, or consequential, i.e. evaluating the impacts that are likely to happen when selecting an option over another.
- Deciding if the study should be made public and, in that case, carry out a critical review (19,20).

2.2 Inventory Analysis

This phase involves the gathering and evaluation of inputs and outputs specific to a product system along its life cycle. All the input materials and processes from cradle to grave need to be evaluated accordingly with the scope definition and scaled in reference to the functional unit, together the output ones.

This analysis relies both on primary data given by the constructor of the specific object examined and secondary data taken from databases. The latter are especially useful because in most cases present already existing processes that can be associated to a specific flow.

The output of the inventory investigation is the life cycle inventory, characterized by a series of determined elementary physical flows for the product system related to the delivery of the function outlined by the functional unit (19,20).

2.3 Impact Assessment

The information obtained from the previous step represent the starting point for the evaluation of the various impacts, i.e. the possible damage to the environment and to the animal species well-being related to the consumption of polluting energy carriers, such as fossil fuels, and their release to the atmosphere.

In accordance with ISO 14044, the impact assessment is made of six elements, of which the first three are mandatory and the last three are optional and allow the collection of the outcomes deriving from the mandatory steps:

- *Selection* of the impact categories associated to the assessment parameters defined during the goal and scope definition phase. Furthermore, a representative indicator is adopted for every impact category along with an environmental model that assesses the indicator variation associated to the elementary flow.
- *Classification,* determined by the assignment of each elementary flow, resulting from the inventory analysis, to the specific impact category depending on the consequences it can have on the environment. For example, considering the climate change impact category, different gases such as methane, carbon dioxide and nitrous oxide have an impact on it.
- *Characterization,* employs environmental models to estimate how each elementary flow influences the indicator of a selected category. By doing so, the characterized impact results can be represented in an unique metric for the impact category. The final output is the collection of each contribution into a single value which describes the product system global impact on that specific category. For example, taking into account three gases mentioned in the previous paragraph, even if they have different impacts on climate change, their contribution can be expressed in terms of grams of equivalent CO_2 by using a global warming potential characterization factor.
- *Normalization,* associates the impact of each category acquired in the characterization level to normalization factors, so that an unique unit of reference can be applied. The result is a product system impact outline characterized by values of the different category indicators defined with the same standards. Usually, normalization factors might concern the impacts of a particular area from a global or per capita point of view.
- *Grouping,* classifies the impact categories on the base of their degree of severity.
- *Weighting,* allocates weighting factors to the different impact categories in order to provide a quantitative expression for assessing the most severe ones. These factors can be computed following three approaches:
    1. Experts' knowledge.
    2. Computing the difference between the actual environmental load and its limit value.
    3. Evaluating the monetary costs needed to eliminate the effects of the impact categories on the environment.

Being available alternative approaches, this step is extremely subject dependent. The results obtained will indeed depend on the specific choices, therefore it is not suggested to perform a weighting analysis on a study whose outcomes will be compared with those of other studies. After the normalization, grouping and weighting steps, all the impact categories results can be condensed into a single indicator representative of the whole potential impact (19,20).

2.4 Interpretation

The last phase interprets the results obtained from the impact assessment in order to relate them with the goals set. The two main purposes are:

- Bettering the life cycle inventory modelling in relation to the study purpose.
- Providing tougher conclusions and useful advice for comparative analysis.

By performing a sensitivity and uncertainty analysis, indeed, the critical points of the study can be highlighted and possible solutions can be suggested for future experiments. Furthermore, a completeness and consistency check are carried out (19,20).

Chapter 3

3 Goal and scope definition

3.1 Objective

The objective of this LCA analysis is to evaluate the environmental impact of WEPA over the entirety of its life cycle, determining which flows and processes are the most impactful ones and evaluating possible alternative solutions in order to optimize the system. Furthermore, a comparison between other LCA studies on different wave energy converters will be provided.

3.2 Functional unit and reference flow

The functional unit adopted in this LCA is 1 kWh of electricity produced and its reference flow is the manufacturing, operation and disposal of that part of device necessary to provide this amount of energy.

3.3 System boundaries

The system boundary comprises most of the flows (materials and energies) and processes utilized during WEPA life cycle, from the raw materials extraction to the decommissioning of the device. The life cycle can be parted into three sections:

- The upstream section, which includes the extraction of the different raw materials, their transportation and processing, the manufacturing of the buoy components, their assembly and the transport of the final device to the deployment site.
- The operative section, which includes the installation, operation and maintenance of the device.
- The downstream section, which includes decommissioning and disposal of the device.

The processes that are not considered in the life cycle are:

- The production of small components such as bolts, rivets, cables and electronic parts.
- The transport of the buoy components to the assembly location.
- The repairs of components due to possible malfunctions.

No geographical or temporal boundaries are set.

3.4 Assessment parameters

The chosen assessment parameters are those that investigate the following impact categories: aquatic acidification, eutrophication and ecotoxicity, global warming, carcinogens, non-carcinogens, ionizing radiation, ozone layer depletion, land occupation, mineral extraction, non-renewable energy, respiratory inorganics, respiratory organics, human health, terrestrial acidification and ecotoxicity, ecosystem quality and resources.

3.5 Study intent

The intent of the study is to be attributional and at the same time consequential. By starting indeed from the evaluation of the impacts relative to the specific materials used for the development of the device, a sensitivity analysis will be performed so that different options can be evaluated and compared.

Chapter 4

4 Life cycle inventory

4.1 Data collection

Primary data were taken from the design drawings of the company and from the expertise of the employees. Secondary data were taken instead from the Environmental footprint database. Since the latter does not provide all the inventory information, various approximations for some manufacturing processes were made according to data found in literature papers.
The majority of the data used, reflect average European conditions, with the exception of electricity, for which the Italian residual grid mix was used.
During data collection, a cut-off criterion of 1% in weight was applied to those components expected to have negligible importance in the accounting of the overall embodied carbon emissions. By doing so, minor impacts are excluded and the system boundaries are better defined.

4.2 Raw materials and manufacture

The beginning of the whole life cycle is defined by the extraction and processing of the various raw materials succeeded by the manufacturing phase which determines the device sub-components' creation. WEPA system is mostly composed by carbon steel, material of the hull and of other internal components such as the shaft, the brackets and the screws, cement, used for the device ballast and reinforced concrete used for the dead weights.
All steel components were approximated with the flow "Steel cold rolled (St)" given by the database. This flow is a perfect fit for the external hull parts but represents a conjecture for other elements. The "Steel billet" flow would have been more appropriate but the only process connected to it involved a gate-to-gate analysis, without considering therefore the cradle part describing all the extraction and processing of iron ore (ferrite). The general processes related to the steel processing involved milling, turning, sandblasting and welding. Being not present in the database, the energy consumption for each of these processes was gathered from literature and implemented in the software in terms of electrical and thermal energy consumed. The electrical consumption was modelled with the "Electricity" flow and the related provider chosen was "Residual grid mix, consumption mix, to

consumer, AC, technology mix, 1kV - 60kV - IT" while the thermal consumption was modelled with the "Thermal energy (MJ)" and the related provider chosen was "Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning, MJ, 100% efficiency - EU-28+3".

The amount of steel used as input was increased by a 20% in weight in order to take into account the scrap rate.

For the ballast the "Portland cement" flow was used without the need of adding further processes while for the reinforced concrete a new process had to be created, involving four different material flows: Clay brick (pored), Concrete C20-25, Solid construction timber (15% moisture) and Steel cold rolled (St). An amount of energy consumption was also considered for the elements assembly and processing of steel.

In order to better visualize the various components materials provided by the manufacturer, a mass-based analysis was performed and shown in the figures below.

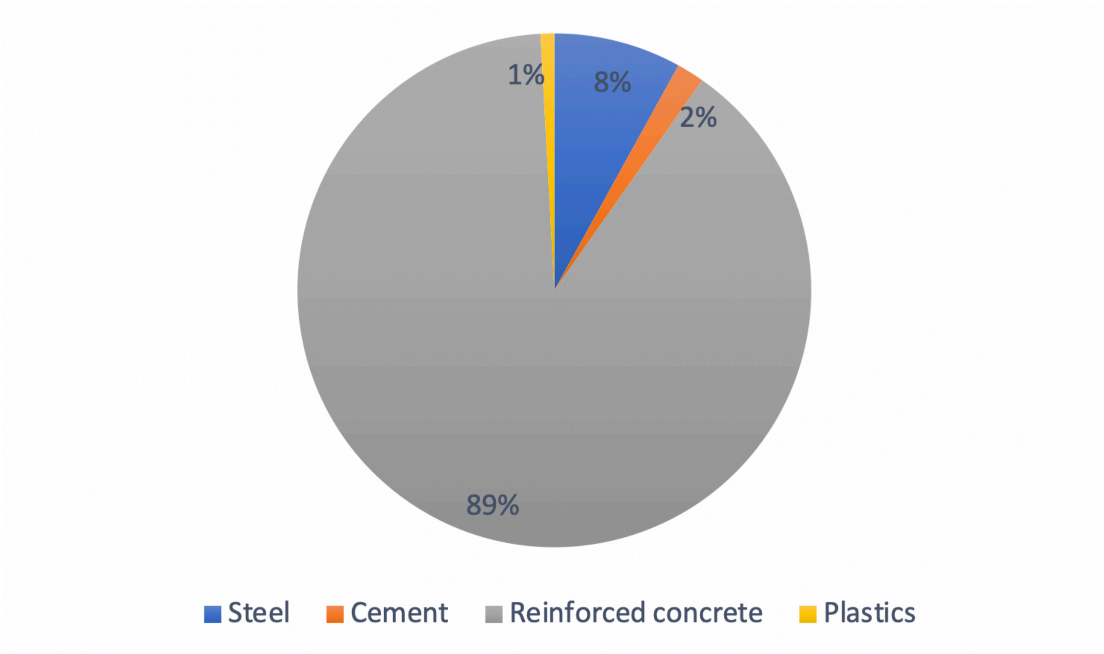


Figure 4.1: WEPA global system material quantities

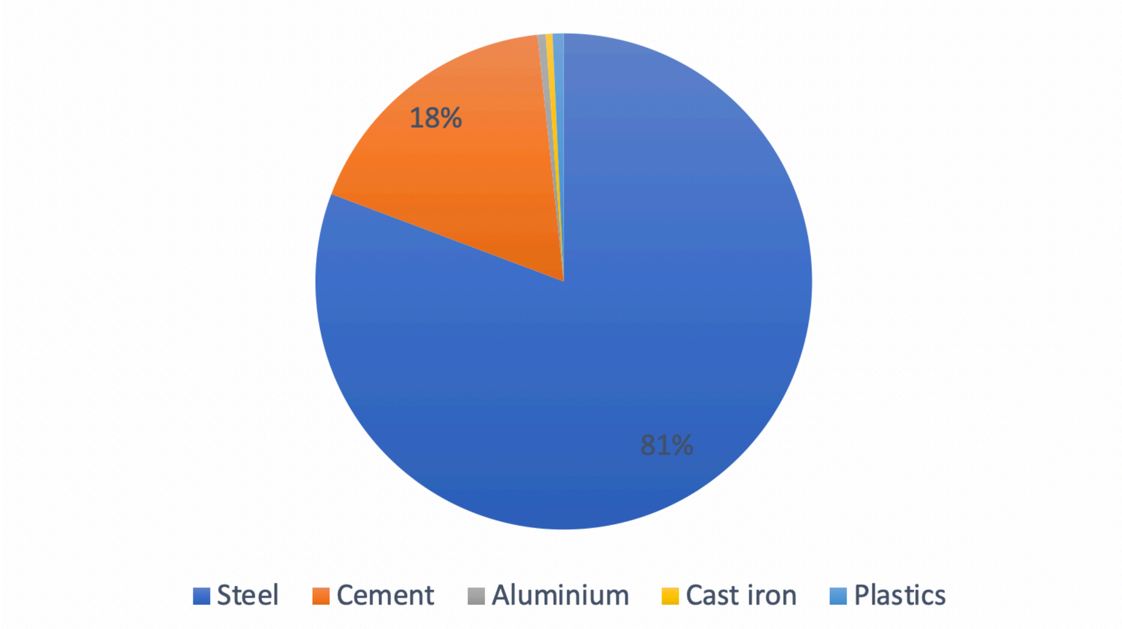


Figure 4.2: WEPA buoy material quantities

4.3 Buoy structure

The buoy structure is mainly made of carbon steel (6900 kg) and cement used as ballast (1598 kg), but also by other materials such as tempered steel, hardened steel, aluminium, cast iron, VITON FKM rubber, PTFE and Dyneema. Paint is also added in order to avoid corrosion and accounts for 60 kg. Both the buoy hull and its mechanical power take off are assembled in a workshop near Turin.

In OpenLCA the buoy structure was modelled breaking it down into three main parts:

- Hull: composed of carbon steel, cement, VITON FKM. The steel was modelled as explained before and the processes of milling, welding and sand blasting were taken into account (24, 25). For milling and sandblasting a consumption of 2.26 MJ_{el}/kg and 0.83 MJ_{el}/m^2 was considered respectively, while the energy needed for welding was estimated assuming a welding velocity of 70 cm/min, 6 kW of power consumption and 189 m of welding distance (other 11 m will be needed to join the hull to the other buoy components). The VITON FKM was modelled using the "Polyvinylidenfluoride (PVDF)" flow and considering a consumption of 0.5 MJ_{el}/kg and 1.2 MJ_{heat}/kg for the extrusion process. The cement was modelled as explained before and no further process was implemented.
- PTO drum assembly: composed of carbon steel, hardened steel, aluminum, "politetrafluoroetilene (PTFE)" and dyneema. Carbon and hardened steel were modelled with

the same steel flow and processes used in the hull. Aluminum was modelled with the "Aluminum ingot" flow and the processes of milling and turning were added. The latter was considered because it is needed to produce the drum and its energy consumption is equal to 3.31 MJ_{el}/kg. Dyneema and PTFE were modelled with the flows "Polyethylene terephthalate compound (PET)" and "Polytetrafluoroethylene granulate (PTFE)" respectively. For both, the energy associated to the extrusion process was considered.

- Spring group: composed of carbon steel and tempered steel. Both steels were modelled as "Steel cold rolled" and the milling process was implemented.

The paint weight added to the buoy internal and external surfaces was estimated knowing the density of each type of paint component, its thickness and the total surface area, equal to 127 m^2. The paint was modelled through the flows "Epoxy resin" and "Acrylic resin; technology mix; production mix, at plant; without butylacetate".

In the buoy structure there is also glycolated water and desalinated water for a total of 90 kg. These two were modelled using "Ethylene glycol" and "De-ionized water" flows.

4.4 Generator

The electrical generator connected to the mechanical PTO is the 1FW3204-1CE62-5AH0, composed by 254 kg of electrical steel, 21 kg of copper windings and 9 kg of neodymium magnets. The electrical steel was once again modelled using the "Steel cold rolled (St)" flow and the processes of milling and turning were considered. The copper windings were approximated with the flow "Copper sheet" instead of "Copper wires" because in the latter the process considered was not cradle to gate. The process taken into account was steel extrusion. Neodymium instead, being only present as an elementary flow and not having any process connected was substituted with magnetite. This change can be justified since its weight is quite negligible with respect to the whole device mass.

4.5 Auxiliaries

The auxiliary components include two types of battery, the LiNMC PJO-440-050-TDG battery and the lead VRLA rechargeable battery, together with a desalination system (Schenker smart100), a wind turbine, a photovoltaic panel and all the electronic components. All these components are bought from the respective producers and installed in the device during the assembly done at a workshop near Turin.

The LiNMC battery was modelled following an LCA tutorial provided by professor Blengini of PoliTo on a similar type of battery. The analysis started from the production of lithium manganese oxide and lithium nickel cobalt manganese hydroxide, components of the cathode, together with the production of graphite for the anode and ethylene carbonate and lithium hydroxide for the electrolyte. Following, the battery cell and the battery pack, taking into account all the necessary electronics were modelled. The VRLA rechargeable battery was instead modelled with the already existing flow “Lead acid battery 1.5-5kVA”.

The wind turbine, the PV panel and the electronics were neglected from the analysis because of the cut off criterion. On the other hand, their energy production will be estimated and taken into account.

4.6 Moorings

WEPA's mooring system features three mooring lines, connected directly to the device and arranged at 120° to each other. Each line consists of an elastic part that allows WEPA to move freely and a synthetic one of greater rigidity that allows station keeping of the system in adverse weather conditions. A jumper separates the elastic line from the synthetic line giving a neutral buoyancy to the mooring line. Each line is connected to a gravity anchor at the end. At the mooring center, there is a rigid synthetic line that is used for power generation, connected with one end to the generator and the other end to the seabed via a dead weight.

The components of the three mooring lines comprise a Seaflex elastic line, a polyester rope, a jumper and a synthetic tether, which are all manufactured in Sweden and transported directly to Porto Conte in Sardinia. In openLCA they are modelled as polyester polyols and polyethylene terephthalate compound (PET). The dead weights, made of reinforced concrete and accounting for the majority of the system weight (81900 kg) are fabricated directly on site and modelled as described before.

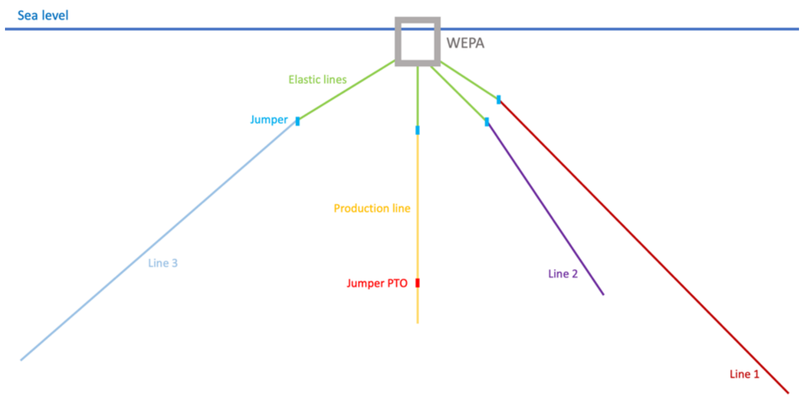


Figure 4.3: Moorings design

Table 4.1: Breakdown of WEPA materials

Type of material/process	Value	U.M.
Buoy structure		
Carbon steel	6900	kg
Tempered steel	94.4	kg
Hardened steel	94.6	kg
Aluminum	48.3	kg
Cast iron	40.1	kg
Concrete	1598	kg
VITON FKM rubber	2.8	kg
AWC400 (PTFE) carbon and graphite	0.7	kg
Dyneema	2.3	kg
Paint	60	kg
Arc welding	102.8	MJ
Sandblasting	105.3	MJ
Milling	2.3	MJ/kg
Turning	3.3	MJ/kg
Extrusion	1.7	MJ/kg
Generator		
Electrical steel	254.5	kg
Copper windings	21.2	kg
neodymium magnet	9.3	kg
Milling	2.3	MJ/kg
Turning	3.3	MJ/kg
Extrusion	1.7	MJ/kg
Mooring		
Reinforced concrete	81900	kg
Steel	14.8	kg
Plastic	160	kg
Dyneema	0.9	kg
Polyester	564	kg

4.7 Transports

The components of WEPA have various manufacturing locations, however the processes already available in the database consider the specific situation in Europe with average transport distances. Therefore, no further consumptions due to transport were added in the modelling of the life cycle.

The only transport that was taken into consideration was that of WEPA, already assembled, from Turin to Porto Conte. Firstly the transport by truck from Turin to Genoa was modelled with the process “Articulated lorry transport, Total weight >32 t, mix Euro 0-5, consumption mix, to consumer, diesel driven, Euro 0 - 5 mix, cargo, more than 32t gross weight / 24,7t payload capacity - EU-28+3”, then the transport by ship was modelled with “Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO”.

4.8 Operation and maintenance

WEPA transport from the port of Porto Conte to the installation site is assumed to happen through a workboat consuming 1490 L of diesel per day. Considering a cruising speed of 3 knots, a distance of 5.44 km and a total of 12 trips to be done (11 for the dead weights and moorings and 1 for WEPA device), a whole day will be needed just to transport the various objects. Estimating other six days of operation to place the moorings and attach the device, a total of seven days is needed for the installation stage. However, during these last six days, the boat will not have to commute anymore, therefore the fuel consumption could be considered negligible. This process is modelled with the flow “Barge, consumption mix, to consumer, technology mix, diesel driven, cargo, 1500 t payload capacity - EU-28+3”.

For what concerns operation and maintenance, during WEPA’s estimated lifetime of 20 years, control inspections are assumed to be planned once every year, for a total of 20 hours of sea vessel active operation and an equivalent fuel consumption of 800 L of diesel (40 L/hour) (23). In this case the consumption is lower than the one considered for the installation stage because the boat used for inspection will be smaller in size and, not needing to tow any device, will require less trust power. It is also assumed that WEPA integrity will be well kept during its whole operation, without the need of primary replacements or repairs.

4.9 End of Life

WEPA decommissioning will approximately require the same energy needed for its installation because the sea vessel utilized and its fuel consumption are considered to be the same. The device will be disconnected and towed back to the port together with the dead weights which can be later used again for other purposes.

Concerning the disposal, up to now just few studies considered the disposal and decommissioning of a wave energy converter. Taking into consideration (24) and its similarities with WEPA both in terms of material composition and weight, the same assumptions regarding the recycling, incineration, landfill and reuse are made.

A recycling rate of 100% was applied to steel components. However, considering an annual corrosion rate of 0.75% in weight during the whole service life of 20 years, 15% of steel will be corroded (24). Concrete and reinforced concrete present the same percentage of deterioration rate, however they cannot be recycled but only reused.

Regarding the other materials composing the device structure, their recycling, incineration, landfill and reuse rates are summarized in the table below.

Table 4.2: WEPA disposal routed (24)

Material	Recycling %	Incineration %	Landfill %	Reuse %
Ferrous metals (buoy)	85	0	0	0
Ferrous metals (other)	90	0	10	0
Non-ferrous metals	95	0	5	0
Plastics	80	20	0	0
Composites	0	100	0	0
Cement	0	0	0	85
Reinforced concrete	0	0	0	85

Chapter 5

5 Life cycle impact assessment

The impact assessment method used is Environmental Footprint (Mid-point indicator) which takes into account 19 impact categories. In the table below all the latter are listed, together with their respective indicator.

Table 5.1: Environmental footprint categories and indicators

EF impact categories	EF impact category indicators
Acidification	mol H+ eq
Climate change	kg CO2 eq
Climate change-Biogenic	kg CO2 eq
Climate change-Fossil	kg CO2 eq
Climate change-Land use and land use change	kg CO2 eq
Ecotoxicity, freshwater	CTUe
Eutrophication marine	kg N eq
Eutrophication, freshwater	kg P eq
Eutrophication, terrestrial	mol N eq
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Ionising radiation, human health	kBq U-235 eq
Land use	Pt
Ozone depletion	kg CFC11 eq
Particulate Matter	disease inc.
Photochemical ozone formation - human health	kg NMVOC eq
Resource use, fossils	MJ
Resource use, minerals and metals	kg Sb eq
Water use	m3 depriv.

5.1 Comparison with Recipe

In the majority of the life cycle assessment studies another impact assessment method is used: Recipe (Mid-point indicator). Therefore, in order to later compare the results of this study with the others found in the literature is necessary to evaluate similarities and discrepancies between the two impact assessment methods. Concerning Recipe, its impact categories are summarized in the table below.

Table 5.2: Recipe categories and indicators

Recipe impact categories	Recipe impact category indicators
Terrestrial acidification	kg SO2 eq
Global warming	kg CO2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Freshwater ecotoxicity	kg 1,4-DCB
Marine ecotoxicity	kg 1,4-DCB
Terrestrial ecotoxicity	kg 1,4-DCB
Human carcinogenic toxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB
Ionizing radiation	kBq Co-60 eq
Land use	m2a crop eq
Stratospheric ozone depletion	kg CFC11 eq
Ozone formation, Human health	kg NOx eq
Ozone formation, Terrestrial ecosystems	kg NOx eq
Fine particulate matter formation	kg PM2.5 eq
Fossil resource scarcity	kg oil eq
Mineral resource scarcity	kg Cu eq
Water consumption	m3

The main differences between the two impact assessment methods are:

- The number of categories taken into account. Recipe considers 18 of them, while Environmental footprint 19. In fact, while the former only considers one parameter for climate change, the latter distinguishes between biogenic, fossil and land use change. Furthermore, EF does not consider marine ecotoxicity. The remaining parameters are instead very similar.
- The units of measurement. While in the Environmental footprints method acidification, freshwater ecotoxicity, human toxicity, ionizing radiation, land use, ozone formation, particular matter format, fossil fuel use, mineral resource use are respectively measured in mol H+ eq, CTUe, CTUh, kBq U-235 eq, Pt, kg NMVOC eq, disease inc., MJ, kg Sb, in Recipe they are assessed as kg SO_2 eq, kg 1.4-DCB, kg 1.4-DCB, kBq Co-60 eq, m^2a crop eq, kg NOx, kg PM2.5 eq, kg oil eq, kg Cu eq.

5.2 Results

Table 5.3 summarizes WEPA environmental impacts. The main parameter is the global warming potential, expressed as climate change, accounting for 448.9 $gCO_2\,eq/kWh$, of which 99.9% has a fossil origin. Another important parameter is the fossil resource use, accounting for 4657 kJ/kWh, because of its similarity with the cumulative energy demand (CED) presented in many other studies. The only difference is that the latter takes also into account nuclear and renewable energies (biomass, wind, solar and geothermal).

Table 5.3: LCA results

Impact categories		
Acidification (A)	1.250 E-3	mol H+ eq/kWh
Climate change (CC)	448.9	g CO_2 eq/kWh
Climate change-Biogenic (CC b)	0.2079	g CO_2 eq/kWh
Climate change-Fossil (CC f)	448.4	g CO_2 eq/kWh
Climate change-Land use and land use change (CC l)	0.3598	g CO_2 eq/kWh
Ecotoxicity, freshwater (F Eco)	4.487 E-2	CTUe/kWh
Eutrophication marine (M Eut)	2.648 E-4	kg N eq/kWh
Eutrophication, freshwater (F Eut)	-1.040 E-5	kg P eq/kWh
Eutrophication, terrestrial (T Eut)	2.870 E-3	mol N eq/kWh
Human toxicity, cancer (HT c)	1.551 E-9	CTUh /kWh
Human toxicity, non-cancer (HT nc)	5.988 E-8	CTUh/kWh
Ionising radiation, human health (IR)	1.573 E-2	kBq U-235 eq/kWh
Land use (L)	94481	Pt/kWh
Ozone depletion (OD)	4.640 E-10	kg CFC11 eq/kWh
Particulate Matter (PM)	3.093 E-08	disease inc./kWh
Photochemical ozone formation - human health (POF)	8.719 E-4	kg NMVOC eq/kWh
Resource use, fossils (RU f)	4657	kJ/kWh
Resource use, minerals and metals (RU m)	9.634 E-6	kg Sb eq/kWh
Water use (W)	0.7512	m3 depriv./kWh

To better comprehend the results, the contribution of the major life cycle steps to each impact category was analyzed and presented in figure 5.1. The steps are differentiated into manufacturing and assembly of the buoy structure and moorings, transport and installation, operation and maintenance, disposal.

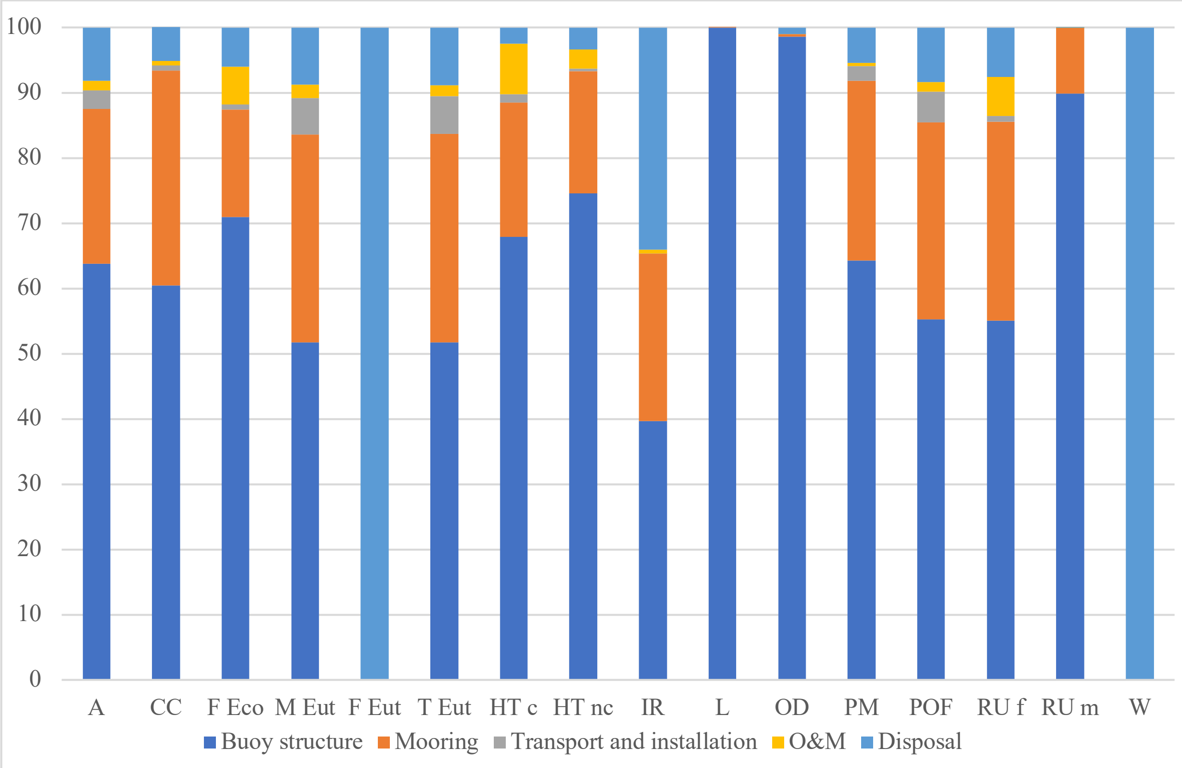


Figure 5.1: Effect of the different life cycle stages on the EF impact categories

In the majority of the cases, the most impactful stage is the manufacturing and assembly of the buoy structure, contributing to 60% of the CO_2 equivalent emissions and to 55% of the energy needed. In particular, the process that shows the highest impact is the production of steel, which determines 47% of the GHG emissions and consumes 39% of the energetic resources.

The second most impactful stage is determined by the production of the moorings, contributing to 34% and 31% of the climate change and resource use categories. In this case, almost the totality of the impact is given by the production of reinforced concrete used for the dead weights which accounts for the majority of the weight. The only exceptions are represented by the ionizing radiation and ozone depletion categories, in which the moorings production is less impactful that the device disposal.

The transport and installation stage is instead almost irrelevant in most impact categories, apart for the marine and terrestrial eutrophication in which reaches values slightly higher that 5%. As the latter, the device operation and maintenance are also not that relevant overall, apart for the human toxicity category in which contributes to the 8%. It also exceeds the 5% threshold in the categories of freshwater ecotoxicity and fossil resource use.

The device disposal shows significant contributions in the ionizing radiation category, in which contributes to more than a third of the kBq U-235 eq emissions. It also contributes to almost the totality of water use and freshwater eutrophication impacts. This is especially due to specific processes needed to recycle the lithium battery, such as the sodium hydroxide and copper cathode production.

5.3 Carbon and energy pay back times

Among the parameters that define the quality of a renewable energy technology, the CO_2eq payback time and the energy payback time play a major role. The former represents the period of time needed by the system to counterbalance the emissions caused by its life cycle. The latter instead indicates the period of time needed by the system to produce the same amount of energy used during its life cycle. These two parameters are computed with the following expressions (25):

$$CO_2eq\ payback\ time = \frac{Total\ CO_2eq\ emissions\ during\ the\ life\ cycle}{Annual\ CO_2eq\ avoided}$$

WEPA total emissions amount to 52109 $kg\ CO_2eq$. Considering then that the Italian residual grid mix has a carbon intensity of 0.549 $kg\ CO_2eq/kWh$, and that the total annual energy production is 5803 kWh, the CO_2eq payback time is 16.36 years.

$$Energy\ payback\ time = \frac{Energy\ spent\ during\ the\ life\ cycle}{Annual\ energy\ produced}$$

Approximating the total energy spent during WEPA life cycle with the result obtained from the "Resource use, fossil" impact category, the value to be considered is 540552 MJ, which corresponds to 150153 kWh. Considering then the value of annual energy production stated before, the energy payback time amounts to 25.88 years.

5.4 Improvement potentials and sensitivity analysis

The most important improvement potentials regard the enhancement of the system reliability and energy conversion efficiency. By doing so, its lifetime could be extended and more electric energy could be produced. These two factors together would be responsible for the increase of energy delivered during the whole lifetime and would determine a reduction of the impact on climate change.

Another way to lower the latter can be achieved by substituting the buoy materials with others less impactful and by employing alternative and more environmentally friendly means of transport.

Starting from the device lifetime, a sensitivity analysis can be performed in order to assess the variation of carbon and energy intensities related to the increase of operational time.

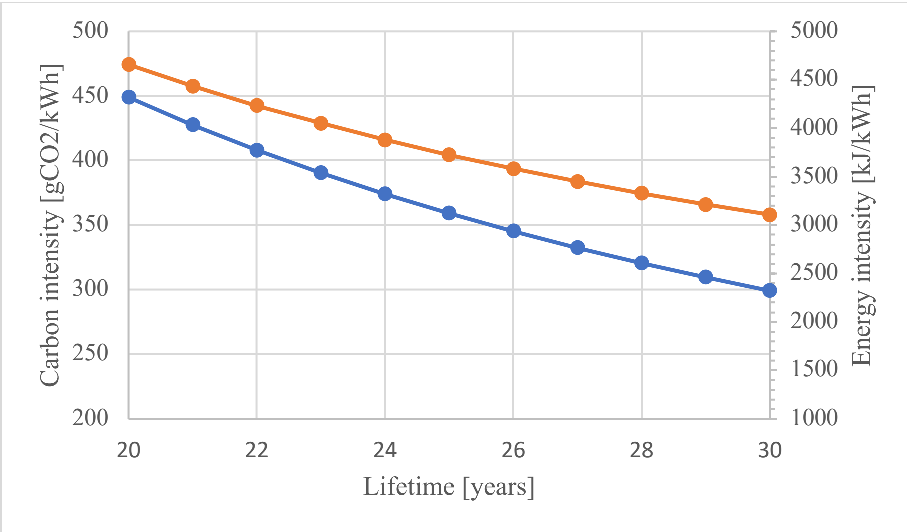


Figure 5.2: Carbon intensity in blue and energy intensity in orange as function of WEPA lifetime

As predicted, the higher is the number of years, the lower are the values of carbon and energy intensity. With a hypothetical lifetime of 30 years, only 299 $g\ CO_2 eq/kWh$ are emitted and the value of energy needed goes down to 3105 kJ/kWh.

Concerning instead the variation of the annual energy produced, a sensitivity analysis will be performed in chapter 10, where the productivity in other potential sites of installation is evaluated.

Focusing now on the choice of alternative materials, able to maintain the same mechanical properties, the best options available on the Environmental footprint database are the stainless steel and the recycled carbon steel. The former, however, due to its chromium rich composition, shows much higher values of carbon intensity whit respect to the already employed material. Recycled carbon steel presents instead values of carbon intensity as low as one fifth of that of normal carbon steel. Considering the result obtained before that showed how steel alone contributes to 47% of the totality of GHG emissions emitted during the life cycle, if the recycled one was employed, the grams of CO_2 equivalent emitted per kilowatt-hour would go down to 280. The energy intensity would reach 2940 kJ/kWh.

About transports, a possible alternative scenario involves the use of electric or hydrogen driven lorries and boats. However, the only transportations that could be changed are those from Turin to Porto Conte and from Porto Conte to the installation site. The others are already considered in the processes of manufacturing and assembly of most of the materials and cannot be changed by the software. This alternative scenario would determine a 2% and 7.5% decrease respectively of the carbon and energy intensity.

Putting together all the alternative scenarios previously presented, the values of carbon and energy intensity would be 185 $g\ CO_2eq/kWh$ and 1792 kJ/kWh.

5.5 Comparison with other ocean energy technologies

Life cycle assessment studies have been applied to other ocean energy technologies. Focusing on the wave and tidal energy converters and considering as reference parameter the $g\ CO_2eq/kWh,$ the following results can be reported (7).

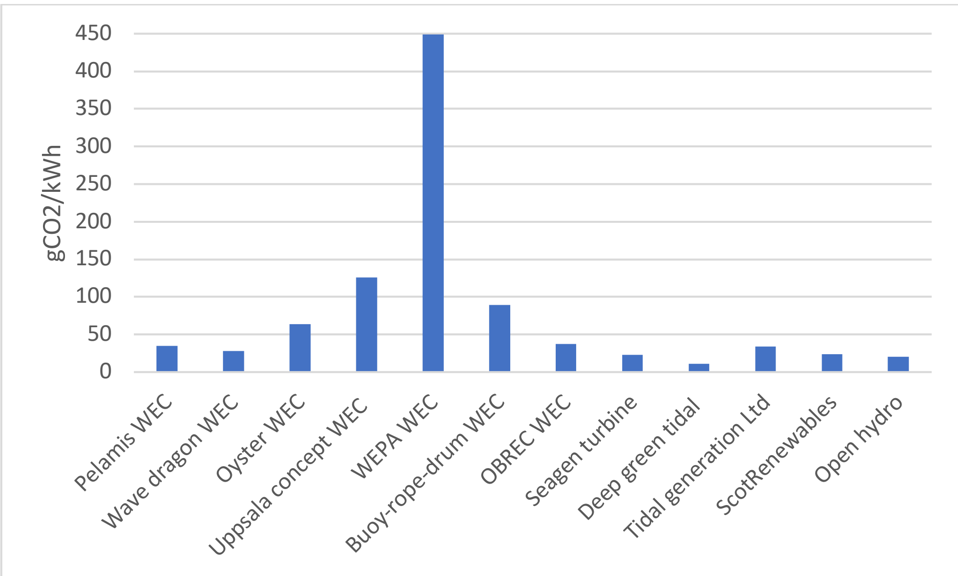


Figure 5.3: Carbon footprints of some ocean energy technologies (7)

Among these ocean energy technologies, the least impactful in terms of greenhouse gases emissions are the tidal ones, reaching values as low as 11 gCO_2/kWh. Concerning the wave energy converters, instead, much higher values are reached, especially in the case of point absorber devices, as shown by the Uppsala concept WEC, with 126 gCO_2/kWh, and by the Buoy-rope-drum WEC, with 89 gCO_2/kWh. The latter, especially, is of relevance because of its mechanical and electric similarities with WEPA and helps to understand why WEPA carbon footprint is much higher than similar devices. The Buoy-rope-drum WEC is mostly composed by steel and reinforced concrete, like WEPA, but in different quantities. In specific, it has 5500 kg of steel and 37000 kg of concrete in excess. However, it produces 35 MWh/y of electricity, six times more than WEPA and this is the main reason why it presents lower values of carbon emissions per kilowatt-hour. In fact, if WEPA had the same productivity, its emissions would go down to 74 gCO_2/kWh, in line with the other studies regarding point absorbers.

Chapter 6

6 Wave energy parameters

6.1 Regular waves

Waves can be defined as regular or harmonic when they show a purely sinusoidal pattern with constant parameters such as period, amplitude and length. Their characteristics can be investigated by analyzing two different perspectives, as shown in figure 6.1. The first represents a snapshot of the wave profile in space in which the abscissa indicates the direction of propagation and the origin of the axis is located at the still water level. The highest point of the wave is the crest, the lowest is the trough and their difference represents the wave height, H. Half of the latter is instead the wave amplitude, ζ_0. The horizontal space between two subsequent wave crests is the wavelength, λ, and d stands for the water depth. The second perspective represents the wave propagation in time, in which, as before, the origin of the coordinate system is still at the average water level. In this case, the difference along the abscissa between two equal points on successive waves is called period, T. Other important parameters that can be derived by the ones just described are: the wave steepness, $\frac{H}{\lambda}$, the wave number, $k = \frac{2\pi}{\lambda}$ [rad/m], the wave angular frequency, $\omega = \frac{2\pi}{T}$ [rad/s], the wave frequency, $f = \frac{1}{T}$ [Hz], the wave crest/phase speed, $c = \frac{\omega}{k} = \frac{\lambda}{T}$ [m/s] (26).

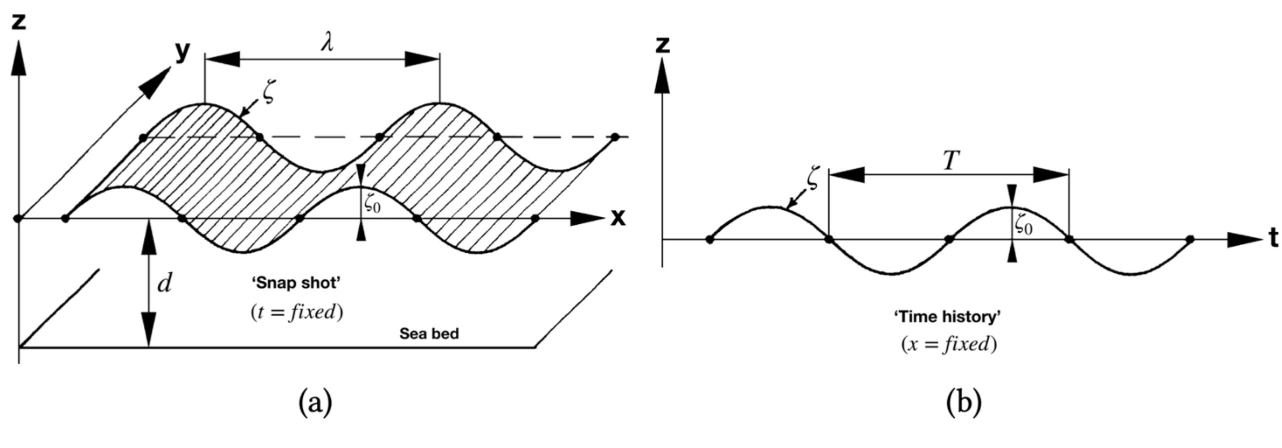


Figure 6.1: a) Wave profile in space. b) Wave propagation in time (26)

Knowing all the necessary parameters in time and space, the equation of motion of the wave can be now defined:

- $\zeta = \zeta_0 \cos(kx - \omega t)$ if the wave propagates in the positive direction.
- $\zeta = \zeta_0 \cos(kx + \omega t)$ if the wave propagates in the negative direction.

6.1.1 Regular wave energy and power

The total energy of a wave is given by the two different contributions: potential and kinetic energy.

The former is computed as follows:

$$P = \frac{1}{2}\int_0^{\lambda} \rho g \zeta^2 \, dx = \frac{1}{4}\rho g \zeta_a^2 \lambda$$

Expressing it per unit horizontal sea surface area:

$$P = \frac{1}{4}\rho g \zeta_a^2$$

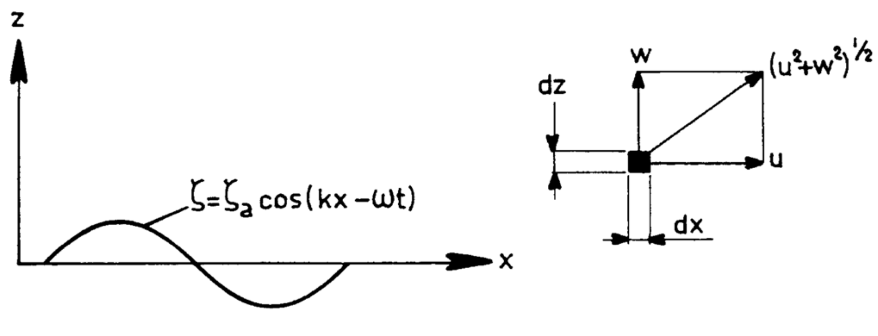


Figure 6.2: Kinetic parameters (26)

Considering figure 6.2, the kinetic energy is computed in the following way:

$$K = \int \frac{1}{2}(u^2 + w^2)\, dm$$

In which “u” and “w” are respectively the horizontal and vertical components of the wave velocity, “dm” is instead the infinitesimal mass of the portion on wave considered.

By applying various trigonometric equations, the final result is the same as the one obtained for the potential energy:

$$K = \frac{1}{4}\rho g \zeta_a^2$$

The total energy is therefore:

$$E = \frac{1}{2}\rho g \zeta_a^2 = \frac{1}{8}\rho g H^2$$

After evaluating the wave energy, its flux across a plane perpendicular to the direction of propagation can be computed. This can also be described as the mean work performed over a wave period and is therefore the wave power.

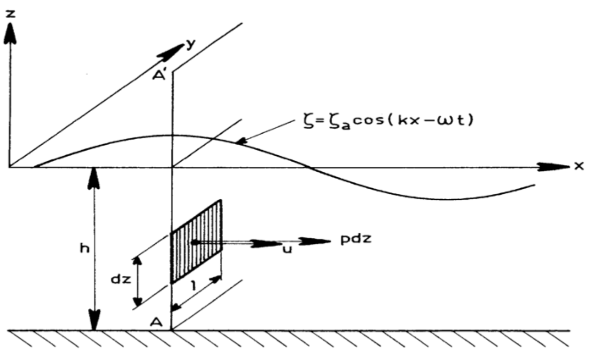


Figure 6.3: Transport of wave energy (26)

Considering figure 6.3, the expression needed is:

$$P = \frac{1}{T}\int_{t}^{t+T}\int_{-h}^{0} p\, u\, dz\, dt$$

In which "p" is the fluid pressure.

By preforming some mathematical steps, the final equation is:

$$P = \frac{1}{8}\rho g H^2 \frac{c}{2}(1 + \frac{2kh}{\sinh 2kh})$$

In the case of deep water, in which h >> λ:

$$c = \frac{gT}{2\pi} \text{ and } P = \frac{1}{8}\rho g H^2 \frac{c}{2}$$

Therefore:

$$P = \frac{1}{32\pi}\rho g^2 H^2 T \left[\frac{W}{m}\right] = 984\, H^2 T \left[\frac{W}{m}\right] \sim H^2 T \left[\frac{kW}{m}\right]$$

6.2 Irregular waves

After discussing the hypothetical case of regular waves, a more realistic scenario is analyzed. The sea surface is indeed irregular and can be approximated as the superposition of harmonic waves with different amplitude, period and direction (26).

To better comprehend the concept, an example of unidirectional superposition is shown in the figure below:

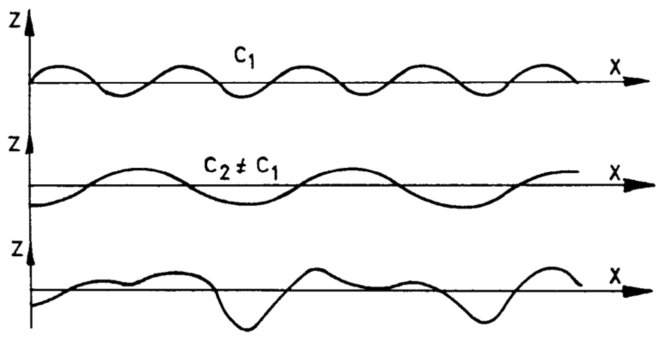


Figure 6.4: Wave superposition (26)

In the case of irregular waves, in order to evaluate the characterizing parameters of the waves, a statistical analysis has to be performed. Given a specific time history of a sea wave, as shown in figure 6.5, the average wave period, the mean wave height and the significant wave height can be computed. The latter, identified with the symbol $H_{1/3}$ *or* H_s , is defined as the mean of the highest third of the waves recorded. Another important parameter to be considered is the wave energy period, defined as the period of a harmonic wave that incorporates the same quantity of energy of the considered irregular wave (26).

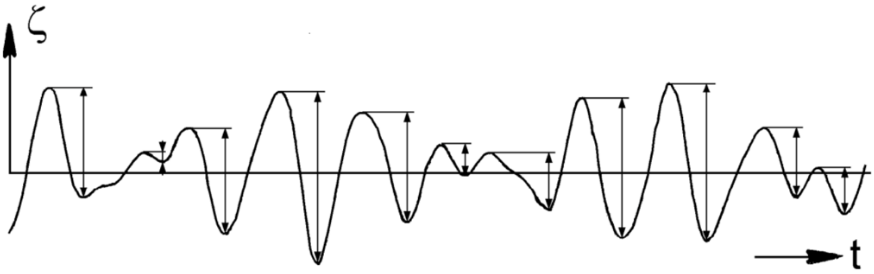


Figure 6.5: Sea wave time history (26)

Knowing the time history elevation of the sea surface, its energy density spectrum can be calculated through the Fourier analysis. By using the latter indeed, the history of an irregular wave profile in time domain can be broken down into a variety of regular waves, each with a specific amplitude, frequency and phase in the frequency domain. For each wave, these parameters can be then associated to the energy spectrum, $S_{\zeta}(\omega)$, as shown in figure 6.6 (26).

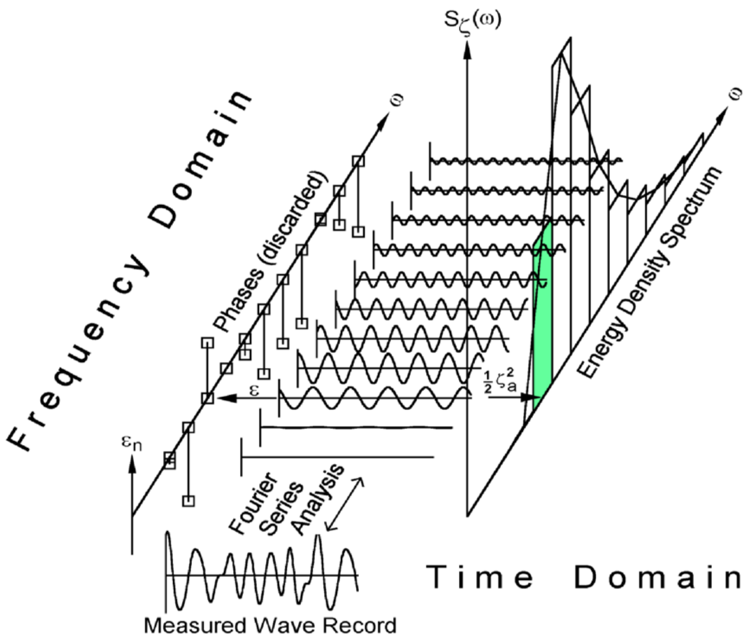


Figure 6.6: Energy density spectrum (26)

Given the energy density spectrum, by computing the different order moments of its area in the $\omega - S_{\zeta}(\omega)$ diagram using formula x, some important parameters needed to estimate the power produced by the irregular waves can be found.

$$m_n = \int_0^\infty \omega^n S_\zeta(\omega)\, d\omega$$

The significant wave height and the energy period are respectively defined as $H_s = 4\sqrt{m_0}$ and $T_e = \frac{m_{-1}}{m_0}$, in which the subscript numbers define the momentum order.

6.2.1 Irregular wave power

The power of an irregular wave can be computed as:

$$P = \frac{\rho g^2}{64\pi} H_s^2\, T_e \sim 0.5\, H_s^2\, T_e \left[\frac{kW}{m}\right]$$

These results show that both the powers embedded in the regular and irregular waves are proportional to the wave period and to the square of the wave height (26).

Chapter 7

7 WEPA productivity

WEPA productivity is obtained through a simulation tool developed by Wave for Energy together with MOREnergy lab, a research center of Politecnico di Torino. This tool uses a time domain mathematical model, built in Matlab-Simulink, based on the Linear Potential Flow Theory and able to simulate the dynamic response of the wave energy converter implementing the Cummins equation (27).

7.1 Linear Potential Flow Theory

The Linear Potential Flow theory is a typical approach for offshore structures analysis based on the assumptions of incompressible, irrotational flow and non-viscous fluid. According to this theory, the forces applied on a buoyant body result from the superposition effect of the pressures due to different wave fields:

- Incident or excited wave field (steady body in a wavy environment):
    - Froude-Krilov: represents the unsteady pressure field generated by undisturbed waves (28).
    - Diffracted: related to the phenomena that take place when a wave comes across an obstacle or opening. In detail it refers to the bending of the waves around the obstacle corners into its region of geometrical shadow. The diffracting object turns therefore into a secondary source of wave propagation (29).

- Radiated wave field (moving body in a non-wavy environment): indicates the disturbances created by the motion of the device without waves.

In the time domain, the dynamics of the buoyant body determined by the applied wave loads can be expressed thanks to the following formulation.

7.2 Cummins equation

The Cummins equation, also known as equation of motion, derives from the second principle of dynamics applied to an oscillating device:

$$m\,X''(t) = f_e + f_r + f_{st} + f_{viscous} + f_{PTO} + f_{moor}$$

Where:

- m: mass
- X'': acceleration
- f_e: wave excitation forces acting on the system
- f_r: force due to radiation phenomenon
- f_{st}: hydrostatic buoyancy force
- $f_{viscous}$: force due to viscous phenomenon
- f_{PTO}: total PTO force
- f_{moor}: mooring system pretension force

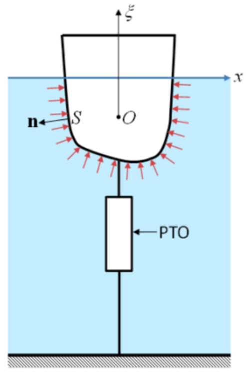


Figure 7.1: Simplified system scheme (34)

The radiation force can be divided into two elements proportional to the body acceleration (X'') and velocity (X'): $f_r = -A\,X'' - B\,X'$, where A is the added mass, indicative of the extra mass that the device seems to have when accelerated relative to an adjacent fluid and B is the radiation damping, representative of the damping experienced by the device when moving into the fluid.

The hydrostatic force is due to Archimedes' principle and its stiffness can be expressed as the ratio between the former and the displacement of the device: $K = \frac{dF_{st}}{dX}$.

Knowing these two formulations and substituting them into the second law equation, Cummins equation can be finally obtained:

$$(m + A)\, X''(t) \; + B\, X' + K\, X \; = \sum_{i=1}^{N} f_{ext,i}$$

Furthermore, considering that f_{PTO} can be modelled as $-B_{PTO}\, X' - K_{PTO}\, X$, in which B represents the PTO damping coefficient and K the PTO spring stiffness, and adding it to the previous equation, Cummins formulation becomes:

$$(m + A)\, X''(t) \; + (B + B_{PTO})\, X' + (K + K_{PTO})\, X \; = \sum_{i=1}^{N} f_{ext,i}$$

Therefore, it is evident that controlling the PTO behavior, also the device response and its power absorption can be modulated.

In order to obtain the final dynamic response of the floating body, the Cummins equation is written for all the six possible degrees of freedom of the floating body: three translations (surge, sway, heave) and three rotations (Roll, Pitch, Yaw) (27).

7.3 Modelling process

The full process of obtaining time-domain simulations involves different subsequent steps.

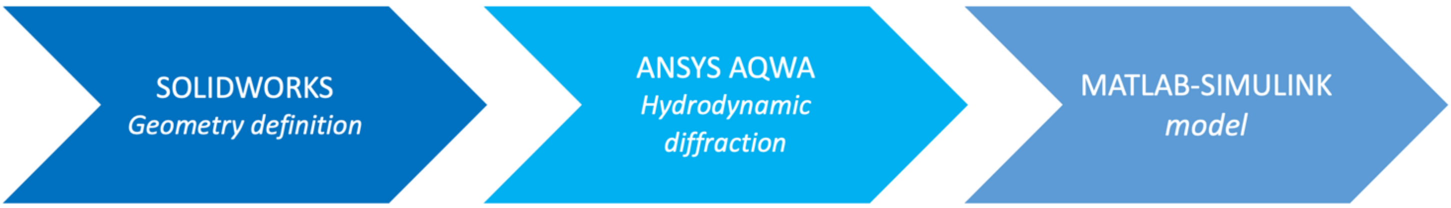


Figure 7.2: Modelling steps

7.3.1SolidWorks

The first step is determined by the modelling of WEPA geometry through SolidWorks, a parametric three-dimensional drawing and design software.

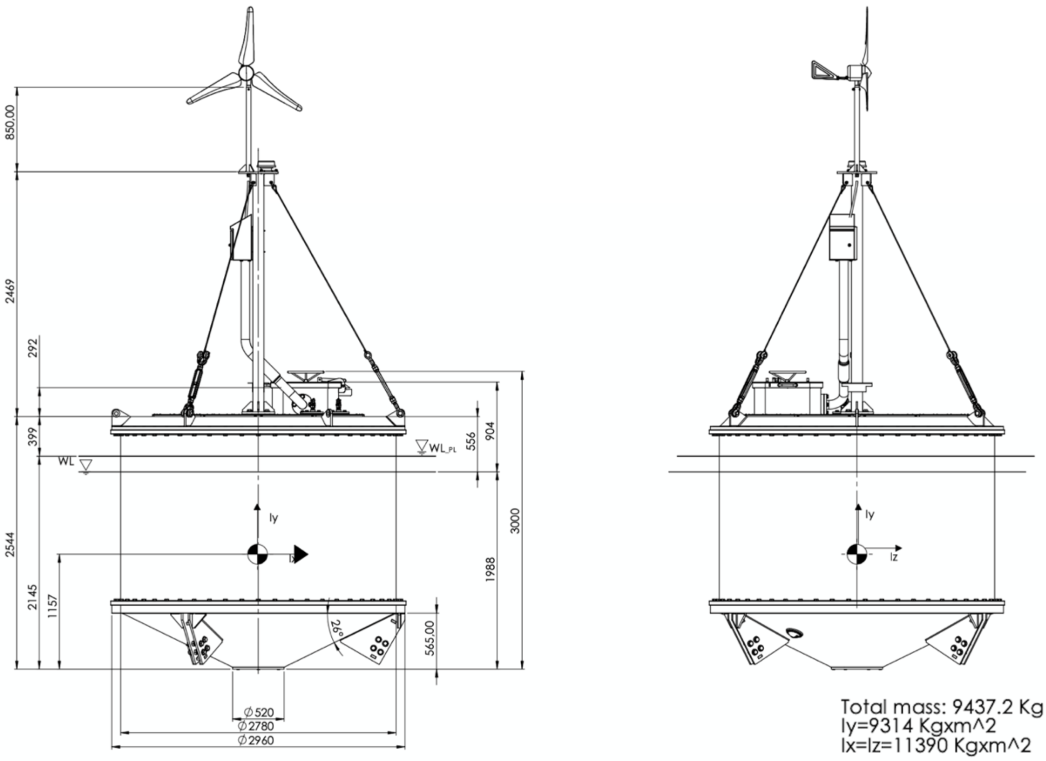


Figure 7.3: WEPA General System

The picture shows WEPA frontal and lateral views, in which the center of mass, the water line of the free buoy (WL) and the water line considering the attached mooring (WL_{PL}) are highlighted. WL_{PL} is higher than WL because the mooring has a preload that brings down the device. The mass and the inertia parameters of the whole system are also shown in the bottom right corner and all the dimensions are expressed in mm.

7.3.2 Ansys Aqwa

The second step is characterized by the implementation of WEPA geometry into ANSYS Aqwa, a hydrodynamics analysis tool which investigates the influence of waves, current and wind on buoyant or fixed offshore marine devices.

In detail, ANSYS Aqwa is a Boundary Element Method (BEM) software able to compute all the necessary hydrodynamic features: added mass, radiation damping and hydrostatic stiffness, which, if inserted into the Cummins equation, determine the dynamic behavior of a specific device.

By uploading WEPA properties into ANYS Aqwa software and using ANSYS hydrodynamic diffraction section, which performs a 3D wave radiation and diffraction investigation, the necessary hydrodynamic parameters are obtained.

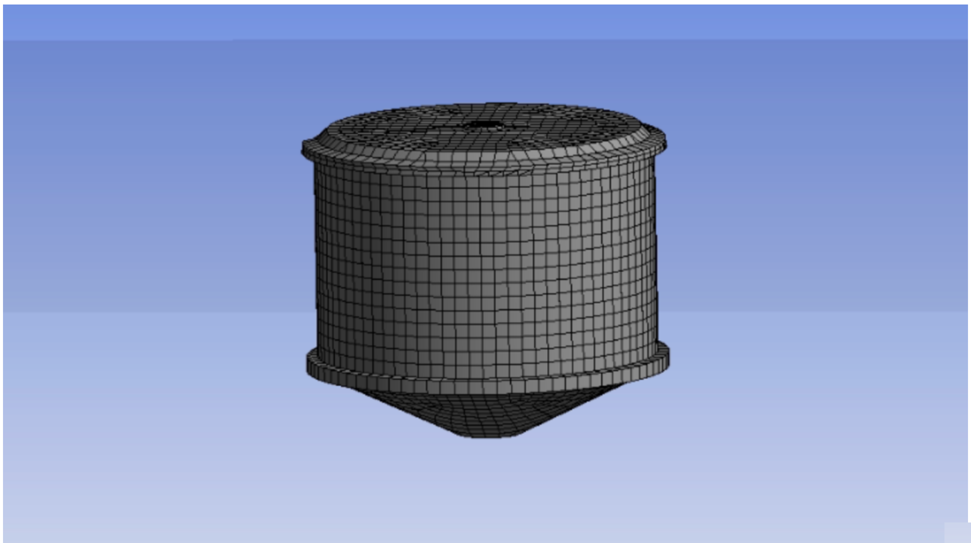


Figure 7.4: Mesh of WEPA device

The steps performed on ANSYS Aqwa are the following:

Firstly, ANSYS hydrodynamic diffraction is chosen among the different analysis systems available, and the file generated from SolidWorks is imported into the geometry section. The x-y plane, which identifies the sea level, is translated in order to be coincident with the water line represented on the SolidWorks scheme and the device is then divided in two parts according to the plane. The bottom part represents the submerged body subjected to the interaction with the waves.

Secondly, moving to the model section, the mass and the inertia values of the system are implemented (mass = 9437.2 kg, I_y= 9314 kg m^2, I_x= I_z =11390 kg m^2) together with the water depth of the installation site (25 m) which can be found among the environmental constants. Subsequently, a proper mesh has to be generated, that accurately captures the input domain geometry especially in those areas significant for the next computations.

Thirdly, going in the analysis setting section, the wave directions and frequencies of the specific site of installation are implemented.

Finally, the model results can be obtained in the solution tab and a ".LIS file" will be generated. The latter will be the input parameter of the Matlab-Simulink model, together with the irregular wave profile from the site-specific statistical data. For this purpose, all the necessary metocean environmental data were gathered and processed, and the heights, periods and occurrences of 224 possible waves were obtained. These 224 waves cover all the sea states that WEPA is statistically exposed to at the installation site.

7.3.3 Matlab-Simulink model

The model was developed using Matlab and Simulink in order to solve the equations of motion through numerical methods. The solver used is ode45, able to compute nonstiff differential equations.

The model was developed considering three of the six possible degrees of freedom. Heave, surge and pitch are indeed sufficient to simulate the performance of a point absorber wave energy converter in any type of sea state.

The results given by the model comprehend all device motions and forces for each time step of the simulation. Knowing the PTO damping coefficient, which is a control parameter, and the tether velocity, representative of the unwinding drum velocity, the power output can be computed according to the following expression:

$$P = \beta \cdot v^2 \ [W]$$

With:

P gross power

β PTO damping coefficient

V tether velocity

The yearly energy production of the device can be then calculated by summing up all the 224 contributions of the different possible sea states at the installation site. Each single contribution is simply obtained by multiplying the average wave power by its annual occurrence.

To better comprehend the model the two sections will be analyzed separately:

7.3.3.1 Simulink model

As shown in the picture below, the model uses as input parameters the incoming waves and the position of the hull in terms of surge, heave and pitch. In specific, these parameters can be represented by three forces: the force determined by the incident waves (Fw), the mooring forces (Fm) and the PTO forces (Fpto). The output is instead given by the new hull position which will be used as input in the next time step. Knowing WEPA location in each time step also other parameters such as the tether velocity can be computed.

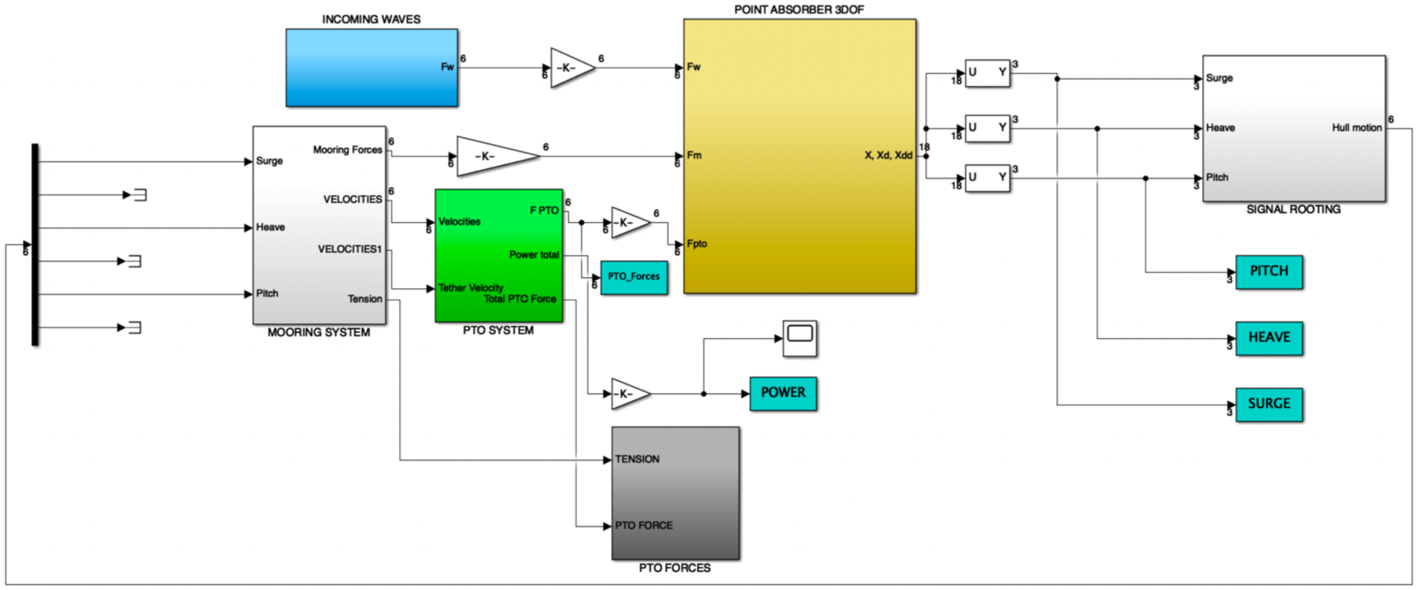


Figure x: Numerical model

In detail, the forces considered in Fw are the excitation ones, given by the superposition effect of pressure field generated by the undisturbed wave and the diffraction phenomenon. The other forces mentioned in the paragraph regarding the Cummins equation are instead function of the buoy velocity (radiation and drag forces) and of its position (hydrostatic forces). These parameters are well described in the pictures below.

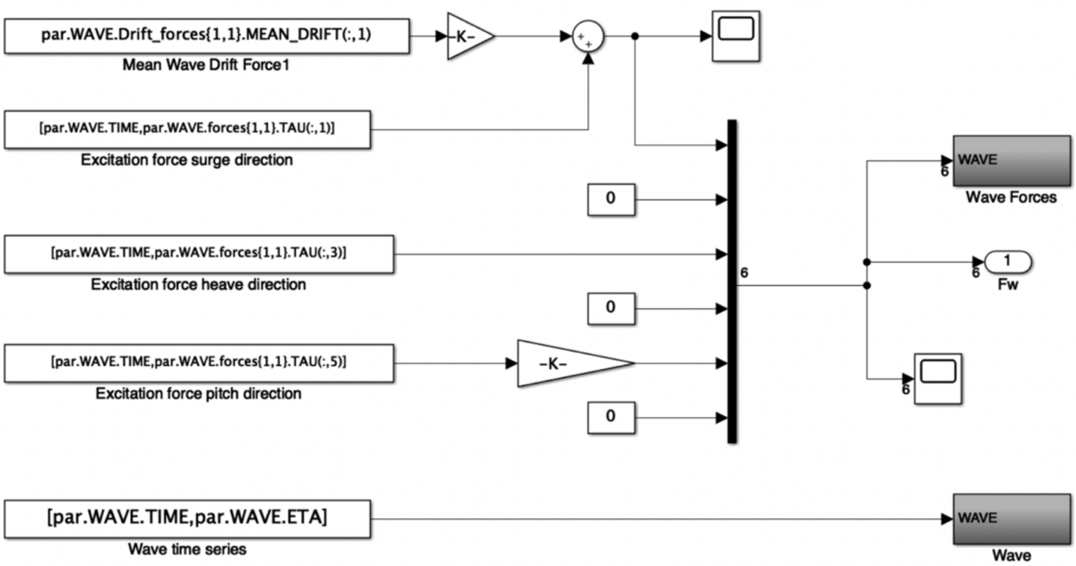


Figure 7.6: Section of wave force generation

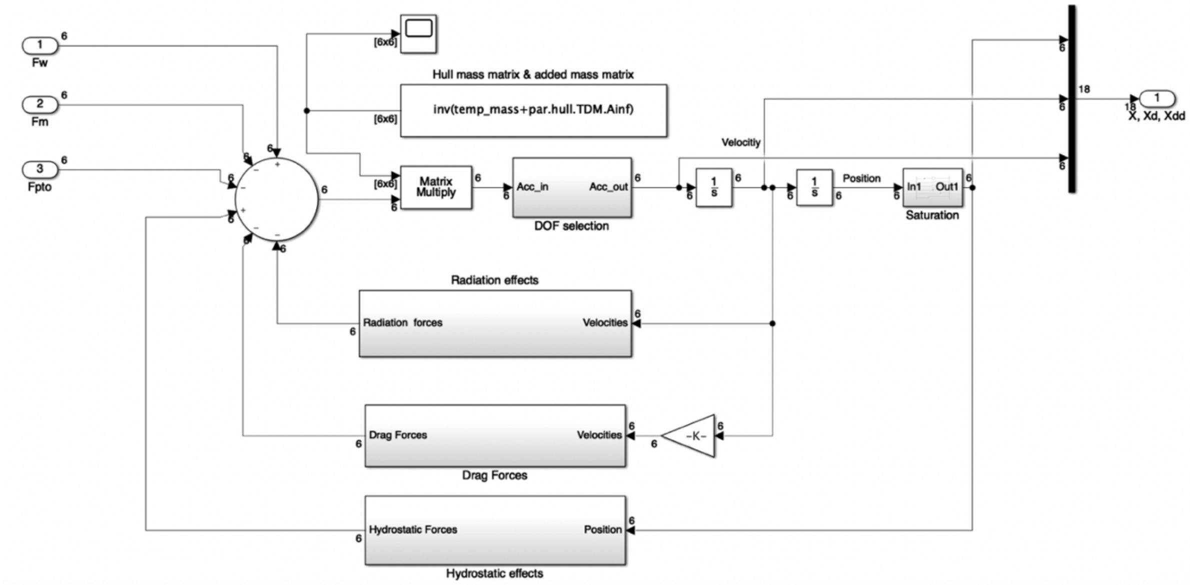


Figure 7.7: Section of numerical integration of the point absorber

7.3.3.2 Matlab script

The Matlab model can be divided in two parts: "pre-process" and "post-process"

7.3.3.2.1 Pre-process

The purpose of this section is to change the input .LIS file into a file that can be read by the model. In order to do so, a specific script able to read the .LIS file and extract the hydrodynamic parameters was developed. Other scripts were instead used to make some modifications to various parameters and rewrite them into a specific format.

In detail, the pre-process part is composed by three scripts:

- Launcher_READLIS.m: reads the .LIS file and puts it into a format that can be used for the rest of the program.
- SCRIPT_PerezLaunch: this script has to be run 5 times changing each time the indexes i and j for the definition of Kij (i and j =1 for the surge, i and j = 3 for the heave, i and j =5 for the pitch, i = 1 or 5 and j = 5 or 1 to couple surge and pitch).
- Build_Hull_3DOF_LAST.m: gives the final output (.mat file) which will be the input of the post-process part.

7.3.3.2.2 Post-process

The basic steps of this process involve many different Matlab files:

- SCRIPT_00_GeneraParametri_Final.m: builds another .mat file modifying the original one. The parameters regarding geometric characteristics, drag forces, mooring stiffness, inertia and PTO properties have to be checked and, if required, changed.
- SCRIPT_01_GeneraCelle_FW.m
- SCRIPT_02_MultiTask.m: launches the Simulink model and performs many simultaneous simulations with all the 224 waves considered in the scatter and all the possible damping coefficients.
- SCRIPT_03_RaggruppaCelle.m: groups all the previous results in the form of tables easier to understand.
- FUNC_05_Optimize_PA_Launcher.m: performs the analysis optimization choosing the best damping factors.
- SCRIPT_05_Optimize_PA.m: uses the results of the function to plot different graphs about gross power, gross energy, PTO and mooring parameters.

In order to simulate how the system performs with a different scatter the two following functions have to be used:

- FUNC_05_Optimize_PA.m: here a different wave scatter can be implemented to simulate the behavior of WEPA in another environment with respect to Porto Conte.
- FUNC_05_Optimize_PA_Launcher.m: allows the implementation of a different sensitivity.

7.3.3.2.3 Results

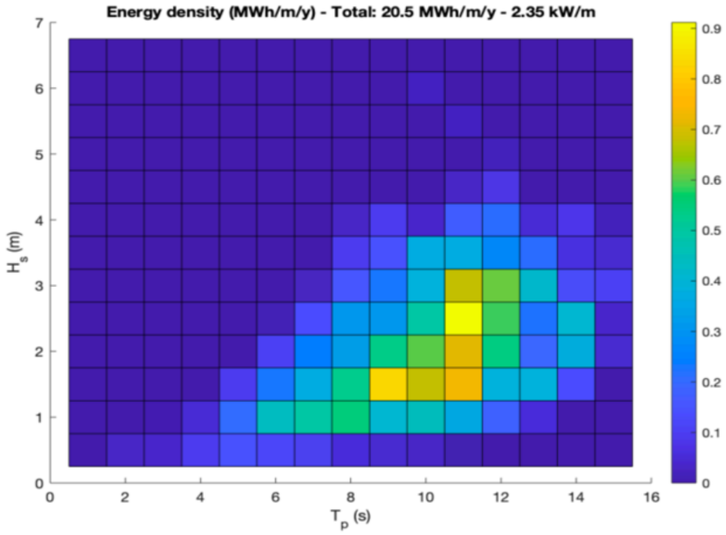


Figure 7.8: Porto Conte Energy Scatter

Given the energy scatter of Porto Conte, shown in figure 7.8, and implementing it in the Matlab script, the annual energy produced by the wave energy converter is of 4.84 MWh, considering a relative capture width, which represents the percentage of energy extracted from the totality of the energy available in the installation site, of 6.9 %.

Chapter 8

8 Auxiliaries' productivity estimation

8.1 Photovoltaic panels productivity

In order to estimate the productivity of the three SR144 Solbian modules the Photovoltaic Geographical Information System (PVGIS) was used. Choosing the nearest location on land with respect to the installation site (latitude 40.570, longitude 8.243) and selecting one of the possible databases (SARAH2 in our case), the monthly irradiation data of a specific year can be obtained. In the image below the last possible data of the year 2020 are shown.

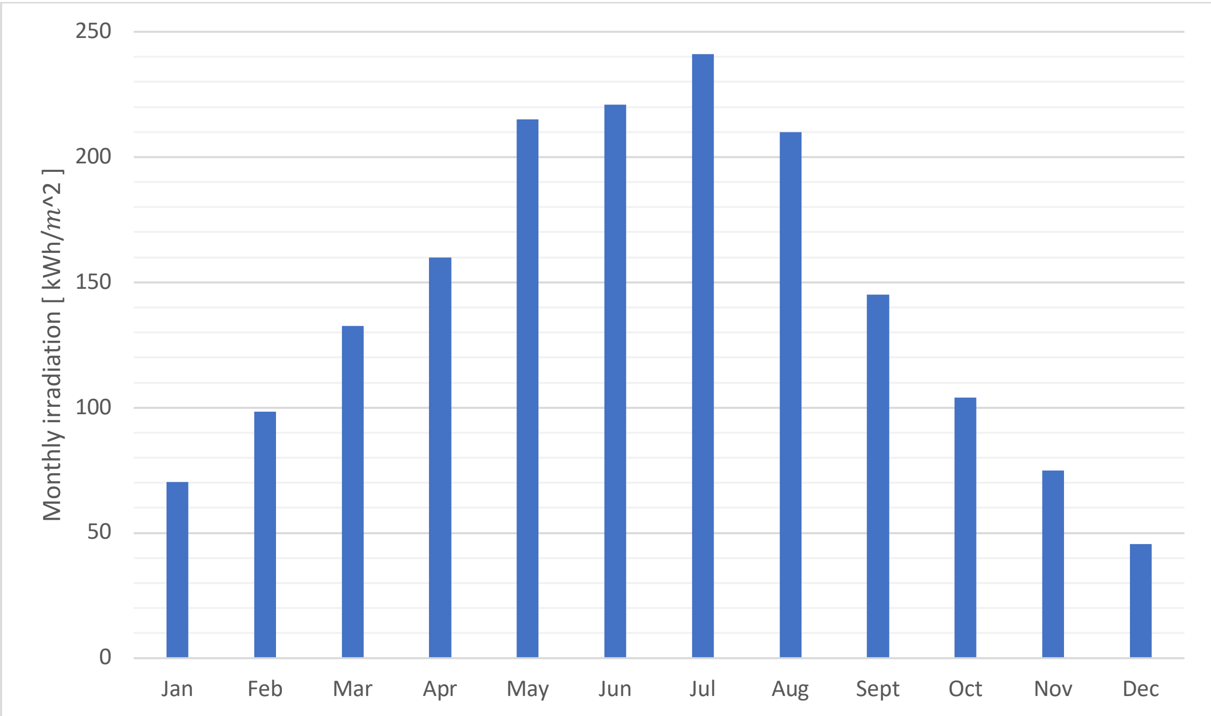


Figure 8.1: Monthly irradiation of 2020 (30)

As shown by the histogram the maximum irradiation value is in the month of July with 241 kWh/m^2 and the minimum one is in the month of December with 45 kWh/m^2. The total yearly irradiation is equal to 1717 kWh/m^2. Being the solar irradiation not constant each year, also the data from 2019 and 2018 were taken and performing an arithmetic mean between the three years the final value of total yearly irradiation obtained is 1675 kWh/m^2. The single SP144 module has a surface of 0.8 m^2 and produces 144 W, its specific power is therefore equal to 180 W/m^2. Knowing that the solar standard conditions power rating used to test all photovoltaic panels is 1 kW/m^2, the module efficiency will be 18%. Knowing the total yearly irradiation, the total surface area (2.4 m^2) and the module efficiency, the theoretical yearly energy produced by the panels is equal to 723 kWh. Furthermore, considering a loss coefficient equal to 14% that takes into account temperature, shadows and dirt losses, the final result is equal to 622 kWh.

8.2 Wind turbine productivity

In order to estimate the productivity of the Rutland 1200 Marine Windcharger, Global Wind Atlas and Wind navigator softwares were used. For the installation location the data of mean wind power density and mean wind speed are the following:

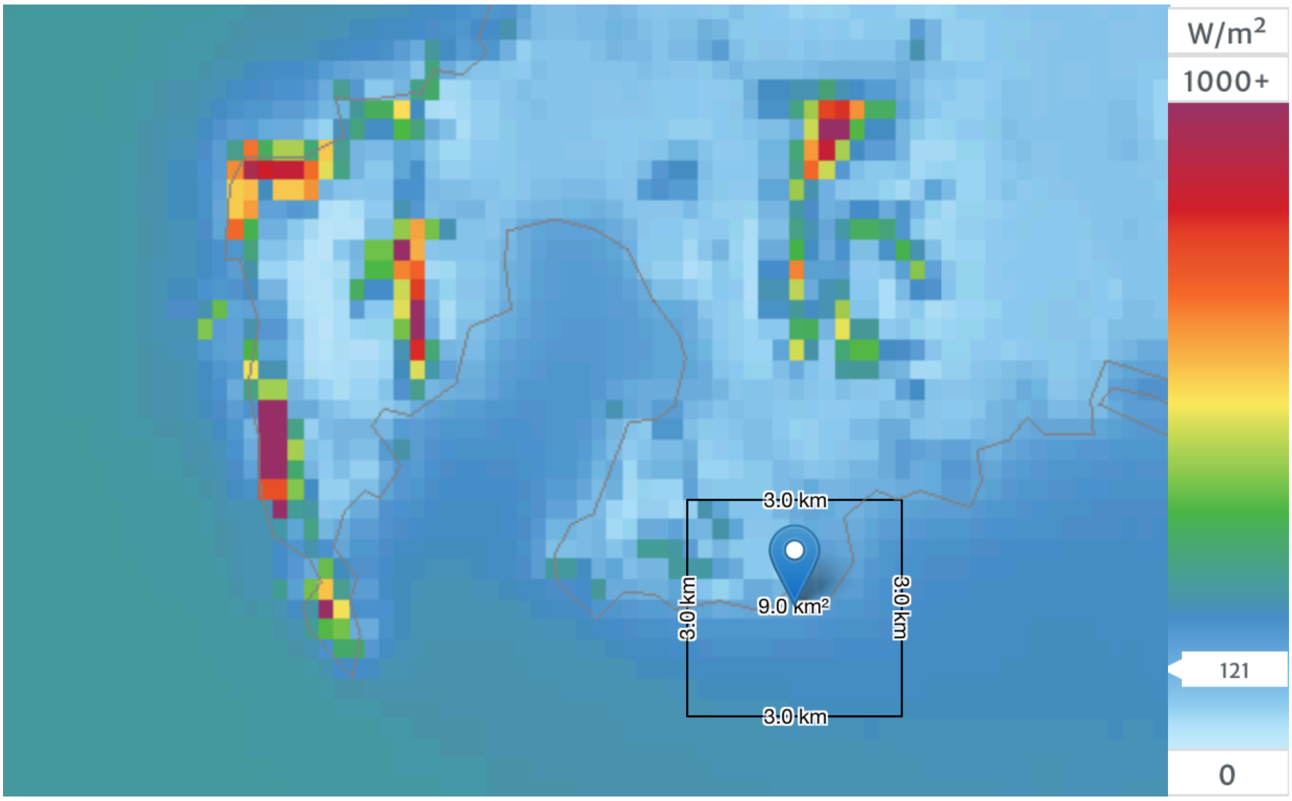


Figure 8.2: Wind power density of Porto Conte (29)

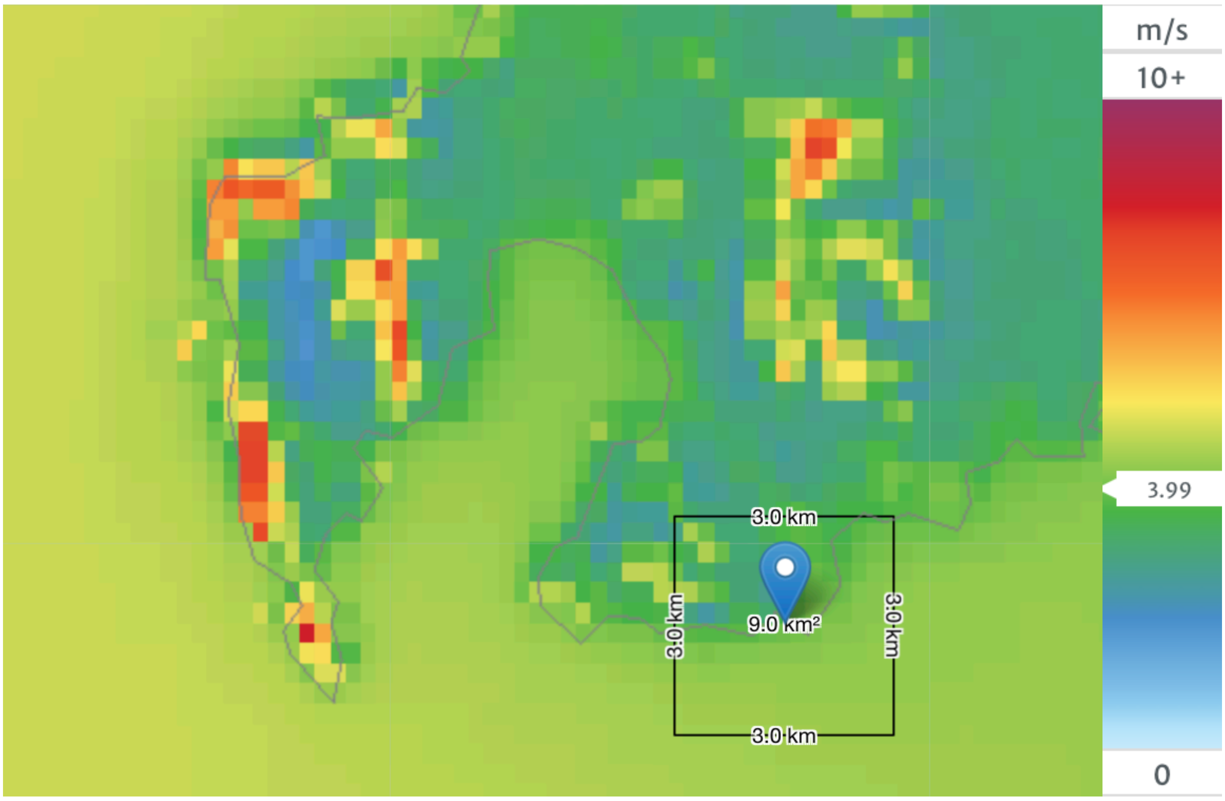


Figure 8.3: Wind velocity of Porto Conte (31)

The mean power density of the 9.0 km^2 area shown in the picture is 165 W/m^2 while the mean wind speed is 4 m/s. In order to be as close as possible to the real conditions, the data are chosen for the lowest possible height, 10 m. This will therefore determine an uncertainty in the estimate of the energy produced because the exact height of the turbine rotor is 5.86 m.

Wind navigator also provides the necessary parameters to determine Weibull statistical distribution of wind speed. Knowing indeed the values of k and A, the probability to obtain a specific wind speed, *v,* is computed through the following expression (32):

$$p(v) = \frac{k}{A^k} v^{k-1} e^{-(\frac{v}{A})^k}$$

Using the values of A and k given by the software and respectively equal to 4.5 and 1.81, the wind speed probability distribution is computed and shown in the graph below:

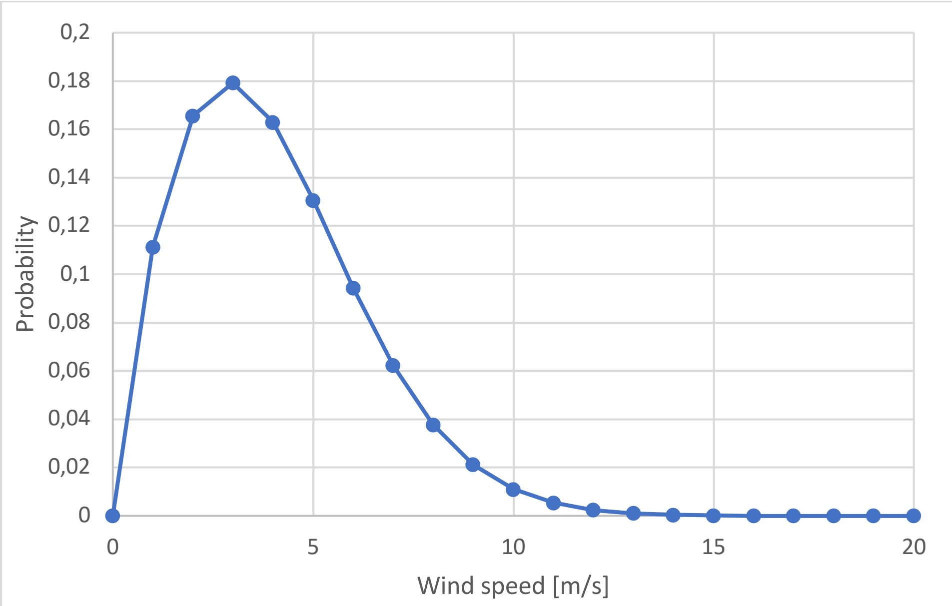


Figure 8.4: Wind speed probability

Extracting then the data from the power curve provided by the wind turbine technical datasheet, the following graph was generated. As shown, the minimum wind speed needed in order to produce power (cut-in speed) is 3 m/s while the limit value (cut-off speed) is 20 m/s. The maximum power output, equal to 483 W, is reached at 15 m/s (33).

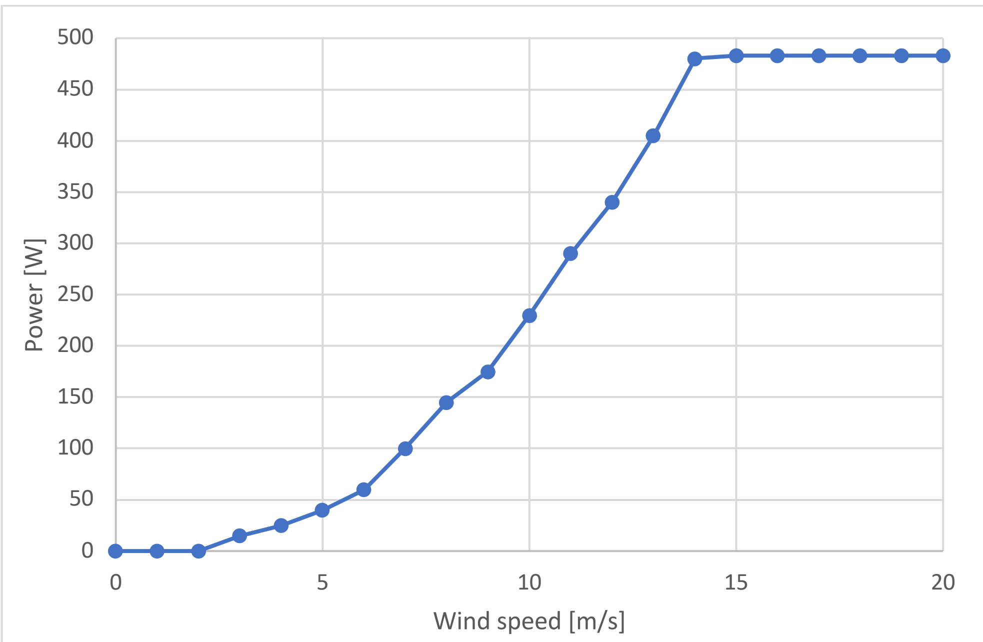


Figure 8.5: Rutland 1200 power curve (33)

Then, multiplying the probability, expressed as number of hours per year, with the power generated at each wind speed, the energy produced can be estimated.

Table 8.1: Wind energy produced

Wind speed [m/s]	Probability	Yearly hours	Power [W]	Energy [Wh]
3	0.1792069	1569.852	15	23548
4	0.1629748	1427.659	25	35691
5	0.1306141	1144.180	40	45767
6	0.0943314	826.343	60	49581
7	0.0621765	544.666	100	54467
8	0.0377069	330.312	145	47895
9	0.0211583	185.346	175	32436
10	0.0110306	96.628	230	22225
11	0.0053600	46.953	290	13616
12	0.0024337	21.319	340	7249
13	0.0010347	9.064	405	3671
14	0.0004127	3.615	480	1735
15	0.0001546	1.354	483	654
16	0.0000545	0.477	483	231
17	0.0000181	0.158	483	76
18	0.0000057	0.050	483	24
19	0.0000017	0.015	483	7
20	0.0000005	0.004	483	2

Summing all the contributions, the total energy produced is 339 kWh.

8.3 Summary

The results of this chapter and of the previous one are summarized in the table below.

Table 8.2: WEPA productivity

Source	**Productivity [MWh/y]**
Waves	4.84
Wind	0.34
Solar	0.62

WEPA total productivity is therefore equal to 5.8 MWh/y.

Chapter 9

9 WEPA productivity estimation

9.1 WEPA productivity in the Mediterranean Sea

Being WEPA productivity a key element for the evaluation of the carbon and energy intensities parameters, other wave scatters related to different locations both in the Mediterranean Sea and in the Ocean were implemented in FUNC_05_Optimize_PA.m.
As said before, the chosen site of installation of WEPA is sheltered from the predominant north-west wind and waves and that's the main reason why the energy produced is low. Considering instead to place the device in the adjacent area on the west side, more exposed to the open sea, the productivity rises up to 10.7 MWh/y which is more than double with respect to the previous value, even if the RCW is reduced to less than a half. This highlights the fact that even if the wave energy resource is much greater, its potential cannot be properly engaged because WEPA has been optimized only for the precise installation site. The wind distribution is also different and the turbine productivity is estimated to show a 26% increase, reaching 429 kWh/y, while the solar irradiation doesn't show any great variation.
The productivity was then evaluated in other relevant Mediterranean sites in order to estimate the best possible location.
Pantelleria was the second spot considered due to its placement in the strait of Sicily and the consequent exposure to the north-west waves. Performing the analysis, the respectively productivities of the buoy, wind turbine and solar panels are: 9.1 MWh/y with a 5.1% RCW, 1 MWh/y, 683 kWh/y.
Further evaluations were performed at the locations of Prezioso Eni Platform, latitude 39.009 north and longitude 14.045 east, and Bonassola. In the former, WEPA would produce 8.8 MWh/y from the waves motion, 667kWh/y from the wind and 680 from the sun radiation, while in the latter it would respectively produce 6.7 MWh, 574 kWh and 668 kWh. Both Prezioso and Bonassola show RCW values higher than those of Porto Conte, which are probably determined by the different wave scatter meshes. Indeed, while the scatter of Porto Conte takes into account the specific installation area, the other ones refer to a 2500 km^2 surface.
Summing up those results, the following table is obtained:

Table 9.1: Mediterranean spots productivity

Location	Total productivity [MWh]	RCW [%]
Porto Conte	5.8	6.9
Alghero	11.8	3.2
Pantelleria	10.8	5.1
Prezioso	10.1	10.6
Bonassola	7.9	11.0

Compared to the 5.8 MWh/y that WEPA is estimated to produce if deployed in the chosen installation point, the values displayed are almost the double. Furthermore, an increase in the amount of energy produced would be beneficial from an environmental point of view because of the consequent reduction of both carbon and energy payback times.
Considering for example the production of 11.8 MWh/y, the emissions related to the climate change impact category would go down to 221 gCO_2/kWh and the carbon and energy payback times would be respectively of 8 and 12.7 years.

9.2 WEPA productivity outside the Mediterranean Sea

But even better performances would be obtained outside the Mediterranean basin. In fact, if WEPA was placed in the same location of Balder ExxonMobil platform in the North Sea, figure 9.1, its total productivity would be of 16.5 MWh/y. As in the other cases, the majority of it comes from the waves, 14.6 MWh/y, even if the RCW is only 1.6 %. This low value of efficiency clearly shows how much potential could be achieved if the device was properly optimized both from the mechanical and control point of view and deployed in more advantageous locations. In this case, the values highlighted before would further decrease to 158 gCO_2/kWh, 5.8 and 9.1 years. However, considering that the depth of Balder platform is of 125 meters, 100 meters more than Porto Conte site, the materials required for the mooring would present an additional mass and the emissions of carbon dioxide would increase.
Putting then together this analysis concerning different alternative sites, with the sensitivity analysis performed in chapter 5, the carbon intensity would reach 65 gCO_2/kWh, value that is completely compatible with the other ocean energy technologies.

Figure 9.1: Balder location

Chapter 10

10 Conclusion

The results of this study highlight the mismatch between WEPA's impact assessment values and the literature data regarding other ocean energy technologies. In fact, while the majority of point absorbers emits at maximum 126 gCO_2/kWh, WEPA exceeds 400 gCO_2/kWh. Furthermore, its values of carbon and energy payback times are respectively 16.4 and 25.9 years, way higher than the average ones. However, the main reason for this anomaly is the low amount of electrical energy produced by the device at the chosen installation point.
For example, by changing the location from Porto Conte to Balder in the North Sea, WEPA's carbon intensity and its values of carbon and energy payback times would drastically reduce to 158 gCO_2/kWh, 5.8 and 9.1 years.
Nevertheless, productivity is not the only factor that affects the variation of this value. As shown by the impact assessment analysis, indeed, among all the flows and processes needed during WEPA's life cycle, materials production is the most impactful one. In particular, steel manufacturing accounts for 47% of the totality of greenhouse gases emitted by the device. Therefore, changing this material with another one that shows the same mechanical properties, but lower values of carbon intensity, would surely be beneficial. The study shows indeed that substituting primary steel with recycled steel and considering the original installation point**,** only 280 gCO_2/kWh would be emitted.
Moreover, this value could be further reduced if the system's reliability was increases, its lifetime extended, and more ecological means of transportation were used.
If all the previous improvements were taken into account, WEPA's values of carbon intensity, carbon and energy payback times would be respectively of 65 gCO_2/kWh, 3.5 and 5.7 years. In this scenario, the device would be perfectly competitive with other point absorbers wave energy converters present in the market.
The study, however, does not only take into consideration the value of carbon intensity but gathers many other indicators so that a broader view of the environmental impact caused during WEPA's life cycle is achieved.

10.1 Future work

In order to further improve the device other changes could be implemented. In fact, using materials such as glass fibers composites or plastics, the device would be lighter and less environmentally impactful. However, the whole structure should be redesigned, with major changes especially concerning the hull.
Another possible improvement involves the substitution of the chosen mooring system with a more innovative one. An example is the new type of anchor developed by the UMACK project, which shows a 40% carbon intensity reduction with respect to the classical concrete gravity anchor which is used for the WEPA system. (34)

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