Techno-economic analysis of breakthrough concepts into the OWC spar-buoy

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Abstract

The intensive research and development in wave energy technologies have underlined some of the barriers and challenges that have prevented the wave energy converters from reaching commercialization. Amongst these there is the reliability and survivability of the devices, the lack of experience in logistics, operation and maintenance and the economic competitiveness of the available technologies. Moreover, contrarily to the traditional renewable energy sources, the wave energy sector does not have a defined leading technology that stands out as the most promising one but there are many different solutions that are studied and developed at the same time. In this context the study focuses on the integration of innovative technology solutions integrated into the OWC spar-buoy, selected as a reference wave energy converter. The OWC spar-buoy is a device developed in IST that belongs to the floating oscillating water column typology. In order to overcome the aforementioned common issues for wave energy converters, six breakthrough concepts have been developed for the OWC spar-buoy, within the scope of the EU H2020 WETFEET project. The breakthroughs are: enhanced added mass (EAM), negative spring (NS), survivability submergence (SS), shared moorings (SM), dielectric elastomer generator (DEG) and tetra-radial turbine (TRT). These innovative concepts are described in the study together with the changes they involve on the reference device. The aim of the study is to assess the effectiveness of the six breakthroughs on the economics of a project involving the installation of a wave energy farm, with a target capacity of 5 MW. Therefore, a detailed LCOE analysis is performed using a model developed at WavEC Offshore Renewables. The six breakthroughs are thoroughly analyzed from a technological point of view in order to understand their effects on both capital and operational expenditures (CAPEX and OPEX), as well as on the annual energy production (AEP). The three aforementioned parameters (CAPEX, OPEX and AEP) affect the final LCOE value of the wave energy farm project that, depending on the breakthrough concept applied, can either improve or worsen. The effects of the breakthroughs on the LCOE are defined, assessed and explained in depth in the study. The analysis revealed that three of them have a positive impact on the economics of the project, namely the EAM, NS and SM concepts. On the other hand, the SS and DEG breakthroughs involve an overall increase of the LCOE but they have a good potential for further implementation. It was not possible to assess the effect of the TRT case because of the lack of data regarding the power outcome. It is important to notice that the breakthroughs were analyzed separately in this study, while the combination of two or more concepts in the same project is expected to have a greater positive impact.

Keywords

Renewable energy; Wave energy; OWC spar-buoy; Breakthroughs; Techno-economic analysis; LCOE

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List of Abbreviations

WEC: wave energy converter

OWC: oscillating water column

PTO: power take-off

REF: reference

EAM: enhanced added mass

NS: negative spring

SS: survivability submergence

SM: shared moorings

DEG: dielectric elastomer generator

TRT: tetra-radial turbine

NPV: net present value

IRR: internal rate of return

LCOE: levelized cost of energy

CAPEX: capital expenditures

OPEX: operational expenditures

AEP: annual energy production

AHTS: anchor handling tug supply

ROV: remotely operated vehicle

CLV: cable laying vessel

1. Introduction

The increase of the global energy consumption expected for the next decades stresses the need to find new technologies in order to deploy pollution-free energy sources, also considering the growing awareness worldwide of the serious damages that traditional energy production systems are causing to the environment. In fact sustainability is the key for the future of energy production and, after the intensive deployment of wind and photovoltaic energy devices witnessed in the last few decades, currently wave energy has been intensively studied because of its great potential. The concept of harvesting energy from sea waves is not new, being dated back to 1799, with the first known patent filed in France by Girard & Son [1]. From that moment hundreds of configurations for wave energy devices have been patented, modelled and some of them have been tested in the sea. In Europe a boost to intensive research and development studies of wave energy conversion was given by the oil crisis of 1973 [1]. Different European countries with exploitable wave power resources introduced support measures and related programmes for wave energy in order to integrate it into the power supply system. The European Commission started supporting the efforts of those countries around 1986, the objective being the development of commercial wave energy conversion technologies [2]. With the ratification of the agreements of 2007, within the “2020 climate and energy package” against climate change, the European Union stated the will of transforming Europe into a highly-efficient and low-pollutant economy, committing to achieve, by 2020, targets such as: 20% reduction of CO_2 emissions, 20% reduction of energy consumption and 20% of renewables in the total energy mix [3].

In this context wave energy appears to be a very interesting topic. In fact, although currently the designed devices are not economically competitive with more mature renewable energy systems such as wind and solar, the interest of governments and industry is still strong because of the great potential of the resource, considered to have the highest energy density amongst renewables. Thus, even if phases of disappointment and reconsideration have been undergone during the last few decades, persistent efforts have been made in the wave energy field, in order to provide a valid alternative to traditional renewable sources. The continuous research and development, together with the experience accumulated throughout the years, have led to a constant improvement in the performance of wave energy technologies, bringing the sector closer to commercial exploitation than ever before. Different systems have proven their applicability under harsh operational conditions and a number of commercial plants are currently being built not just in Europe but in many countries all over the World. Some devices are in the final stage of testing and show prospects for successful implementation. Nevertheless, extensive research and development work is continuously required, at both theoretical and application level, in order to find new ideas, new concepts to improve constantly the performance of the available technologies, or even to find new and more effective ones, and to establish their competitiveness in the global energy market.

1.1. Current state of the art of wave energy

1.1.1. Wave energy resource

Waves are generated by winds blowing across the seas and they can travel thousands of kilometers from the point where they are formed with just a little energy loss. The energy fluxes occurring in deep-water sea-waves can be very large. The main parameters to assess the power carried by a wave are its amplitude (wave height) and period. The power of a wave is usually expressed referring to the length of its crest, so in kW/m of wave crest. Typically sites where the wave energy resource is considered to have a good level for exploitation show annual averages between 20 and 70 kW/m [1]. When the waves travel towards the shoreline and enter shallow waters, they are affected by the seabed through physical processes such as refraction, bottom friction and wave breaking. It can also happen to find specific sites where the interactions with the sea bottom are such that there is energy concentration on the shore: they are called “hot spots”.

The main disadvantage of wave energy is that the resource is highly variable on different time-scales: from wave to wave, within a certain sea-state; from day to day, depending on the main winds blowing on the oceans; from month to month, with a remarkable seasonal variation. The assessment of the energy resource is a critical step for a strategic planning for wave energy development. In fact, the characterization of the wave climate in offshore sites is essential both for defining the potential installation areas and for the design of the devices. Some useful data for this purpose can be obtained from other sectors, like navigation, coastal and offshore engineering, but specific surveys are needed in order to assess the wave energy resource. In this context, the creation of the European Wave Energy Atlas, supported by the European Commission [1], clearly shows the importance of data collection for resource assessment in that specific field. Through the combination of high-quality results from numerical modelling and wave measurements, the Atlas offers a basic knowledge of the offshore wave climate conditions. Since near-shore the conditions are highly dependent on the shape of the sea bottom, specific measurements campaigns have been conducted where sites were considered to be potentially adequate for testing or deployment of devices.

1.1.2. Wave energy converters

The irregularity in time of wave parameters (wave height, period and direction) implies that the devices for wave energy deployment should be highly sophisticated, from the point of view of the hydrodynamic response and of the control system effectiveness, in order to have good efficiency over a wide range of excitation frequency. Moreover, extreme loads and the harsh marine conditions should be considered during the design phase of the devices, since in offshore sites storms are common events and sometimes the devices can undergo severe sea-states, with loads several times higher than the average ones.

It is clear that a wave energy converter (WEC) has to be operationally efficient and reliable on the one hand and economically feasible on the other, making the design process truly challenging. In other words: devices need to be big enough so that they can achieve resonance between their natural frequency and the predominant frequency of the average incoming wave field, but at the same time they need to be as small as possible to reduce costs and achieve economic feasibility.

It is important to notice that there is not one reference technology for wave energy, as it happens for instance with other renewable energy sources such as wind and solar, but there are many possible designs with completely different features.

The main WEC concepts developed throughout time can be divided in the following classifications, according to sources [2], [4]:

- Oscillating water column (OWC) devices (fixed-structure or floating);
- Oscillating body systems (single-, two-, multi-heaving body systems, fully submerged heaving systems, pitching devices, bottom hinged systems);
- Overtopping converters.

Another possible way of categorizing can be based on the installation location and the devices:

- Offshore, when the devices are deployed in deep waters;
- Nearshore, when they are deployed in shallow waters;
- Onshore, when they are deployed on the coastline.

For the devices installed offshore and nearshore there can be a further classification since they can be both floating and submerged, while normally the devices onshore are fixed structures.

Finally, among all the possible configurations developed or studied for WECs, the main power take-off (PTO) systems are usually the following ones:

- Self-rectifying air turbines;
- Hydraulic turbines;
- High-pressure hydraulic systems;
- Linear generator;
- Dielectric elastomer generator (still in research and development phase).

Two different devices are presented here as examples of converters that have been installed at their full-scale in Portugal:

- The Pico plant, in the archipelago of Azores. It consists of an OWC device, equipped with a Wells self-rectifying air turbine and installed on the coastline. The plant is shown in Figure 1, it has been installed in 1999 [4] and since then it has been instrumental in the testing of equipment testing and for improving the experience with operation of wave energy devices, despite its onshore location which makes its maintenance operations easier when compared with offshore devices.

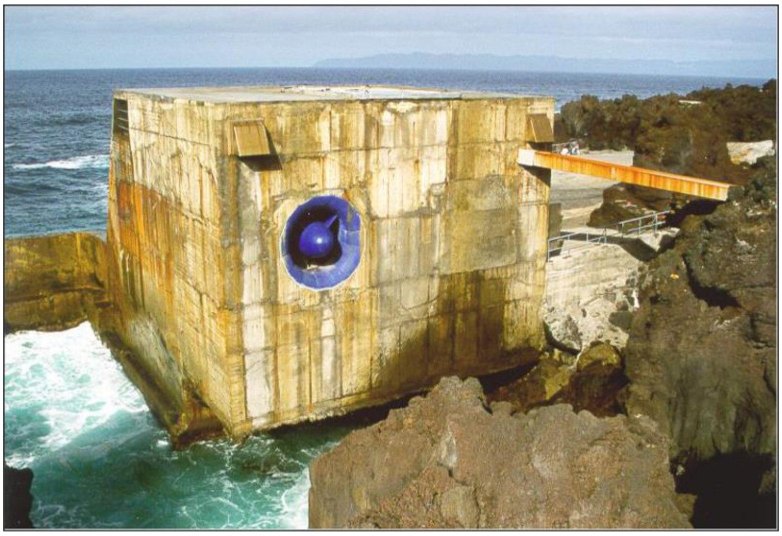

Figure 1: Pico plant, onshore OWC device, Azores, Portugal [4]**.**

- The Pelamis wave farm, composed by three floating devices deployed off the coast of northern Portugal in 2008 [1]. The Pelamis is an oscillating multi-body system based on high-pressure hydraulic PTO equipment and installed in deep waters, as shown in Figure 2.

Figure 2: Pelamis plant, offshore floating devices with hydraulic PTO system, Aguçadoura, Portugal [1]**.**

1.2. Challenges

Despite the considerable progress witnessed during the past decade in the development of wave energy devices, which led to the deployment of a number of prototypes at sea, the technological evolution in the field did not attain the expected trend. According to source [5], the most relevant obstacles that wave energy has faced are related with the following aspects of the WEC design and development processes:

- Reliability of technical components, especially the PTO system;
- Survivability of entire system;
- Long, complex and cost-intensive road to a marketable product;
- Unclear path towards economic competitiveness, including support mechanisms;
- Unclear path towards industrial scalability, meaning the effective possibility of installing farms in the range of hundreds of MW.

The conjuncture of these issues has slowed down the progress to date. Due to the pressures coming from the intention of shortening the time and money needed for the development, some full-scale devices were designed without a sufficient evaluation of risks and alternatives. In fact, there is evidence that some early-stage design decisions were made to speed up the process of prototype construction, sometimes missing an overall accuracy from the engineering point of view, both for technical aspects and material choices. Moreover, the underestimation of the effects of the ocean conditions on the deployed devices also greatly contributed to the current state of affairs in the wave energy sector. Due to the lack of continuous experience of plant performance in real sea conditions, the true challenges related with installation, operation and maintenance of devices offshore remain largely unknown.

Nevertheless, new and innovative ideas have been developed in order to overcome the recognized issues related with wave energy. In fact, breakthrough concepts have been introduced within the EU’s Horizon 2020 WETFEET project[1] as solutions to overcome the stagnation in the development of the wave energy sector. The WETFEET project aims at the identification of the main constraints impairing the progresses in wave energy harvesting through a detailed and comprehensive analysis of the status and demands from a traditional technological point of view, but also from cross-referential aspects like economic, societal and environmental. For instance, the increase in the reliability and survivability of the system and the improvement in the overall economic performance are some of the targets of the breakthrough concepts. Two main technologies of WECs are considered in the WETFEET project:

- The OWC spar-buoy: a floating oscillating device of the OWC typology;
- The Symphony: a variable volume, submerged point-absorber that features an water turbine as PTO equipment.

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[1] The WETFEET (Wave Energy Transition to Future by Evolution of Engineering and Technology) project has received funding from the European Union's Horizon 2020 programme under grant agreement N° 641334.

In the present study just the first of the two wave energy converters is taken into account and it is described in the section 2.1.

2. Oscillating water column

In the OWC concept the mechanical process of energy absorption from the waves is carried out through a moving air-water interface subject to a time-varying pressure. The air-water interface is created through a fixed or floating hollow structure which has an opening towards the sea, below the water surface. Air is trapped in the so-called air chamber, between the inner free-surface of the water and the hollow structure. The action of the incoming waves results in the motion of the inner surface of the water that alternatively compresses and decompresses the trapped air, forcing it to pass through an air turbine coupled with a generator.

The energy conversion chain of an OWC device can be represented as following, according to source [6]:

- Mechanical wave power: corresponds to the power resource available in the incoming wave field the OWC device is subjected to;
- Pneumatic power induced by the water column: part of the incoming power carried by the waves induces a vertical motion in the water column, inside the OWC hollow structure, converted into pneumatic power through the compression/expansion cycles of the air enclosed in the inner chamber of the WEC;
- Mechanical turbine power: the time-varying pressure caused by the water motion inside the chamber drives a mechanical air turbine, located in between the inner air chamber and the exterior atmosphere;
- Electrical power: the turbine shaft is coupled with an electric generator, and the necessary power electronics, that turns the mechanical power into electricity, considering the occurring losses due to the conversion process, which can ultimately feed the grid.

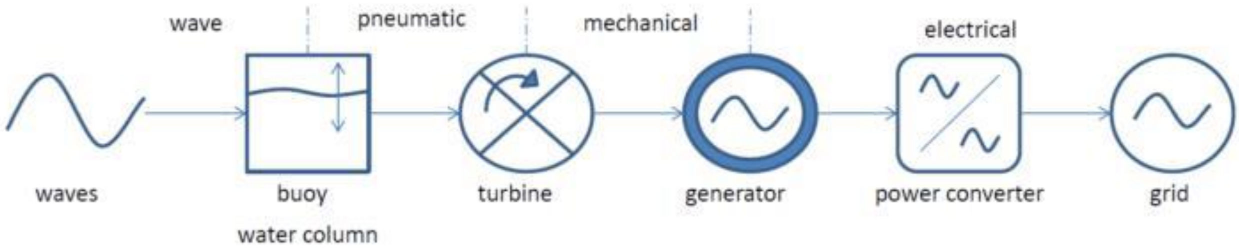


Figure 3: Power conversion chain for a floating OWC device [6].

The first appearance of the OWC concept in published papers is dated back to 1978 [4]. The main advantage of this technology is that it is mechanically relatively simple, since the only moving part of the PTO system is the turbine, and it is kept above the water level. Moreover, the OWC technology can be deployed in isolated shoreline or nearshore solutions, integrated into a breakwater, or in single- and multi-OWC floating plants, meaning it has a wide range of possible applications for different sites and wave climate conditions.

The control system has a great influence on the performance of an OWC, in particular in the case of a floating device. In fact, the highest efficiency of wave energy absorption is attained when there is resonance between the wave field and the motion of the WEC. The problem is that for many devices the natural frequency of resonance is higher than the typical frequency of the waves. In this context, phase control has been introduced to try to match the two frequencies as much as possible. Among the different possible configurations of a control system for floating WECs, the latching control scheme appears to be the most effective. In the case of an OWC device, latching control is achieved through a valve in series with the air turbine. There are specific problems related to latching control of an OWC: the main one being the compressibility of the air inside the chamber that acts as a spring and prevents the water column to remain fixed with respect to the structure, even if the air flow is stopped at the entrance to the turbine. Besides, it should be noted that such compressibility may remove the constraint of the latching threshold having to coincide with an instant of zero (relative) velocity. Another issue is that short-term wave forecasting is needed to perform control strategies efficiently.

2.1. The OWC spar-buoy

The spar-buoy is an OWC device of the floating type, designed to be deployed offshore in deep waters. It is composed by an upper floater and a lower hollow column that extends underwater and that is open at its bottom. The opening is submerged and allows water to get into the column so that an air-water interface is created at the height of the floater, at the level of the free surface of the sea. Being the spar-buoy a floating structure, the hydrodynamic process of energy absorption from the incoming waves is highly affected by the interference between the incident wave field and the radiated waves produced by the motion of the device itself. In general, it can be said that a good wave energy absorber must be a good wave radiator. In fact, with the proper structural design and control system, the oscillations generated by the motion of the floating device (radiated waves) are expected to enhance the power extraction efficiency from the incoming wave field.

As already mentioned in section 1.2, for the OWC spar-buoy some new features intended to increase its performances have undergone research and development processes. The so-called “breakthrough concepts” are the new ideas supposed to facilitate the OWC spar-buoy development path and they will be described in section 3, while, in order to distinguish the basic converter, without innovative features applied, it is going to be named as “reference case”.

2.1.1. Reference case device structure

The reference case corresponds to the first design of the OWC spar-buoy. Such first device was not yet optimized by changing its original structure through the computational hydrodynamic analysis that were performed subsequently.

The OWC has a predominantly vertical motion inside the tube and the air chamber has a uniform cross section. The enlargement of the tube at the bottom part increases the advantageous inertia characteristics of the water column, while avoiding an increase of the tube length. The turbine is located at the top of the air chamber (Figure 4). Ballast is introduced in two compartments at different levels inside the structure to control the mass distribution and the natural pitch/roll period.

As it can be seen in Figure 4, where all the dimensions of the structure are presented, the device has a diameter of 12 meters and a total height of 51 meters, for a draft of 36 meters [7]. All the surfaces have an equal thickness of 15 millimeters and the selected material for the structure is steel. The total mass of the steel structure is of 248 tons.

The structure can be divided in three main sub-structures, according to source [6]:

- A floater: the upper cylindrical surface;
- A small thickness tube: the central column;
- A large thickness tube: the bottom of the column, where the cylindrical surfaces are slightly enlarged.

It is important to notice that in the last two sub-structures the “thickness” refers to the cross-section of the tube, which is smaller in the center and enlarges towards the bottom of the structure.

The first and the third sub-structures are ballasted through the insertion of concrete inside dedicated compartments in the device structure, for a total amount of 964.4 tons.

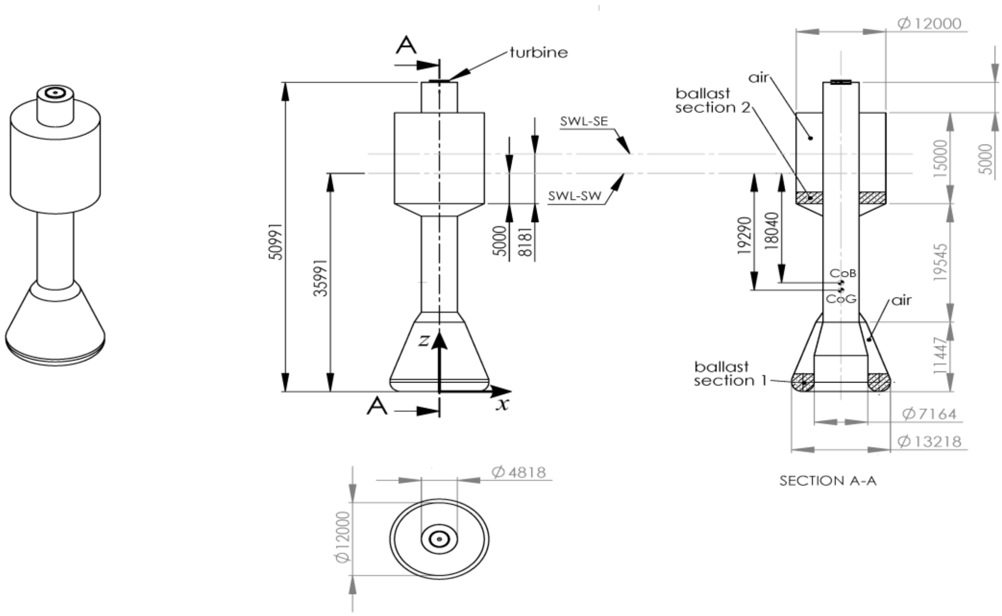


Figure 4: Structural dimensions of the OWC spar-buoy [7].

2.1.2. Reference case device PTO system

The PTO system of an OWC device is generally composed by an air turbine, which converts the pneumatic energy of the air chamber into mechanical energy, coupled with a generator, which makes the final conversion of the produced energy into electricity that can be carried onshore, to feed the grid. Since the air turbine is an essential component of the device, its design is a matter of critical importance, considering that it is subject to much more demanding conditions than more conventional turbines (water, gas, steam, wind): in fact, the air flow rate is largely random, varies widely with sea-state, and its direction is reversed twice in each wave cycle. Therefore, traditional turbines are not adequate for this specific application, being mono-directional and thus requiring a system of rectifying valves, which is not very practical. This is the reason why self-rectifying turbines are preferred for the application in OWC converters, since they keep their rotational direction regardless of the direction of the air flow. Almost all the proposed and tested self-rectifying air turbines are axial-flow machines of two basic types: the Wells turbine and the impulse turbine. The Wells turbine, invented in 1976 by Alan A. Wells [8], equipped most of the OWC prototypes deployed at sea. It has been largely tested and generally shows a high rotational speed and a relatively narrow operating flow range, meaning that efficiency is quite sensible to changes in the Reynolds number and it drops sharply for increasing flow rates, when stalling at the rotor blades occurs. On the other hand, the impulse turbine has a wider operational flow range but a considerably lower efficiency due to high aerodynamic losses at the rotor exit.

The reference case of the OWC spar-buoy is equipped with a third typology of self-rectifying air turbine: the bi-radial turbine. Such turbine belongs to the family of impulse turbines, with the difference that the flow is not axial but it is radial, both at inlet and outlet. The turbine is symmetrical with respect to a plane perpendicular to its axis of rotation, the rotor is surrounded by a pair of axisymmetric ducts, each duct being formed by a pair of parallel discs and there are two rows of axially movable guide vanes, rigidly connected to each other. Therefore the whole set of guide vanes can be displaced, preventing it from obstructing the flow coming out of the rotor and reducing the aerodynamic losses. In an alternative configuration, the two sets of guide vanes are not movable but instead they are radially offset from the rotor to reduce the stalling losses at the second row of guide vanes.

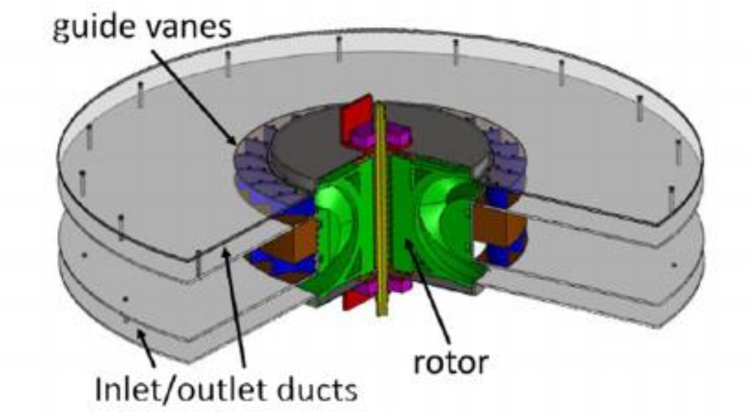


Figure 5: Schematic section of a bi-radial turbine [9]**.**

The turbine is coupled with a permanent magnet synchronous generator with a nominal power of 150 kW.

In order to complete the PTO system, control and safety instrumentation is needed. The latter tasks in the OWC spar-buoy device are performed through two different valves [6]:

- One relief valve, mounted in parallel with the turbine and connecting the pneumatic chamber with the atmosphere. The purpose of the relief valve is to release the air directly into the atmosphere without passing through the turbine and is used for very large flow rates in order to avoid stall conditions.
- One high-speed stop valve, installed in series with the turbine and activated to lock the air flow and so perform latching control. The response time of the valve, when the signal for its closure is issued, should be very short in order to have an effective control over the system.

2.1.3. Reference case device mooring system

The OWC spar-buoy is a floating device and so it needs a mooring system to ensure station-keeping. The connection with the sea bottom is designed as a slack-mooring system with three equally-spaced mooring lines. The lines are made of spiral-strand steel wire and they are composed by three segments:

- The first one connects the OWC to a weight, suspended in the water;
- The second one connects the weigh to a submerged buoy;

- The third one connects the buoy to a studded chain.

The studded chain is formed by a light chain, half suspended and attached to the third section of the mooring line, and a heavy chain, lying down on the ground and attached to an anchor fixed on the sea bottom. With this configuration the system is never fully stressed because even under extreme line tensions the heavy chain, that is normally lying down on the sea bed, gets suspended above it and the stiffness of the system is increased.

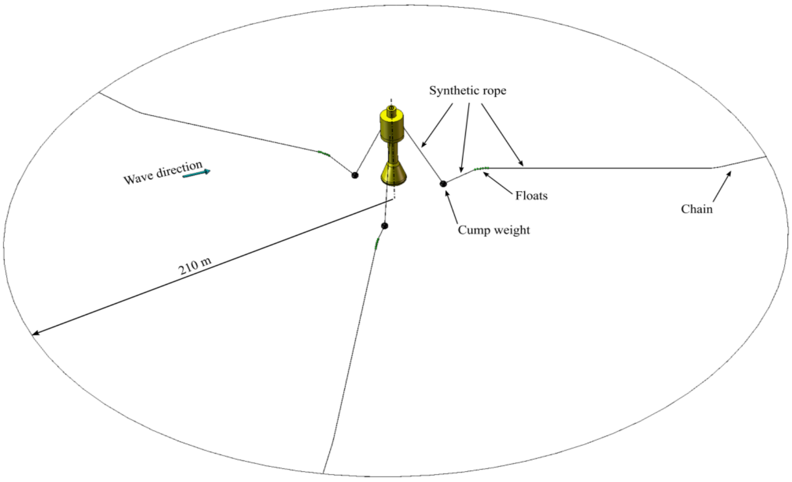


Figure 6: Mooring system schematic layout [7].

It is important to know that the mooring system design was optimized with the objective function of maximizing the horizontal restoring force for an extreme horizontal displacement.

3. Breakthrough concepts

As already mentioned in section 2.1, the breakthrough concepts are innovative ideas to improve the effectiveness of the OWC spar-buoy device. They are all at an early stage of development at the moment but they have been identified as solutions for the challenges described in section 1.2 and as potential ways for improving the performances and reducing the costs associated with the OWC spar-buoy technology.

The six breakthrough concepts developed are:

- Enhanced added mass (EAM);
- Negative spring (NS);
- Survivability submergence (SS);

- Shared moorings (SM);
- Dielectric elastomer generator (DEG);
- Tetra-radial turbine (TRT).

The breakthrough concepts can be divided in the cost-reduction pathways they belong to, according to [6]:

- Optimized structural design and device profile: the negative spring, the enhanced added mass and the survivability submergence concepts are implemented to obtain a more efficient and resilient structural design;
- Increased system reliability: the submergence under harsh environmental conditions and the dielectric elastomer generator system aim to improve the overall lifecycle reliability of the devices;
- Array optimization: the shared moorings concept, applied through rigid and non-rigid connections among devices in a farm, intended to have a positive impact on the total cost of the project by reducing the overall number of anchoring points and of bottom lines;
- Improved power conversion: both the dielectric elastomer generators and the tetra-radial turbine are new PTO concepts that aim at enhancing the overall energy production.

3.1. Enhanced added-mass

The third sub-structure of the OWC spar-buoy, defined in section 2.1.1 as the large thickness tube, has a geometry that can be modified in order to increase the inertia of the vertical motion dynamics of the device. Therefore the natural frequency of the device can be adjusted to the dominant frequency of the incoming waves through the tuning of the mass and the geometry of the large thickness tube. The enhanced added mass breakthrough concept aims to obtain the described effect in an optimized way.

As it happens in the reference case, the inner surface of the third sub-section of the structure is progressively enlarged, causing an increase in the mass of water displaced by the motion of the device without changing its cross sectional area in the other sub-sections and thus without affecting the hydrodynamic performance near the water free surface. In this way high performances can be achieved keeping the draft of the structure as short as possible. It is important to notice that, in general, the bottom part of the device cannot be located too close to the water free surface but it has to be submerged deep enough so that its interference with the characteristic radiation field of the floater, which is essential to maximize power absorption in the case of heaving converters, is reduced. The EAM breakthrough concept is a further step in the optimization of the large thickness tube, already partially implemented in the reference case, aiming to an overall reduction of the LCOE without sacrificing the original performance of the device.

The structure keeps the same overall length and draft as in the reference case (respectively 51 and 36 meters) but, as shown in Figure 7, the small thickness tube is slightly longer when the EAM breakthrough is applied and the large thickness tube has both the internal and external surfaces reduced. This feature allows a reduction in the overall material needed for the construction of the device. The total amount of ballast weight is also lower respect to the reference case one, corresponding to 798.6 tons. Moreover, it is all located in the large thickness tube sub-structure while there is none in the floater. Thus the center of buoyancy results to be higher, meaning closer to the free water surface, compared with the reference case while the center of gravity results to be lower.

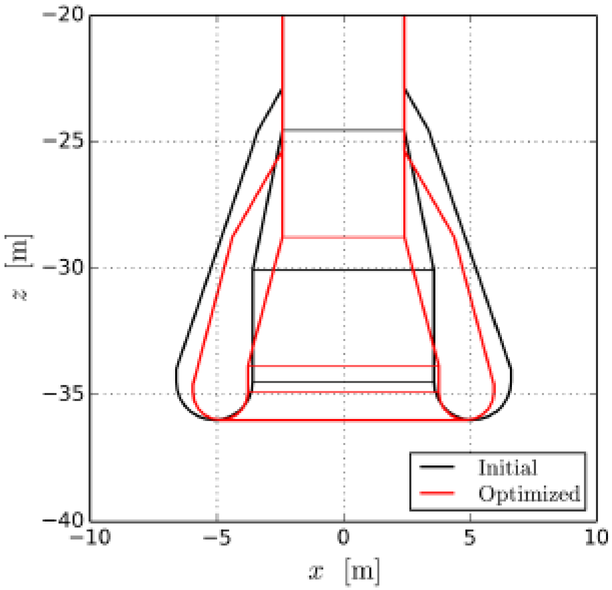


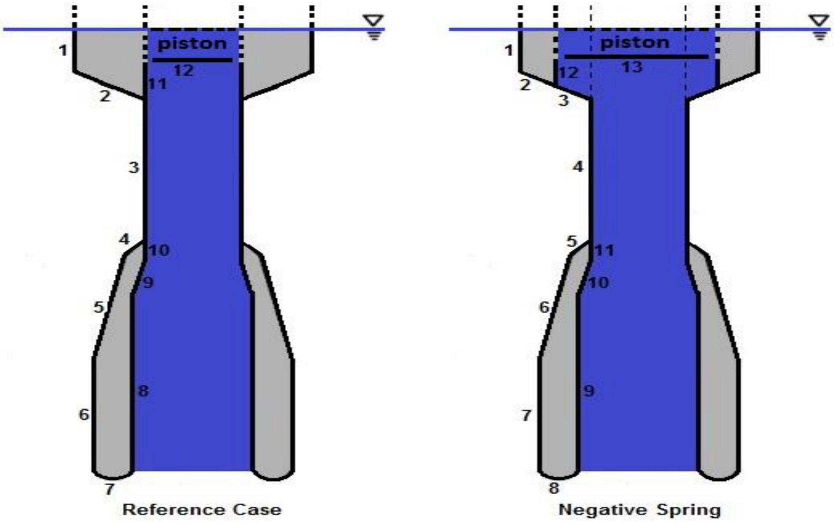
Figure 7: Large thickness tube geometry for reference case (black) and EAM case (red) [10]**.**

The general idea is to control accurately the volume and mass distribution of the large thickness tube, in order to optimize the pitch/roll stability of the whole device.

3.2. Negative spring

As already explained in section 2.1, the OWC spar-buoy uses the relative heaving motion between the water column inside the device and the device structure to drive the air flow through the turbine and produce energy. It has been shown that a heaving point absorber, as it is the case of the OWC spar-buoy, should operate in resonance with the incoming waves in order to achieve optimal energy absorption conditions [4]. Therefore, converters should be designed to have large dimensions and mass in order to counterbalance the high hydrostatic spring effect associated with heaving devices. Another possible solution to adjust the device's natural frequency is to apply a negative spring effect to compensate the very strong hydrostatic spring-like effect, thus keeping the WEC at small dimensions and decreasing the stiffness of the system at the same time.

It is possible to modify the OWC spar-buoy's inner structure and directly act on the hydrodynamic properties of the device in order to produce a negative spring effect without requiring any mechanical or electrical component. In fact, the negative spring effect can be produced by enlarging the air chamber inside the floater, as shown in Figure 8. This is expected to increase the level of reliability of the system as problems associated with the fatigue of mechanical or pneumatic springs are avoided.



Reference Case

Negative Spring

Figure 8: Geometry schematic description for reference case and NS case [11].

The OWC spar-buoy with the negative spring breakthrough applied is considerably smaller than the reference case device. In fact, although the floater and the large thickness tube (section 2.1.1) keep the same external dimensions, the small thickness tube is 10 meters shorter. That reflects on a reduction of 10 meters in the total height and draft of the device (becoming respectively 41 and 26 meters). Moreover, the floater has a greater inner surface since it is enlarged in order to produce the negative spring effect. For the study the cross-sectional area of the floater is considered to be reduced by the 30% of the value it has in the reference case in order to make room for the expanded air chamber.

3.3. Survivability submergence

Floating WECs, such as the OWC spar-buoy, are fully exposed to the ocean climate, including very harsh conditions like severe storms. This is one of the major causes for the conspicuous survivability issues affecting wave energy technology. The survivability submergence breakthrough aims to solve those issues by temporarily submerging the device during extreme events. In fact, a few meters below the water free surface, structural loads are significantly lower.

Concerning the OWC spar buoy, the submergence of the structure from its operational condition (floating on water surface) can be achieved by:

- Actively controlling the mooring elements so that a pulling force towards the sea-bottom is applied to the fairleads of the device;
- Ballasting the structure to increase the submerged mass of the body;
- A combination of the two previous methods.

The third option is liable to produce the most efficient results and, consequently, it is the one that will be considered in this work. In order to implement the survivability submergence breakthrough, it is considered that two water pumps are located in two of the three sub-structures of the device: the floater and the large thickness tube. The pumps are used to fill some defined chambers inside the device structure. The water provides the ballast needed to sink the spar-buoy. Moreover, because of the selective filling of the available space, the structure also starts to tilt on one side. In the meanwhile the winches located at the connection points of the mooring lines are activated in order to keep pulling the device in the direction of its first inclination due to the ballast chamber filled with water. In order for this method to be effective, three extra mooring lines, compared to the reference case mooring system (section2.1.3), have to be installed and attached to the lower part of the structure, at the bottom of the large thickness tube. In fact without the extra set of lines it would not be possible to drag down the device and keep it in the desired final position: lying almost horizontally under the water surface, as shown in Figure 9.

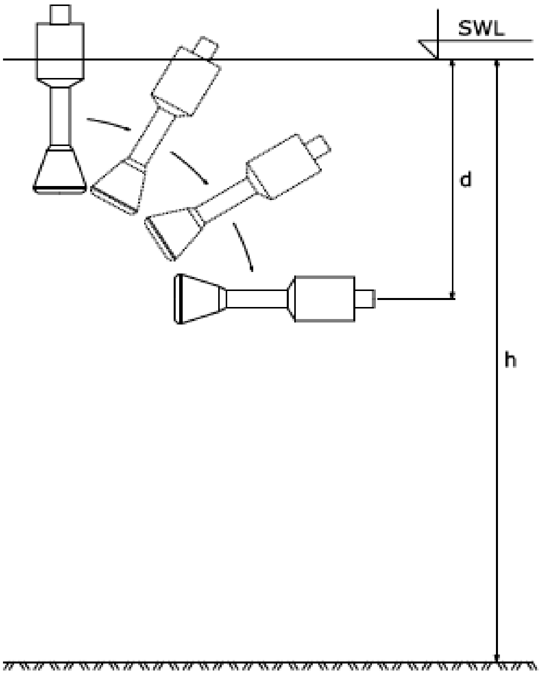


Figure 9: Final submerged position of the OWC spar-buoy when the survivability procedure is applied [12].

Although the concept would be very effective for the survivability of floating devices, as proven by hydrodynamic computation in sources [12] and [13], there are some critical engineering issues associated with the submergence strategy, such as:

- Submergence and position restoring procedures and their hydrodynamic analysis;
- Hydrodynamic behavior of the submerged device;
- Ensure proper sealing and protection of all on-board electro-mechanic and power electronic equipment fitted in the OWC spar buoy;
- Risk of collision with the seabed;
- Material corrosion, and in particular, the areas of the structure alternatively exposed to the atmosphere or the ocean environment;
- Fatigue of the critical active parts of the submergence procedure.

Nevertheless the survivability submergence breakthrough is considered to have an attractive potential regarding the facilitation of the logistics in case of severe marine events that could reflect on a decrease of the operation and maintenance cost of a farm composed of OWC spar-buoy devices.

3.4. Shared moorings

The shared moorings breakthrough is the only one specifically referring to an application of multiple devices and not just to a feature of the single converter. For wave energy to become economically viable large farms are more likely to be installed rather than single devices, also considering that the rated power of a single WEC is normally quite low. The concept of shared mooring answers to the need of an organization of a potential wave farm aiming to bring both logistic and economic benefits to the project.

Many configurations have been proposed and studied for sharing moorings in an array of devices. Three of them are presented here and they all have the common feature of considering the arrays composed of five devices, disposed with four of them forming a square and the fifth located in the middle, as shown in Figure 10.

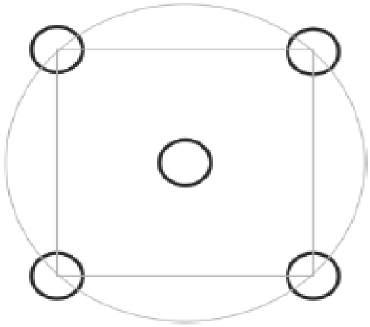


Figure 10: Disposition of five devices in a cluster to form an array [7]**.**

In the first configuration (configuration B, since configuration A refers to the situation where the breakthrough is not applied, Figure 11 on the left) for shared moorings each of the four corner devices (Dev. 1-4 in Figure 11) has two mooring lines anchored on the seabed. Those lines have the same features as the ones described in section 2.1.3 for the reference case design (rope and chain sections, clump weights and floaters) but different lengths. The devices are interconnected through some extra lines that feature a clump weight at the half of the way in between each couple of converters connected in this way.

In the second configuration (configuration C, Figure 11 in the middle) there are still the same interconnection lines as in configuration B but the corner devices just have one line to the sea bottom each, instead of two.

Finally in the third configuration (configuration D, Figure 11 on the right) there are just four bottom lines, one for each corner device, and just four interconnection lines, one for each corner device, all connecting them with the central device.

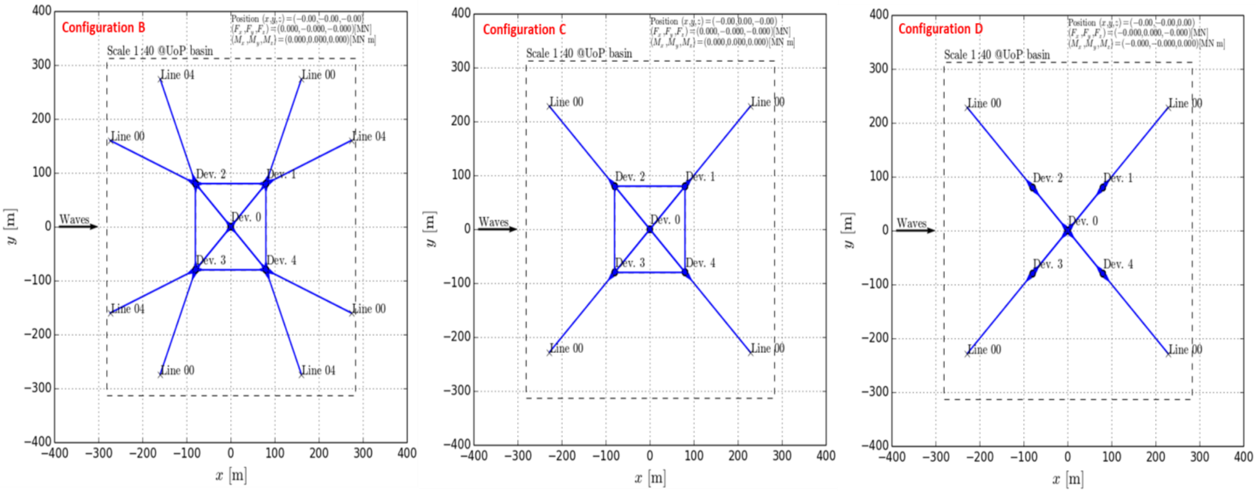


Figure 11: Schematic layout of the three possible configurations for the SM breakthrough (internal WavEC data)**.**

All the configurations described are intended to reduce the amount of mooring lines connected to the bottom of the sea, thus the total number of anchors, aiming to reduce the capital expenditure for materials and installation, without compromising the safety of the farm or the performance of the single devices in the arrays. A natural consequence is that when less mooring lines are installed they need to be more resistant in order to perform properly and keep the devices in position. Therefore the thickness of the ropes and chains needs to be increased and so does the cost per meter of the lines composing the mooring system. Accordingly, a balance between the number of lines installed and their dimensions has to be reached in order to decrease the costs. A complete review of the mooring systems, both for reference case and breakthroughs, is presented in section 5.3.3.

3.5. Dielectric elastomer generator

Typically OWC devices employ an electro-mechanical PTO system to convert the energy carried by the waves into electricity. The presence of moving parts, as air turbines, installed on a device continuously subjected to very harsh marine conditions can affect the reliability and increase the need for maintenance of the whole system. Moreover, the air turbines currently available for wave energy applications show limitations in efficiency or flow rate ranges, implying that they can even not be the optimal solution for the OWC technology. In this context, recently arose the idea of applying dielectric elastomer generator systems into WECs to replace the traditional PTO equipment. The DEG concept is based on a solid-state deformable transducer made of elastic polymers that can produce directly electricity from the mechanical stress induced on them, exploiting the variable-capacitance electrostatic generation principle. Hence, instead of the self-rectifying air turbine, inside the hollow structure of the device is placed a soft/deformable rubber-like membrane.

In the present study a DEG PTO system composed by three circular membranes located on top of the floater sub-structure is considered, as shown in Figure 12. In turn each of the three DEGs is composed by four modules of silicone elastomers, as four different layers stacked on top of each other. Moreover each module is considered to be independent from the others and individually replaceable in case of failure.

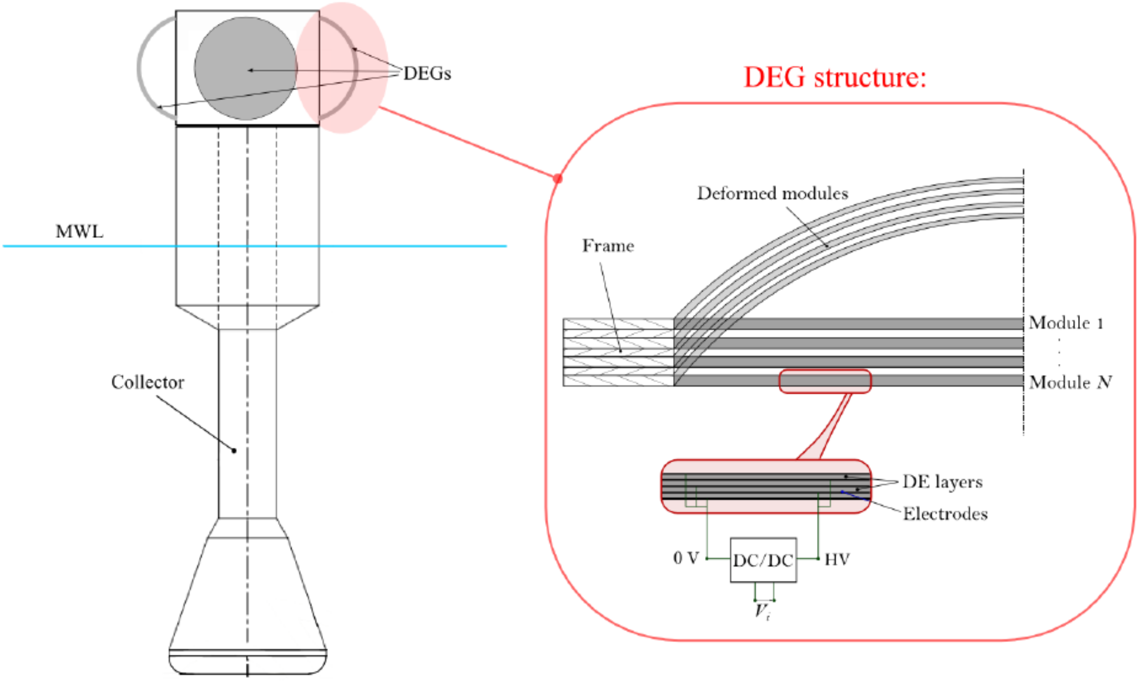


Figure 12: DEG PTO system schematic architecture [14].

The DEG system concept is still in an early phase of development, although DEGs have been tested in experiments reproducing operating conditions in laboratory in order to assess their real potential in wave energy conversion [15]. Small-scale prototypes, with nominal power in the range of one Watt, have shown an average energy density of 0.7 kJ/kg wave-to-wire energy converted for each cycle by a unit of employed dielectric material. Moreover a value of conversion efficiency of nearly 25% has been reached [6]. The future perspective is to increase both energy density and efficiency by the introduction of new materials, more efficient and adequate for wave energy application than the silicone elastomers already tested.

The wave energy sector can potentially take great advantages from DEG technology, compared with traditional PTO systems, mainly considering that the former features direct drive cyclical operation with good energetic efficiency that is almost independent of wave period, easier installation and maintenance processes and lower costs.

3.6. Tetra-radial turbine

The last breakthrough concept is related with the PTO system, as the previous one. It consists of a new generation self-rectifying air turbine: the tetra-radial turbine. The turbine features two sets of rotor blades, each one with a set of guide vanes, mounted on the same shaft and axially offset from each other. The whole rotor can be seen as formed by two conventional single-stage radial turbines, respectively T_1 and T_2, as shown in Figure 13. The name “tetra-radial” comes from the two inlets and two outlets resulting from the twin turbine rotor configuration.

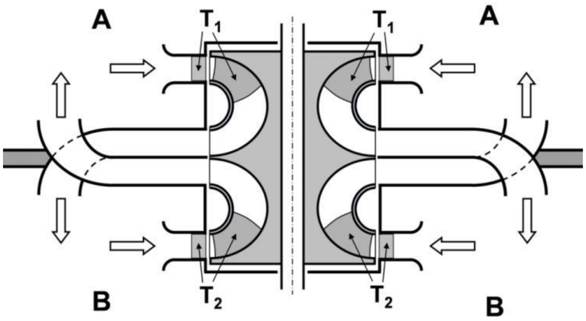


Figure 13: Tetra-radial turbine schematic configuration [16].

The spaces A and B, shown in Figure 13, are respectively the OWC air chamber and the atmosphere:

- When the pressure inside the chamber is higher than the atmospheric pressure ($p_A > p_B$), the air flows just through the blade set T_1;
- When the pressure inside the chamber is lower than the atmospheric pressure ($p_A < p_B$), the air flows just through the blade set T_2.

The air flows in the right directions because of a double set of curved ducts arranged circumferentially and alternately open to space A and space B. In between the rotor blades and the corresponding set of curved ducts there is a bladeless space, bounded by curved and plane walls of revolution, that acts as a diffuser allowing a partial recovery of the kinetic energy at the exit of the rotor.

An axially-sliding cylindrical valve located at the exit of the ducts helps in preventing the air to flow in the wrong direction. The valve has three different working positions, as shown in Figure 14:

- Configuration a (on the left): shows the position of the valve when $p_A < p_B$;
- Configuration b (in the middle): shows the position of the valve when the rotor is blocked, for safety reasons or in order to perform control strategies over the device motion. In fact, if the valve actuator is fast enough, it is possible to phase-control the system by latching.
- Configuration c (on the right): shows the position of the valve when $p_A > p_B$.

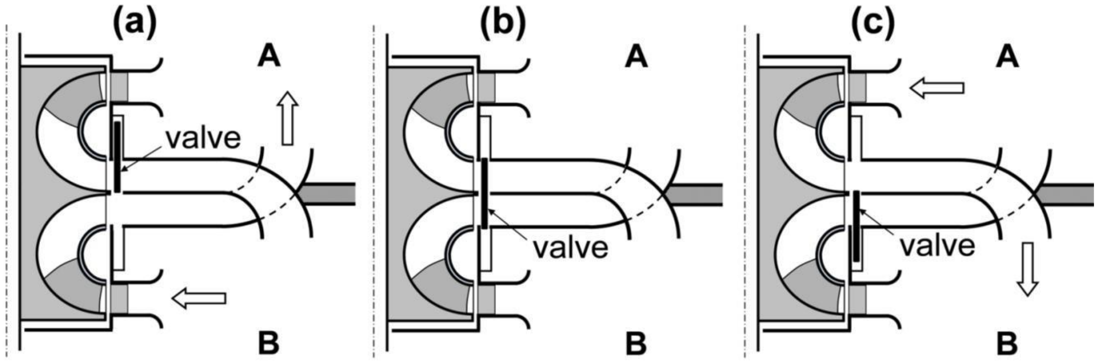


Figure 14: Three different positions for the axially-sliding valve in a tetra-radial turbine [16].

The tetra-radial turbine has been designed as an improved version of the already existing self-rectifying air turbines, so that it could guarantee a higher energy production of an OWC device. Its efficiency has been studied and it has proven to perform better than the other turbines. In fact, as can be seen in Figure 15, which presents a comparison of the efficiencies of five different typologies of air turbine, the tetra-radial technology stands over the others throughout all the flow range computed in the study [16].

As mentioned in section 2.1.2, the Wells turbine has high peak efficiency but a narrow operating flow range. The axial-flow impulse turbine with Fixed Guide Vanes (FGV) has the lowest peak efficiency, due to the losses at the entry of the downstream row of guide vanes. The situation improves substantially, 10-15% peak efficiency increase, with Moveable Guide Vanes (MGV), although the complexity of the system increases too. The bi-radial turbine shows better performances than both Wells and axial-flow impulse technology. In the version with axially displaceable guide vanes it reaches a peak efficiency of 79%. As for the axial-flow impulse typology, also the bi-radial turbine with fixed guide vanes suffers from losses at the entry of the downstream row of guide vanes. On the other hand, the curved-duct manifold configuration of the tetra-radial removes the downstream row of guide vanes allowing the use of a very efficient rotor that does not need to be symmetric as the case of the other turbines. In fact peak efficiencies of about 86% have been numerically predicted.

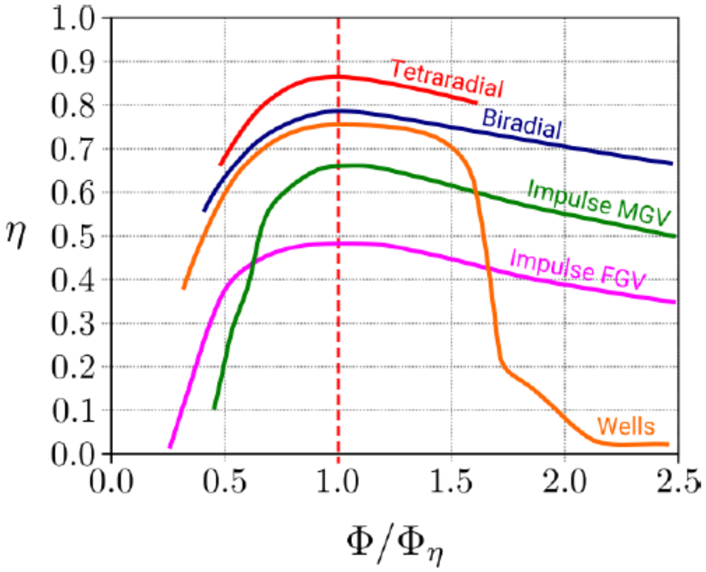


Figure 15: Efficiencies of different typologies of self-rectifying air turbines [16]**.**

The effect of the tetra-radial turbine on the economics of a wave energy project is not going to be assessed in this study because of the lack of data regarding the costs and the power outcome of the new generation self-rectifying air turbine.

4. Methodology

4.1. Techno-economic analysis

One essential step in the development of a new technology for energy production is its economic assessment. As any other project that involves consistent investment, the installation of a WEC or of an array or WECs forming a power plant has to be accurately considered from the economic point of view. There are many indicators that can be used both by developers and investors to understand the effectiveness of a project, the main ones being:

- Net present value (NPV): the NPV of a project consists in the sum of cash flows, both negative (expenses) and positive (incomes), throughout its life time and discounted to its beginning, in order to take into account the time value of money. If the sum, so the NPV, is positive the project is economically profitable.
- Internal rate of return (IRR): the IRR represents the rate of return that makes the NPV on a particular investment equal to zero. The higher the IRR is above the discount rate a project is expected to have, the more desirable it is to undertake the project.

- Levelized cost of energy (LCOE): the LCOE is the ratio of total lifetime expenses versus the total expected output of energy production, both the terms expressed as present value equivalents. The LCOE is conventionally defined as the average cost per MWh of useful electrical energy produced by a generation facility and it can be seen, roughly, as the lowest selling price of electricity for a project to break-even in a financial cash-flow analysis.

The understanding of the notion of discount rate is essential in order to grasp the three aforementioned concepts. The discount rate can be seen as the return that investors ask to put their money in a certain project, as a cost for lending money. Thus a higher perceived risk attracts a higher discount rate. The normal depreciation in time of money, mainly due to inflation, the cost of lending money for a risky project instead of investing it in safer ones and the perceived risk of the project itself are the parameters that affect the discount rate.

4.2. LCOE analysis for wave energy systems

While the NPV and the IRR are used, often together, to assess the economic feasibility of a given project, the LCOE is a metric that allows the comparison between the analyzed energy source and others, thus being able to understand if a specific system would be competitive in the energy market.

As already mentioned in section 4.1, the terms of the LCOE equation are expressed as present value equivalents. It means that the expected cash and energy flows for the future are brought to the present, meaning at the beginning of the project, when the farm starts to be operational. The process of reporting future values to the present is performed through a discounting factor:

$$f_d(t) = \frac{1}{(1+r)^t} \qquad (1)$$

Where:

- f_d is the discount factor;
- r is the discount rate;
- t is the time, expressed in years from the beginning of the project.

The discounting process performed to obtain the present value equivalents is based on the idea that a lower value, so a greater discount, should be attributed to future cash and energy flows than on present ones, since the former flows may not occur.

The LCOE formula is the following:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{(I_t + O\&M_t + F_t + C_t + D_t)}{(1+r)^t}}{\sum_{t=0}^{n} \frac{AEP_t}{(1+r)^t}} \qquad (2)$$

Where:

- I_t are the investment costs during year t;
- $O\&M_t$ are the operation and maintenance costs during year t;
- F_t are the fuel costs during year t;
- C_t are the carbon costs during year t;
- D_t are the decommissioning costs during year t;
- AEP_t is the annual energy production during year t;
- n is the lifetime of the project.

The investment costs include all the expenses needed to bring the farm to its operational state. They start with the pre-operating costs, for preliminary studies and environmental impact analysis, and they go on with the construction or purchasing costs for the farm element and their installation at the deployment site. The investment costs are also known as capital expenditures (CAPEX). For the LCOE analysis all those expenses are normally brought at the beginning of the project, even if many of them were performed in the previous years. The discount factor is reversed and multiplied by the present value of each cash flow in order to find its future value, corresponding to the time zero, hence the beginning of the project. Another approach is to consider all the investment costs as performed at time zero. In that case they are known as overnight costs because the farm is considered to be built and installed overnight, without considering the financial costs. Then the interests during construction can be taken into account considering the expenses were equally distributed along the construction time. Therefore the annual expenses would be annuities since every year the same amount of money is spent. The annuities are computed by dividing the total overnight cost by the construction time, in year. Finally the found result can be brought to time zero, considering the interests, multiplying by the factor for the future value of an annuity:

$$f_a = \frac{(1+r)^n - 1}{r} \qquad (3)$$

Where:

- f_a is the factor for the future value of an annuity;
- r is the discount rate;

- n is the construction time, in years.

The operation and maintenance costs represent all the expenses throughout the farm lifetime, from the beginning of operation until the decommissioning. They are mainly composed by costs related with management and administration, inspection and maintenance procedures. The operation and maintenance costs are also known as operating expenditures (OPEX). There are many issues related with the computation of the OPEX for wave energy farms. In fact it is often complicated to assess the failure modes and the consequent maintenance procedures needed throughout the farm lifetime. Because of lack of experience in WEC operation at sea for long periods of time, the information for operation and maintenance expenses are normally taken from other fields such as oil and gas industry or offshore wind. Of course many approximations and assumptions are done during the failure modes assessment. The OPEX is computed as a fixed amount of money spent every year and all of the terms are discounted to present time in the LCOE formula.

The fuel and carbon costs are respectively the expenses for the procurement of the fuel used to run the power plant and for the emissions during its operation. Of course those expenditures are related with non-renewable sources like coal or gas and thus they are not part of the equation for wave energy.

The decommissioning costs are related with the farm dismantling at the end of its lifetime. It is always computed as a percentage of the CAPEX. The expense just occurs once at the end of the farm lifetime and it is discounted to time zero, as all the other terms in the LCOE formula.

The annual energy production is computed using the available data on the wave climate of the deployment location and the characteristic energy production of the device for the different conditions. The mechanical and electric losses are considered and the final value of produced energy is considered to be constant throughout the farm lifetime.

5. Description of the model

The hereby presented techno-economic assessment of a potential wave energy farm of OWC spar-buoy devices is based on the LCOE metric and it is performed using a spreadsheet (Excel-based) model developed by WavEC Offshore Renewables. The idea of the model is to reduce as much as possible the uncertainties and the approximations made during the economic assessment of a wave energy project. In fact it aims at being comprehensive of all the input data that have an influence on the final LCOE.

The next part of the report is going to be organized following the different tabs of the model itself in order to describe the tool used and the data required to perform the analysis.

5.1. Location

For the performed study two different locations where taken into account: Wave Hub pilot zone and Leixões deployment site. These two sites were considered as adequate for possibly hosting a first wave energy farm composed of OWC spar-buoy devices. The parameters related with the deployment location that have a considerable influence on the final LCOE value mainly consist of: distances from site to shore and to both nearest small and large ports, presence of an onshore substation and distance from shore to a substation, if existing, or to the grid connection directly and water depth at the farm central deployment location. The information needed to fill the model were extracted from sources [17], [18] and [19].

Table 1: Parameters depending on deployment site position.

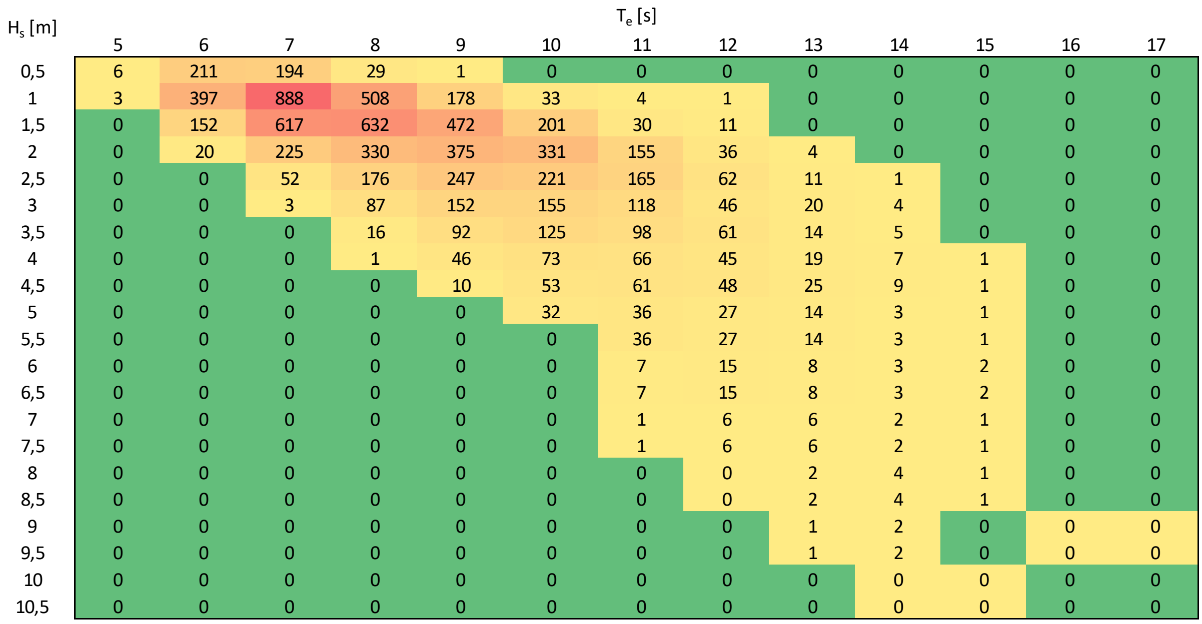
Data	Unit	Wave Hub	Leixões
Distance from site to nearest large port	km	100	30
Distance from site to nearest small port	km	9	30
Distance from site to shore	km	11	30
Distance from shore to substation/grid	km	4	2
Water depth at deployment location	m	50	106

All the aforementioned parameters have an impact on the total CAPEX of the project. In fact for instance the total length of the electric cables used to carry the electricity produced from the farm to the grid, such as the static export cable and the onshore cable, depend respectively on the distance from shore and the distance from the grid connection. Moreover the water depth influences as well the electric system and the mooring system since the lengths of both dynamic cables and mooring lines depend on that parameter. The electric configuration of the farm is presented in detail in section 5.3.2, while the mooring system is described in section 5.3.3.

Concerning the distances from small and large ports, they mainly affect the logistics for the installation operations and the maintenance procedures for the farm, since they directly influence the time necessary to reach the deployment site, which in turn can have a significant impact on the weather windows available to perform such operations. The concepts of logistic, O&M and weather windows are going to be explained more in detail further in this report (sections 5.4 and 5.5).

In general, looking at Table 1, it can be said that in Leixões there is a little advantage when relevant marine operations, like the installation of devices, have to be done because the nearest large port is closer. On the other hand small port and shore are more distant from the deployment site, increasing costs for small maintenance procedures and for carrying the electricity to shore. Finally the water depth is substantially lower in Wave Hub, reducing consistently the costs for dynamic cables and mooring lines.

The last very important information about the deployment sites provided in the *Location* tab concerns their typical wave climates, which are summarized in the form of scatter diagrams. A scatter diagram is a matrix that represents the joint probability of wave height and period combinations during the time frame considered. Normally the time periods considered are long enough to account for seasonal and inter-annual variability and the data collection is carried through many repeated periods so that average values for wave climate conditions can be computed and expressed as average number of hours in a year characterized by a given combination of wave height and period. As an example, the scatter diagram for Leixões deployment site is presented in Figure 16 (the scatter diagram of Wave Hub pilot zone is reported in *Annex*, Figure 25).



H_s [m]	T_e [s] 5	6	7	8	9	10	11	12	13	14	15	16	17
0,5	6	211	194	29	1	0	0	0	0	0	0	0	0
1	3	397	888	508	178	33	4	1	0	0	0	0	0
1,5	0	152	617	632	472	201	30	11	0	0	0	0	0
2	0	20	225	330	375	331	155	36	4	0	0	0	0
2,5	0	0	52	176	247	221	165	62	11	1	0	0	0
3	0	0	3	87	152	155	118	46	20	4	0	0	0
3,5	0	0	0	16	92	125	98	61	14	5	0	0	0
4	0	0	0	1	46	73	66	45	19	7	1	0	0
4,5	0	0	0	0	10	53	61	48	25	9	1	0	0
5	0	0	0	0	0	32	36	27	14	3	1	0	0
5,5	0	0	0	0	0	0	36	27	14	3	1	0	0
6	0	0	0	0	0	0	7	15	8	3	2	0	0
6,5	0	0	0	0	0	0	7	15	8	3	2	0	0
7	0	0	0	0	0	0	1	6	6	2	1	0	0
7,5	0	0	0	0	0	0	1	6	6	2	1	0	0
8	0	0	0	0	0	0	0	0	2	4	1	0	0
8,5	0	0	0	0	0	0	0	0	2	4	1	0	0
9	0	0	0	0	0	0	0	0	1	2	0	0	0
9,5	0	0	0	0	0	0	0	0	1	2	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0
10,5	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 16: Scatter diagram, expressed in hours per year, for Leixões deployment site, Portugal (internal WavEC data)**.**

As it is possible to notice from Figure 16, the scatter diagram uses the significant wave height and the energy period to describe the wave climate, respectively taken in intervals of half meter height and one second period. The significant wave height (H_s) corresponds to the mean wave height, trough to crest, of the highest third of the time-series of waves observed, representing a certain sea state. On the other hand, the energy period (T_e) represents the mean wave period with respect to the spectral distribution of energy. Their annual average values for the sites under consideration are reported in Table 2, together with the average annual wave power.

Table 2: Parameters depending on site location wave climate (internal WavEC data)**.**

Data	Unit	Wave Hub	Leixões
Average annual wave power	kW/m	13.3	28.2
Average H_s	m	1.5	2.0
Average T_e	s	7.8	8.6

As it is possible to notice from Table 2, in Leixões the power per meter of crest is higher compared with Wave Hub, meaning that the former location has a greater resource potential.

The data used to fill the scatter diagrams for the two selected locations, Wave Hub and Leixões, were gathered by WavEC in previous collaborations focused on the same testing areas. For Wave Hub the data were collected using monitoring buoys deployed at site for one year while for Leixões the data are the result of a numerical model based on information related with wind fields for a ten years period.

The scatter diagrams can be used to compute the total annual energy production, together with the power matrix of the device. These concepts will be explained better in the sections 5.2 and 6.3.

Table 3 presents the values of the main factors contributing to the LCOE (CAPEX, OPEX and AEP) and the values of LCOE for the two different locations considered in the study. Both CAPEX and OPEX are lower for Wave Hub since both coast and small dimensions port are closer in that case compared with Leixões, reducing the costs for electric cables and offshore maintenance. The comparison has been done considering the “string” configuration for the electrical system that is explained in detail in section 5.3.2. Moreover, the cost for the mooring system is considerably lower due to the difference in the water depth. On the other hand, in Leixões the wave climate offers better conditions for energy harvesting, reflecting on a higher mean annual energy production.

Table 3: CAPEX, OPEX, AEP and LCOE values for the two locations selected for the study.

Data	Unit	Wave Hub	Leixões
CAPEX	€/kW	17478	23130
OPEX	€/kW	1585	1709
AEP	MWh/y	9157	14104
LCOE	c€/kWh	221.6	176.0

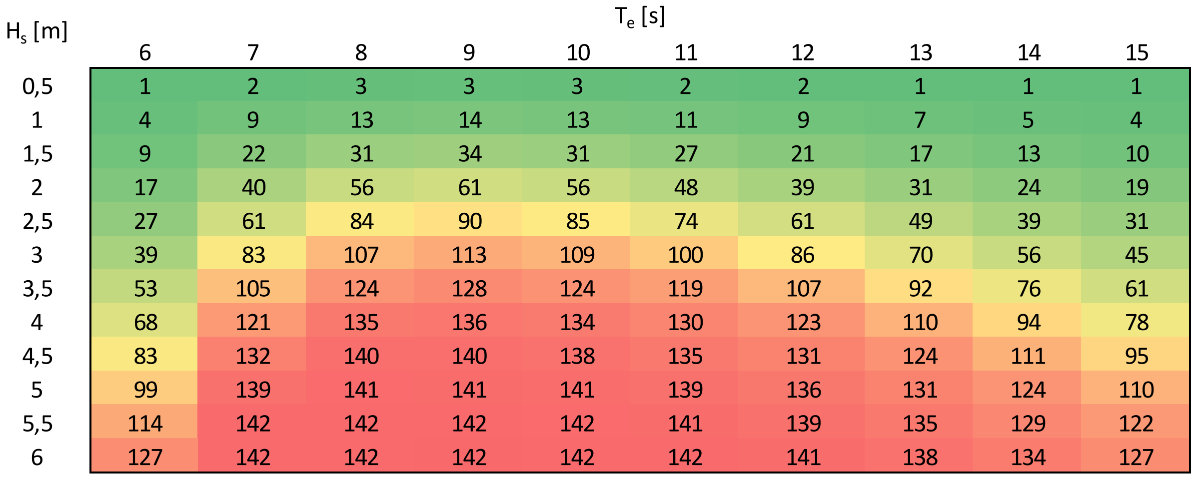
As can be noticed from Table 3, in Leixões the best LCOE value is achieved, meaning that the effect of a greater energy production prevails on the higher costs. Therefore, Leixões is the location that is going to be considered in all the next comparisons in the report.

The values of LCOE presented in Table 3 are high compared to the other sources available in the energy market. Nevertheless, it should be noted that the values refer to a prototype and that the system was not optimized for the locations chosen for the study.

5.2. WEC design

In this section the main characteristics of the device, as its structure and PTO system are described. Moreover here is also introduced the distinction between the reference case and the ones with each single breakthrough applied. In fact in this module of the model there is the possibility to choose which breakthrough to study in detail. It is important to underline that in the presented model each of them is analyzed on its own and they cannot be put together in order to apply more than one at the same time.

Depending on the choice of the case under focus, some of the characteristics of the device might change all over the model. In the *WEC design* module the first very important change that depends on the selected case concerns the power matrix of the device. The power matrix of a wave energy converter indicates the electric power output, in kW, that is expected to be obtained for the whole possible range of sea states the device can be subjected to. As it can be seen from Figure 17, a specific power output, defined through modelling at first and then validated through small-scale testing, is associated to each combination of significant wave height and energy period values, with the same intervals used for the scatter diagrams in the *Location* tab. The combination of the power matrix of a device and the scatter diagram of a location leads to the assessment of the total energy that can be produced (section 6.3).



H_s [m]	T_e [s] 6	7	8	9	10	11	12	13	14	15
0,5	1	2	3	3	3	2	2	1	1	1
1	4	9	13	14	13	11	9	7	5	4
1,5	9	22	31	34	31	27	21	17	13	10
2	17	40	56	61	56	48	39	31	24	19
2,5	27	61	84	90	85	74	61	49	39	31
3	39	83	107	113	109	100	86	70	56	45
3,5	53	105	124	128	124	119	107	92	76	61
4	68	121	135	136	134	130	123	110	94	78
4,5	83	132	140	140	138	135	131	124	111	95
5	99	139	141	141	141	139	136	131	124	110
5,5	114	142	142	142	142	141	139	135	129	122
6	127	142	142	142	142	142	141	138	134	127

Figure 17: Power matrix, values expressed in kW, of the reference case device (internal IST data)**.**

Since the pneumatic and the mechanical power that can be absorbed from the converter are influenced respectively by its structure and its PTO system, as there is a change in those parameters, introduced by a breakthrough, the power matrix changes too.

5.2.1. Device structure

The only two breakthroughs that involve some changes in the structure of the converter are the enhanced added mass and the negative spring ones, while for all the other cases the device keeps the same structural characteristics of the reference case. The main differences have already been explained in sections 3.1 and 3.2. Hence, Table 4 presents a summary of the effect of the structural changes of the two breakthrough cases compared with the reference (REF), mainly regarding the surfaces of the three sub-structures and the total weights of the structure and of its ballast.

Table 4: Structural dimensions of the devices for reference, EAM and NS cases.

Data	Unit	REF	EAM	NS
Floater diameter	m	12	12	9
Structure draft	m	36	36	26
Sub-structure 1 surface	m^2	1094	1094	919
Sub-structure 2 surface	m^2	245	277	89
Sub-structure 3 surface	m^2	751	575	751
Total structural weight	t	248	231	208
Total ballast weight	t	964	799	765

The data presented in Table 4 are significant for the computation of the structural costs related with the construction of the devices. In fact they have been assessed through an approximation related with the amount of material used and its price. The structure is realized in steel, with 7900 kg/m^3 of structural density and a cost of 3500 €/ton. Consequently, from the given structural dimensions it is possible to compute the total amount of raw material needed and consequently the total cost. The ballast material is considered to be concrete, with a structural density of 2500 kg/m^3 and a price of 70 €/ton. The ballast is used to keep the structure floating with the exact draft established to be optimal through hydrodynamic analysis.

Considering both steel structure and ballast, the estimated final procurement costs for the three sub-structures, for the reference spar-buoy device, are listed in Table 5.

Table 5: Structure costs for reference case device.

Data	Unit	Reference case
Sub-structure 1	k€	482
Sub-structure 2	k€	102
Sub-structure 3	k€	350
Total structure	k€	1028

It is important to notice that the final value for the total structure does not correspond to the exact sum of the three sub-structures costs because there is a 10% factor introduce to consider contingencies such as a higher price for the desired shapes that would not have been taken into account simply multiplying the amount of material used and its market price.

Table 6 presents the percentage variation of cost for the device structure for the five analyzed breakthroughs compared with the reference case.

Table 6: Percentage variation in the structure costs for the five analyzed breakthroughs compared to the reference OWC spar-buoy.

Data	EAM	NS	SS	SM	DEG
Sub-structure 1	-6%	-21%	0%	0%	0%
Sub-structure 2	13%	-64%	0%	0%	0%
Sub-structure 3	-16%	4%	0%	0%	0%
Total structure	-8%	-16%	0%	0%	0%

Table 6 represents the percentage of cost variation corresponding to the different changes in the device structure associated to each breakthrough. In fact, the only two breakthroughs with significant structural modifications are the enhanced added mass and the negative spring concepts, while the others keep the exact same structure of the reference case. In the survivability submergence case there is a little variation in the ballast weight for sub-structures 1 and 3 because the weight of the pumps, needed for the submergence process, has been considered as ballast. As shown by the table, the variation has no effective consequence on the procurement cost and can be neglected.

5.2.2. PTO system

Concerning the PTO system, in the reference case the spar-buoy is considered to be equipped with a bi-radial turbine coupled with a permanent magnet synchronous generator, as explained in section 2.1.2. The only analyzed breakthrough that has different equipment for energy conversion is the dielectric elastomer generator case (sections 3.5). Conversely, the application of either the shared moorings or the survivability submergence breakthroughs is not considered to have any influence on the power output of the device, since there is no change in the structure and in the PTO system compared with the reference case. Of course that is as well an approximation because in both cases there are some substantial changes in the mooring system design and that can potentially slightly change the performance of the WEC but the assessment of that influence is complex and computationally demanding and off the scope of the present work.

Since no information concerning cost functions for the mechanical equipment was found, an available correlation for Wells turbines [20] was used to estimate the order of magnitude of the procurement cost for the PTO system:

$$C_{mech}(D) = C_{mech,0}\left(\frac{D^3}{D_0^3}\right)^x \qquad (4)$$

Where:

- C_{mech} is the cost for the energy conversion mechanical equipment, the air turbine;
- $C_{mech,0}$ is a reference cost, equal to 330 k€, calibrated through the studies at the Pico wave energy plant;
- D is the diameter of the turbine;
- D_0 is the reference diameter, equal to 2.3 meters, as in the Pico plant;
- x is an empirical exponent, assumed to be equal to 2/3.

For the electrical and ancillary equipment another function was adopted, based on the rated power (P_{rated}) of the device:

$$C_{elec} = 3.3P_{rated}^{0.7} \qquad (5)$$

The costs for the whole PTO system of the reference bi-radial turbine case are derived from the two aforementioned correlations (equations 4 and 5).

On the other hand, for the DEG system the cost function is based on a cost per weight of dielectric material used. In fact the price for procurement of the elastomer material, in an actual industrial scenario for the technology, is assessed to be of 7.5 k€/ton. As already mentioned in section 3.5, the DEG PTO is composed by three membranes, each featuring an amount of elastomer material corresponding to 3.21 tons. Moreover the electrodes have to be considered, accounting for 0.48 tons for each membrane. Thus the mass of each membrane is 3.69 tons and the whole PTO system consists of 11.07 tons of material. Finally, it is important to notice that the device has an overall rated power of 150 kW, as in all the other cases, when the DEG breakthrough is applied and since the PTO system is composed by 12 modules each of them has a rated power of 12.5 kW.

The procurement costs for the reference spar-buoy device are reported in Table 7.

Table 7: PTO system costs for reference case device.

Data	Unit	Reference case
Energy conversion equipment	k€	122
Electrical & ancillary equipment	k€	110
Total PTO system	k€	232

Table 8 presents the percentage variation of cost for the PTO system for the five analyzed breakthroughs compared with the reference case.

Table 8: Percentage variation in the PTO system costs for the five analyzed breakthroughs compared to the reference OWC spar-buoy.

Data	EAM	NS	SS	SM	DEG
Energy conversion equipment	0%	0%	0%	0%	-32%
Electrical & ancillary equipment	0%	0%	7%	0%	0%
Total PTO system	0%	0%	3%	0%	-17%

The survivability submergence concept has a higher cost for the electrical and ancillary equipment because the water pumps used for the submergence procedure are taken into account as an extra electrical component, even if they are not properly part of the PTO system.

The DEG breakthrough has a positive effect on the procurement cost of the energy conversion equipment since the PTO system is cheaper compared with the reference case.

5.3. Farm design

5.3.1. Farm layout

In this tab the outline of a farm composed of spar-buoy devices, featuring the breakthrough eventually chosen in the *WEC device* tab, is defined. The target total capacity has to be set as well as the disposition of the devices. They are disposed at sea following a scheme of rows and columns, forming a geometric configuration on the water surface that is defined by selecting a number of rows in the composition of the farm layout, since the consequent number of columns will depend on the one of the rows. It is important to notice that the "rows" are defined by the number of consecutive devices, equally spaced, that the incoming waves encounter on a straight line, ideally perpendicular to the shore line, on their way from the open sea to the coast. The "columns" are the lines of WECs disposed perpendicularly to the rows. The number of rows has to be an even number, due to the peculiar disposition of the arrays in the farm. In fact, according to what was assessed as the best disposition for the shared moorings breakthrough, described in section 3.4, the devices are grouped in clusters of five WECs, disposed with four of them at the corners of a square and the last one placed in its middle. In order to keep coherence amongst all the different cases, the devices' disposition is always considered to be the aforementioned one. Consequently the number of rows has to be even because every two rows one array is displaced, being the central WEC considered as an "extra-device" inserted in a squared basic texture and just the corner devices being forming the rows in the farm layout.

Arrays are the fundamental units of any possible farm configuration in the model and the actual total capacity depends on the number of installed clusters, thus it can be slightly different from the desired target initially set. In the defined model a single array has always two rows and two columns of devices.

Moreover, as for the shape of the array, also the distance in between rows is assumed to be always constant and equivalent to the value computed for the shared mooring case through an optimization program. The distance between columns is equal to the distance between rows and it is defined as 13.3 times the diameter of a device (12 m), meaning that two devices in two different rows, or columns, are located around 160 meters away from each other, as shown in Figure 18.

For the negative spring breakthrough concept the 160 meters distance between rows and columns is kept but, since the devices have a smaller diameter (9 m), it corresponds to 17.7 times its value.

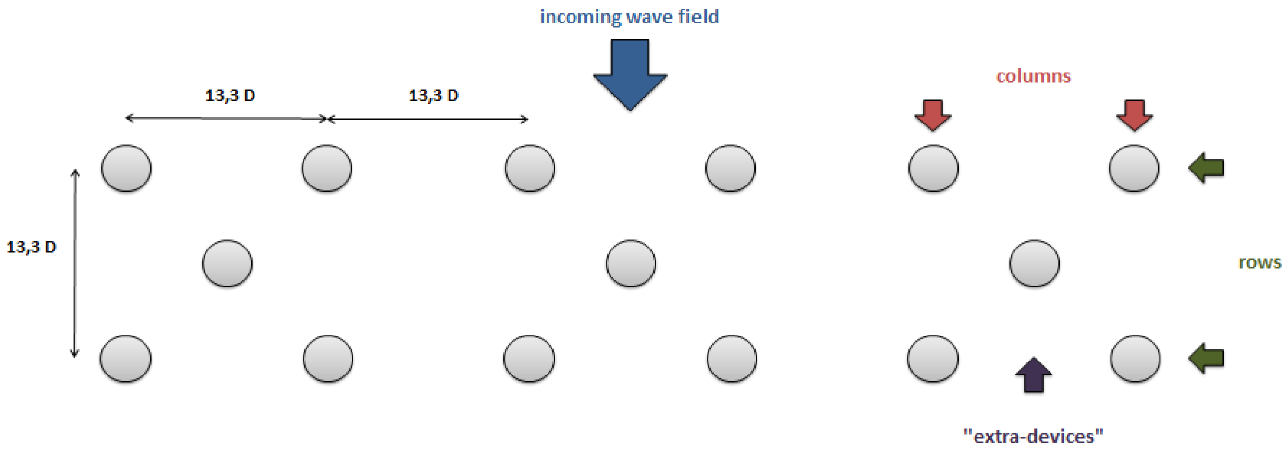


Figure 18: Schematic layout of a wave energy farm composed of OWC spar-buoy devices.

For the study a 5 MW farm was defined, being that value of total capacity a possible target for a first installation in a real case. The arrays are of five devices each and the devices have a rated power of 150 kW each, therefore seven arrays, for a total of 35 devices distributed on two rows and seven columns, were considered in order to reach a final capacity of 5.25 MW. Knowing the disposition and the distances it is possible to compute the area occupied by the farm, including a security perimeter around the devices and the export cable that has to be properly signaled through marker lines. The distance from marker line and edging devices in the farm is assumed to be 500 meters, while 100 meters have to be left from both sides of the export cable. Since the length of the export cable depends on the location, also the total safety area depends on it. On the other hand the offshore safety area just depends on the farm layout. Therefore it can be computed and it has a value of about 3.5 km^2. The total area, considering both farm and export cable, has to be considered for surveys and for the environmental impact analysis (EIA), influencing the total CAPEX of the project.

5.3.2. Electrical system configuration

The electric system is composed by electrical cables, connectors and collection points. There are two main categories of cables: dynamic and static ones. Dynamic cables are flexible and hence they are normally connected to the floating devices and due to their characteristics they are able to stand the continuous movements, stresses and bending forces they are subjected to. On the other hand static cables are stiffer and are normally laid on the sea bottom and then fixed to it or directly buried into it. Thus dynamic cables are used to connect devices amongst them or with the connectors on the seabed, where static cables are located to carry the electricity of the arrays first to a common collection point and then to shore.

The definition of the farm layout is very important for the computations related with the lengths of the electrical cables. In fact the positions of the devices on the water surface define the distances that have to be covered by the cables. However the electric configuration employed is another really relevant element to assess the final cost of the system. The two typologies of electrical layout considered are string and star:

- String configuration: the dynamic cables connect all the devices in a series and then the whole array to the static array cable. Therefore all the devices are connected together and the cables have to be sized so that they can support the power output of the whole array (0.75 MW).

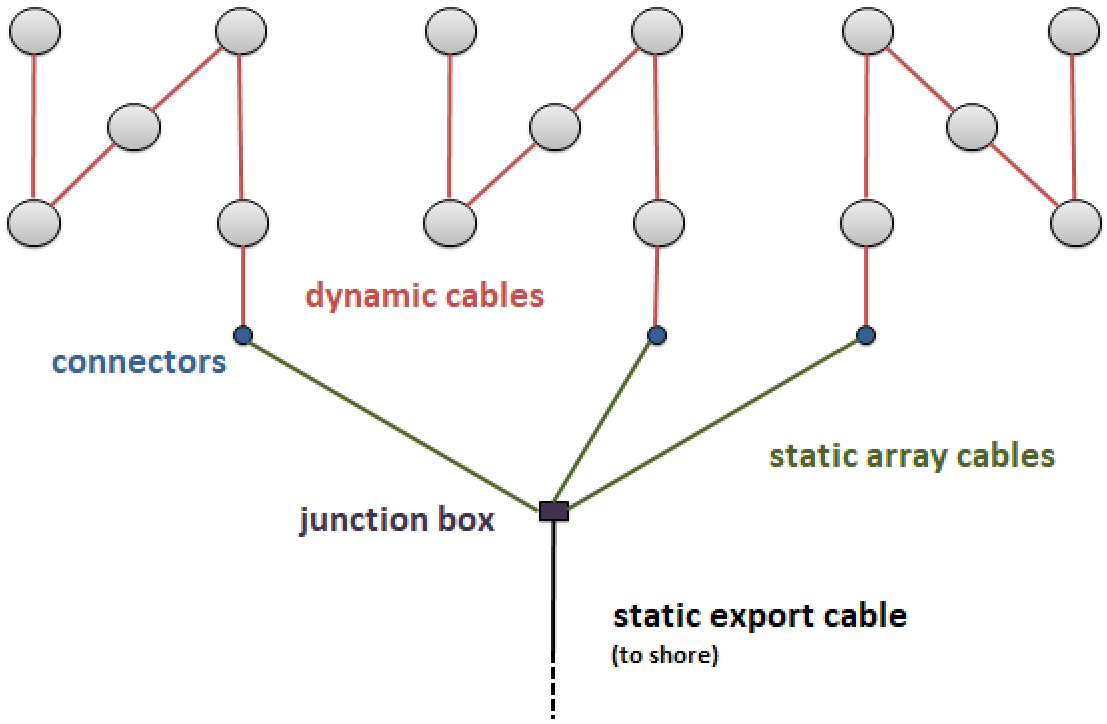


Figure 19: Schematic representation of the string electrical connection.

- Star configuration: every single device in an array is directly connected to the static array cable. The dynamic cables just have to carry to the connectors the power produced by one converter, thus they are sized considering the 150 kW nominal power.

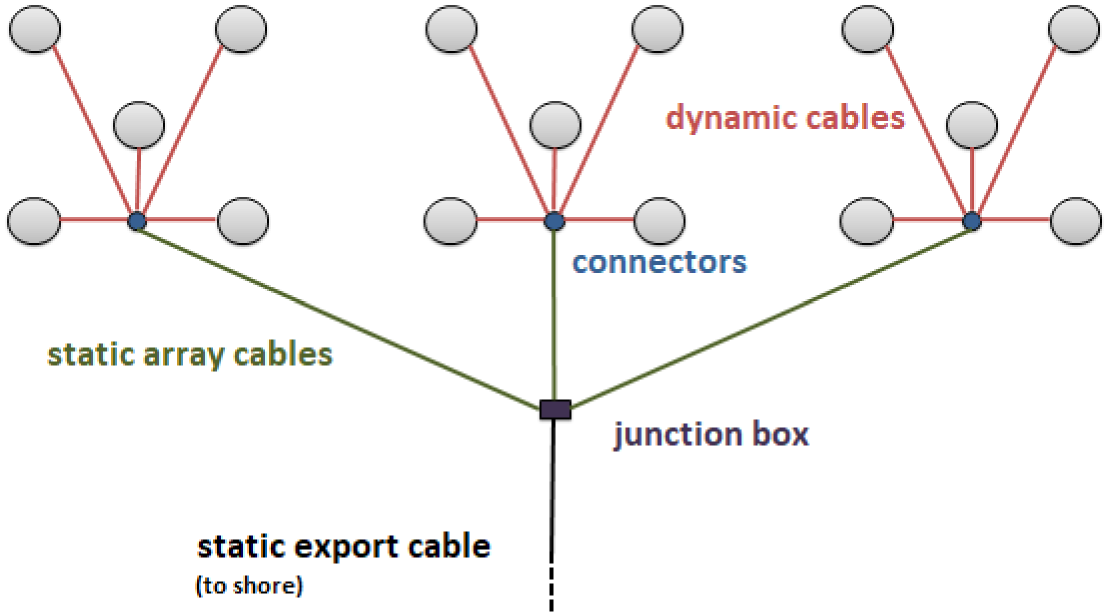


Figure 20: Schematic representation of the star electrical connection.

The different sizing of the dynamic cables in the two different configurations has impact on both the capital costs and losses in the system. In fact the cost functions, taken from sources [21],[22] and internal WavEC data, are based on empirical coefficients and on the cable rating, meaning the maximum amount of apparent power, measured in Volt-Ampere (VA), allowed to flow through the cable. The cable rating in turn depends on the input power (W) the cable is designed for and its size factor. The size factor of a cable is given by the ratio between the rated apparent power of the cable and the actual input apparent power:

$$cable\ size\ factor = \frac{S_n}{S_{in}} \qquad (6)$$

Where:

- S_n is the rated power, $S_n = 3V_{rated}I_{rated}$ [VA];
- S_{in} is the input power [VA].

The rated power is the maximum allowed power that the cable can handle. The input power is defined by the rated power of the device (150 kW) divided by the required power factor. The power factor is the ratio between real and apparent power in a circuit and it is normally required to be in a close interval of the value 1, typical values being between 0.96 and 0.98.

The cable size factor is always greater than 1, meaning that the cables are generally sized in order to be able to carry a rated power greater than the one that they supposedly have as input. In fact, the cable size factor acts as a safety factor for the cables: since there might be some peaks in the electricity production, the cables should be able to carry it anyway, without suffering any damage. Another reason is that by increasing the cable size factor it is possible to decrease the losses in the system, being computed with the formula taken from source [21]:

$$P_{loss} = P_0 l + C_0 l^3 + P_k l \frac{S_{in}^2}{S_n^2} \qquad (7)$$

Where:

- P_{loss} are the losses [W];
- P_0 and C_0 are no-load parameters;
- P_k is a load parameter;
- l is the length of the cable [km].

As it is possible to notice from equation 6, the factor of the last term of equation 7 is equivalent to the reverse of the cable size factor, squared. Thus the greater is the cable size factor the smaller are the losses in the cable.

It is important to know that losses have to be kept below a certain level in order to achieve a good overall performance of the farm. The maximum allowed value of total losses in the model is set at 5% of the energy production. In order to stay below the imposed threshold the cables have to be oversized, meaning that their cable size factor has to be high so that losses are reduced. The problem is that the increased size of cables causes also an increase in their cost. The system needs to be optimized aiming to find the meeting point in between the energy efficiency and the overall economic of the project.

Depending on the configuration adopted the connectors that convey the electricity produced to the static cable are located in different positions, as shown in Figure 19 and Figure 20. Therefore the static array cable, used to bring the collected energy of each array to a common collection point, have as well different lengths according to the electric layout. It is important to notice that the connectors are of the dry-mate typology, meaning that the connection between them and the cables has to be performed out of the water. Thus there is a need to introduce a safety factor for cable lengths since the connectors have to be lifted from the seabed to the water surface and the cables have to be long enough to allow this operation to be performed whenever is needed to connect or disconnect some cables. The lengths of the cables in the two configurations are presented in Table 9.

Table 9: Cable lengths for the two electrical configurations considered (string and star), referring to Leixões deployment site.

Data	Unit	String	Star
Dynamic cables lenght/device	m	374	270
Static array cables length/array	m	634	708
Static export cable length/farm	km	35.7	35.7
Total cables lenght	km	53.4	50.1

Finally, the collection point is a marine substation where a step-up of the voltage is performed through a transformer in order to reduce the transmission losses throughout the static export cable. Since the export cable conveys the whole farm power output its input power is really high compared with all the other cables. Moreover, it is the longest one and thus the one with the greater losses. In order to keep the losses at a low level, the cable size factor has to be high and consequently the cable rating is high as well. Therefore, the step-up is necessary in order to keep low the price for the export cable since it would be much higher for a lower voltage due to the high cable rating. The trends of cable costs, shown in Figure 21, clearly grow sharply with the cable rating, mainly for lower voltages. In the study the voltage is considered to be raised from 11 kV to 66 kV in the marine substation, in order to keep the electrical losses below 5% in both string and star configurations for the electrical system.

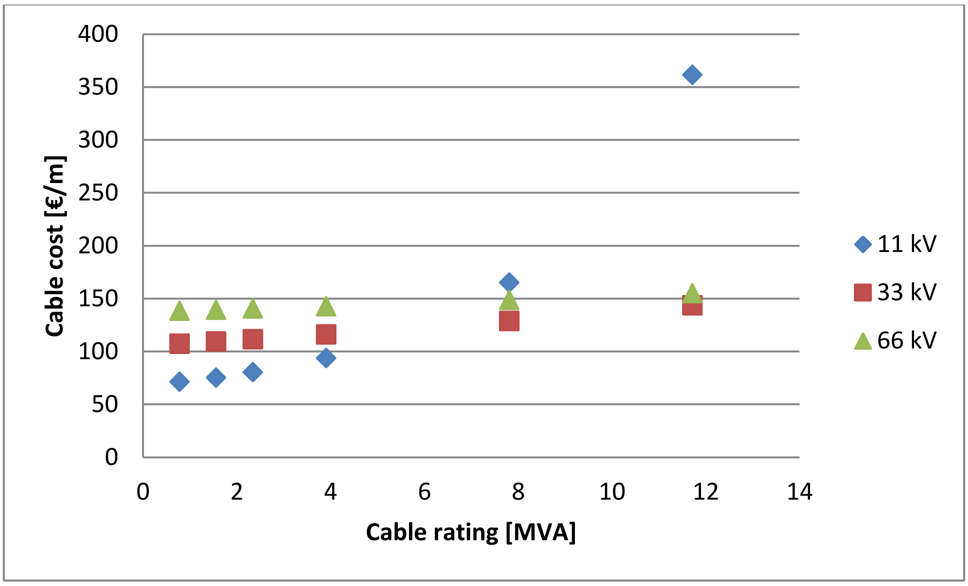


Figure 21: Trend of cable cost versus cable rating for three different cable voltages ([21], [22] and internal WavEC data).

Table 10 presents a comparison of the total cost for the electric system and the effect it has on the LCOE value between the two different electrical configurations described: string and star.

Table 10: Electric system cost, losses and influence on the overall LCOE value for the two electrical configurations considered (string and star), referring to Leixões deployment site.

Data	Unit	String	Star
Total cost of the electrical system	k€	9885	9531
Total electrical losses	%	3.1%	3.9%
Total LCOE	c€/kWh	176.0	178.8

Although it has a higher total cost, the string configuration is more effective from the LCOE point of view, mainly because the total electrical losses are lower, and thus it is going to be used as a reference for comparing the cases featuring the breakthroughs with the reference case.

5.3.3. Mooring system configuration

The characteristics of the mooring system change accordingly to the analyzed breakthrough. The three possible configurations for the shared moorings concept are described in section 3.4 while the standard mooring system is defined in section 2.1.3. Moreover, since for the survivability submergence process three extra mooring lines are needed at the bottom of the device, the change in the mooring system is taken into account when the breakthrough is applied.

All the possible configurations for the mooring system considered in the model have a different number of lines, with different lengths, and a variable number of anchoring points. In order to assess the capital cost related with the mooring system, a method based on an average number of anchoring points per array was adopted. The total number of lines and their total lengths were computed for a whole array of devices and then divided by the number of devices in a cluster, which are considered to be five, as explained in section 5.3.1.

Table 11 shows lengths and diameters of lines for the reference case and the survivability submergence breakthrough since they both have the same configuration of the mooring system. In fact, although in the survivability submergence case two sets of mooring lines have to be installed, the lower set has the same characteristics of the upper one.

Table 11: Mooring system characteristics for reference and SS cases referring to Leixões deployment site.

Data		Unit	REF	SS
Water depth		m	106	106
Wire length	upper set lower set	m	265.7	252.0 116.0
Chain length	upper set lower set	m	61.2	61.3 90.2
Bottom radius	upper set lower set	m	278.3	278.3 198.8
Wire diameter		mm	65	65
Chain diameter		mm	180	180
N° anchoring points/array			15	30

Table 12 presents the characteristics of the mooring lines in the shared mooring case, for the three configurations considered. It is important to notice that, while the diameter of the wire remains the same as in the reference case, the chain has a greater diameter in the shared mooring case. Since there are less bottom lines than in the reference case but they still have to provide the same station-keeping effect, the chains need to be heavier when the breakthrough is applied.

Table 12: Mooring system characteristics for SM case referring to Leixões deployment site.

Data		Unit	SM configuration B	 configuration C	 configuration D
Water depth		m	106	106	106
Interconnections	corner-corner corner-centre	m	75.8 52.6	75.8 52.7	0 53.4
Bottom line wire length		m	245.2	228.3	190.2
Bottom line chain length		m	102.3	142.0	180.1
Mooring system bottom radius		m	318.0	344.5	344.5
Rope diameter		mm	65	65	65
Chain diameter		mm	237.3	237.3	237.3
N° anchoring points/array			8	4	4

The cost functions for the mooring lines were taken from source [23] and from internal sources at WavEC. They are empirical correlations based on the diameters of wires and chains, respectively:

$$Cost_{wire} = (7.9243 d_{wire} - 125.24) \times 1.164 \qquad (8)$$

$$Cost_{chain} = 0.05688d_{chain}^{2} \tag{9}$$

Where:

- d_{wire} is the diameter of the steel wire;
- d_{chain} is the diameter of the steel chain.

The anchors are assumed to be of the weight typology, made of concrete (2500 kg/m^3 density). The total weight of each anchor is 40 tons and they have a rectangular base of 10 m^2, with the two sides respectively of 4 m and 2.5 m, and a height of 1.6 m. The total number of anchoring points depends on the breakthrough applied and on the chosen configuration, in case of the shared mooring one, as shown in Table 11 and Table 12, and the cost of each anchor is computed assuming a cost of 200 €/ton of material.

The procurement costs for the mooring system, both mooring lines and anchors, of the reference case are listed in Table 13.

Table 13: Mooring system costs for a farm composed of reference case devices, installed in Leixões deployment site.

Data	Unit	Reference case
Mooring lines	k€	24504
Anchors	k€	840
Total mooring system	k€	25344

The total cost for the mooring system for the whole wave energy farm results to be high compared to the expected value. In fact, the mooring system should account for around the 20% of the total procurement cost of the farm (WEC manufacturing cost) while the computed value for the total mooring system cost represents the 40.8% of the WEC manufacturing cost in the CAPEX computation (section 6.1). The overestimation of the mooring system procurement cost is mainly related with the great value of water depth given for the selected site and corresponding to 106 m. It is realistic to assume that a real wave energy farm would be installed in a location with a lower value for the water depth, which directly influences the length and thus the cost of the mooring lines. The water depth in the analysis was kept as the value given from an internal WavEC source while a more realistic mooring system cost computation, related with Wave Hub pilot zone and thus based on a water depth value of 50 m, is presented in *Annex* (Table 27, section A.5.2).

Table 14 presents the percentage variation of the mooring system cost for the five analyzed breakthrough cases compared with the reference case.

Table 14: Percentage variation in the mooring system costs for the five analyzed breakthroughs compared to the reference OWC spar-buoy, referring to Leixões deployment site.

Data	EAM	NS	SS	SM			DEG
				B	C	D	
Mooring lines	0%	0%	91%	14%	-23%	-19%	0%
Anchors	0%	0%	100%	-47%	-73%	-73%	0%
Total mooring system	0%	0%	92%	12%	-25%	-20%	0%

The enhanced added mass, negative spring and DEG concepts have the same mooring system as the reference spar-buoy device. The survivability submergence breakthrough has a considerably higher mooring system cost due to the double set of mooring lines for each device, needed for the submergence process. It is interesting that not all the three shared mooring configurations offer a better performance than the reference mooring system. In fact, for configuration B the costs for anchors are reduced because the number of anchoring points is reduced, but the cost for mooring lines, which is the greatest part of the overall mooring system cost, is higher. On the other hand, the other two configurations appear to be effective for cost reduction. Since configuration C has the greatest saving percentage it is going to be considered as the reference for the shared mooring breakthrough in the future comparisons.

The analysis for a more realistic value of water depth, corresponding to 50 m and related with Wave Hub pilot zone, and the percentage variation in costs for the five analyzed breakthrough cases compared to the reference case is presented in *Annex* (Table 28, section A.5.2).

5.4. Logistics

The installation of marine devices is a complex and costly process that needs to be adequately planned ahead. The different steps that lead to the device deployment at sea are here divided into sub-processes that have to be performed separately. Inside every sub-section below the main operations are defined specifically together with an approximation of their time duration.

A couple of general considerations are worth to be done before introducing the logistic processes for the farm installation, as defined for the model:

- Because of the lack of direct experience in marine operations specifically referred to wave energy devices, the data used in the model come mainly from the oil and gas industry since it has a large practical knowledge with spar structures deployed at sea. Moreover also the offshore wind sector gives an important contribution because of its greater level of maturity compared with wave energy.
- The operations are performed through dedicated vessels that are rented for the purpose. The vessels are chosen for each operation according to the specific needs. The choice is based on the vessel characteristics and rental price, as taken from an internal database at WavEC.

- Since the vessels are rented they have a mobilization time that has to be taken into account and represents the time that they take to reach the port from where the installation process starts. The mobilization time is assumed to be fixed for all the vessels selected for completing the installation and it has a given value of 48 hours. During the mobilization the vessel travels continuously, so in two working days of 24 hours each it reaches the destination port, and the rental cost is assumed to be 75% of the normal amount, since the crew is not working at the project but just reaching the starting point of the operations.
- Normally the working shifts at sea are of 12 hours each and the return to the port is foreseen at the end of each of them. Nevertheless there are exceptions, such as for the cable laying operations that are considered to be performed continuously, so through 24 hours shifts, until they are completely carried out.
- Different ports can be used to support the installation procedure. In fact some operations need a bigger and more equipped port while others can be performed exploiting smaller ports located closer to the deployment site.
- For each sub-process an operation sequence is defined. Some of the operations are performed at port, others at sea. The time durations are computed for all of them. Moreover for the operations at sea are also defined the adequate weather windows and the related waiting times. The weather windows are defined as a period of time during which the conditions at sea are within some defined limits, given by the specific vessel used. In fact, in order to be working in safety, every vessel has a set of operational limit conditions, according to the performed operation. In general the conditions concern the maximum wave height, the wave period, the current and wind speeds. In order for those parameters to be under the required threshold level throughout all the time needed to perform the operation at sea, thus having an adequate weather window for such operation, it might be necessary to wait at port, with the vessel ready to sail, for a certain amount of time, the so called waiting time. Since the vessel is rented the waiting time at port increases the cost for the overall installation process. Therefore it is recommended to deploy devices at sea during the summer, at least in the northern hemisphere, because normally wave climates are less harsh in that period of the year, allowing lower waiting times.

5.4.1. Installation of gravity based structures and mooring lines

The anchors are the first item to be installed, together with the mooring lines, so that when the devices is brought to the deployment site it can be immediately secured and kept in position. The operation is carried out through anchor handling tug supply (AHTS) vessels. The choice of the most adequate vessel was done considering the lifting capacity of the crane, the deck dimensions and the cargo capacity. In fact the crane of the vessel should be at least able to lift a weight equal to the anchors' one (40 tons). Moreover the deck dimensions and the cargo capacity are important parameters to assess how many anchors can be transported and installed during one single trip, in order to reduce the total number of round trips from port to deployment site. Considering the aforementioned concerns, an adequate vessel was chosen from an internal database at WavEC. For every AHTS vessel used a multicat vessel and a remotely operated vehicle (ROV) of the inspection typology have to be rented as well in order to provide support during the marine operations.

The operation sequence for the installation of the mooring system is composed by:

- Mobilization;
- Vessel preparation and loading;
- Transportation from port to site;
- Vessel positioning at site;
- Anchor lowering;
- Pre-lay of moorings;
- Transportation from site back to port.

As already mentioned the mobilization time takes 48 hours while the preparation and loading operation is assumed to take one hour for each anchor loaded on deck. The number of anchors that can be installed on one single round trip is assessed considering the limit of 12 hours for the shifts at sea. The time of all the operations at sea is fixed, once the deployment location has been selected. In fact the transportation from port to site and all the way around depends on the speed of the boat and on the distance from the port. For anchors loading a small port can be used. One vessel positioning every three anchors, which is the amount of anchoring points of the reference case device, is considered and it is assumed to take one hour every time. Then each anchor is lowered and the moorings are laid for a total operational time of one hour and half for each line. The lines are finally attached to some buoys on the water surface, waiting that the device is deployed on site to perform the hook-up phase.

There is no demobilization phase because the same vessels used for the installation of the mooring lines are used for the devices as well, as explained in section 5.4.2.

5.4.2. Installation of devices

Once the mooring lines are put in place the devices can be transported to the deployment location. The operation sequence of the device installation is:

- Assembly at port;
- Vessel preparation and loading;
- Transportation from port to site;
- Vessel positioning at site;
- Device positioning and connection;
- Transportation from site back to port;
- Demobilization.

As suggested in [6], the device is assumed to be assembled in the horizontal position. Then all the PTO equipment has to be securely fastened before initiating the load-out operation. The latter can be carried out by lifting the device through a land based crane. The device has to be lifted and then lowered in the sea since it is towed, and not loaded directly on deck, to the deployment site. An alternative option consists in a float-away load-out strategy. It can be applied if the assembly of the device is performed in a dry dock that is then flooded when the operations are concluded. In order to be able to adopt the second strategy the hosting port has to feature a dry dock with adequate dimensions to fit the device.

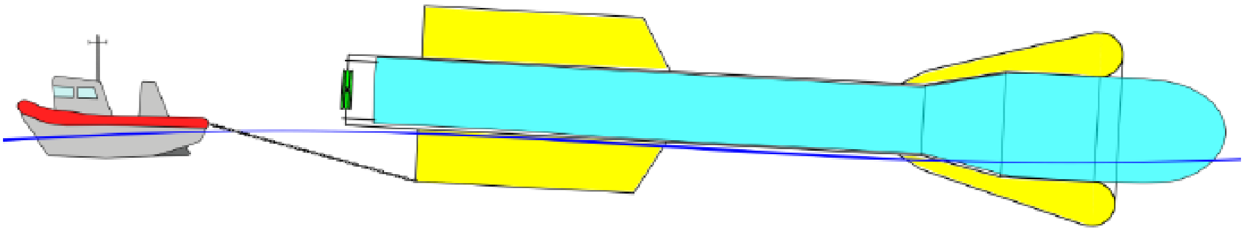


Figure 22: Representation of the towing position for devices during installation procedures [6]**.**

As shown in Figure 22, the device is towed in an almost horizontal position, with a small angle of inclination in order to keep safely out of the water the sensitive components of the PTO equipment located in the top of the floater, thus avoiding potential damages due to impacts with the water during transportation. The device is kept in the desired position through an inflatable auxiliary floater attached inside the OWC tube that provides the additional buoyancy required and counterbalances the natural righting moment of the structure. The inclination angle should be small in order to keep the drag effect low and it is defined by the auxiliary floater's dimensions.

In [6] the use of AHTS vessels is recommended for the towing task. The same vessels used for the installation of the mooring system can be used for the devices as well, also with the same support composed by a multicat and an inspection class ROV for each AHTS vessel. So there is no need for a mobilization phase since the needed vessels are already at port. The number of AHTS vessels to be rented was defined in the model taking into account the device installation logistic phase more than the mooring system one. Moreover, in the choice of the adequate AHTS to be rented, the bollard pull of the vessel was an essential factor since it has to be able to tow the devices.

For the transportation operation the vessels are considered to travel at reduced speed when towing the devices. Concerning the assembly, the vessel preparation and the device positioning and installation phases there are no data available, since the device has never been assembled nor deployed at sea, and thus educated guesses were formulated. The total duration of assembly and vessel preparation operations is assumed to take one full day of work (12 hours), while the device connection is considered take 2 hours for each device.

At the end there is the demobilization phase, when the vessels come back, and it is supposed to last as the mobilization one, being the vessel rental paid in the same way (75% of the total rental price).

5.4.3. Installation of electric cables

The electric cables are installed in three different trips at sea:

- One for the static export cable;
- One for the static array cables;
- One for the dynamic cables.

Here the description of the procedures is grouped since they have many similarities.

First of all, the procedures at port are the same for all the three cases, as well as the vessels used, so there are just one mobilization and one demobilization phases for the overall cable installation process. A cable laying vessel (CLV) is needed to perform the task, supported by two multicats and a work class ROV. The CLV is equipped with a turntable that has to be able to host the whole length of the cables. The vessel preparation and loading procedure, performed at port, consists in the winding of the cables in the turntable on deck. The operation proceeds at the fixed speed of 450 meters of winded cable per hour, according to source [24].

Secondly, the static cables, both export and array, have the same marine operation sequence, composed by:

- Downstream termination connection;
- Cable burial tool deployment;
- Cable lay and burial;
- Upstream termination connection.

The upstream connection is the one closer to the device while the downstream one is more on the grid side. The cable has to be buried under the sea bottom to avoid damages. The task is performed through the exploitation of a cable burial tool that opens a trench in the sea bed, lays the cable into it and covers it up. The cable burial tool has to be rented as well and it is essential for the electric system installation. The equipment is supposed to be working at a fixed speed, assumed to be equal to 350 meters of cable laid and buried per hour [24].

As mentioned above, in section 5.4, the cable laying operations are performed through 24 hours shifts that imply an increase in the total cost of the vessel rental. In fact the salary of the crew of the vessel is included in the rental price and it increases when the crew has to work continuously since more workforce is needed in order to have a shift change at sea. The vessel cost is considered to suffer a raise equal to 50% of its initial price when continuous operations are required.

Finally, dynamic cables have a slightly different installation procedure, due to their different characteristics compared with static ones. In fact since they connect the device with the static array cable they have to be free to move in the water to follow the device oscillations. Thus there is no need to use a burial tool, while all the other equipment remains the same as for static cables' cases. Also the procedures at port are the same, with the dynamic cables winded around the turntable at a rate of 450 meters per hour. On the other hand, the marine operation sequence for dynamic cables can be summarized as:

- Connection to static array cable;
- Cable lay;
- Connection to device.

The connection to the static array cable phase takes much more time compared to the other two to be accomplished. The reason is the fact that the static array cables are considered to be installed before, laid on the sea bottom waiting for the connection with the dynamic cables. There are two typologies of connectors that can be employed:

- Dry-mate connectors;
- Wet-mate connectors.

The first ones are very sensitive to sea water therefore the connection cannot be performed underwater because that could damage the equipment. In fact the extremities of the static array cables, that are considered to be installed before the dynamic ones, have to be lifted out of the water in order to accomplish the task, and then the whole connector with the two cables attached is lowered to the sea bottom. On the other hand wet-mate connectors allow the junction to be performed underwater, reducing the time needed for the operation and simplifying the logistic of the process. Although the dry-mate connectors require a more time-demanding procedure they are normally preferred to the wet-mate ones because of the considerably higher cost of the latter typology.

5.4.4. Installation of offshore collection points

The collection point is the last item needed to complete the overall farm installation. It consists of a sub-station to be installed whether on the sea bottom or piercing at the water surface. In both cases the structure is quite heavy and so special equipment is required. Specifically a crane vessel with adequate lifting and deck cargo capacities has to be rented for this purpose. Moreover, it needs a multicat and an inspection class ROV to provide support for the operation that shows the following sequence:

- Vessel positioning;
- Collection point positioning and connection.

As it happens for the dynamic cable installation the junction to the collection point can be performed through both dry-mate and wet-mate connectors. If the dry-mate ones are preferred, the extremities of the array cables and of the export one have to be lifted and connected out of the water.

5.5. Operation and maintenance

The study of the O&M is based on two main procedures:

- Preventive maintenance: based on annual inspections of the farm performed in order to reduce the risk of unexpected failures during the operation;
- Corrective maintenance: consisting on the actual repairs of the devices that break during the operation.

The damages that the farm suffers can have different levels of importance, for simplicity here are just divided into minor and major damages that require respectively just an intervention at sea or the device to be brought on shore in order to be fixed. The need for maintenance procedures is assessed through failure rates, adopting a linear distribution of the failures throughout the lifetime of the project.

The three main systems that can suffer for failures are:

- The device structure and PTO system;
- The mooring system;
- The electric system.

5.5.1. Inspections

It is assumed that inspections are carried out annually to every of the three main systems, so that if any anomaly is found it can be fixed right away, before causing a greater damage to the farm. Moreover if the repair is performed before the actual breakdown the downtime can be substantially decreased.

One inspection for each of the three systems described in section 5.5 is assumed to be performed every year, employing a tugboat and an inspection class ROV. They are considered to happen all during the summer period, so that the adequate weather windows for the operation should be more likely to happen without having long waiting times.

5.5.2. Minor repairs

Minor repairs are performed when items or components can be repaired or replaced directly at sea, without having to bring the devices back at port. The probability of occurrence is defined through failure rates, and the objectives are mainly the electric cables, divided into dynamic, array static and export, the electrical sub-station, the mooring lines, composed of ropes, chains, connective points and anchors, and the devices themselves, as much for the structure as for the PTO system and its electric equipment.

The failure rates, referring to minor failures, related with the three main systems (electrical, mooring and device) are listed in Table 15.

Table 15: Components minor failure rates, for reference case device ([22], [25] and internal WavEC data)**.**

Data		Failure rate
Electrical system	Electrical dynamic cable (MV)	0.0091
	Electrical static cable (MV)	0.0091
	Electrical export cable (HV)	0.1519
	Transformer	0.0216
Mooring system	Steel wire	0.0024
	Chain	0.0038
	Moorings (general/unknown)	0.0002
	Anchor	0.0081
Device	Device structure	0.1000
	PTO system	0.2000
	Generator	0.0546

All the failures are supposed to happen separately and repaired individually. Therefore, every time a failure event occurs a trip at sea is needed. As it happens for the installation procedures, described in section 5.4, the vessels needed in order to perform the repairs have to be rented. Mobilization, vessel preparation, round trip at sea, repair and demobilization operations have to be assessed in order to define the total rental time of vessels. Moreover, the waiting time for adequate weather windows has to be considered and the chosen location has a great influence on that parameter, as well as on the round trip time. Finally, the waiting time for the spare components needed to perform the repairs is assessed since they might not be already available at port.

The vessels used for the repairs are multicats, supported by working class ROVs. Since the failure happen randomly throughout the year, the waiting time is computed considering the annual average length of weather windows.

5.5.3. Major repairs

If the devices suffer for major damages they have to be brought back to port in order to perform the needed repair operations. Such measure is considered to be necessary just when the structure or the PTO system are seriously compromised. The same procedure used for the installation of the devices (section 5.4.2) is used to take them out of the sea, just reversing the sequence of the operations. Moreover, the same vessels are employed: AHTVs supported by multicats and inspection class ROVs.

The failure rates referring to major failures are listed in Table 16.

Table 16: Components major failure rates, for reference case devices (internal WavEC data)**.**

Data	Failure rate
Device structure	0.0500
PTO system	0.1000

In the overall time needed to perform the repair is also considered the time needed to get the necessary components to port and, since the failure can happen in any time of the year, the waiting time for an adequate weather window is computed considering the annual average length of weather windows.

5.5.4. Midlife overhaul

Since the devices are deployed in a very harsh environment such as marine water, an overall control of the WECs is conducted in depth bringing them back to port, instead of just checking them at site as it happens during the regular annual inspections. The devices are repainted and some elements are replaced during that operation. The overhaul is a planned maintenance procedure that is carried out just once at the half of the lifetime of the farm. Since it is an expected operation it is normally scheduled for summer time, so that the waiting times for weather windows are normally shorter. The equipment and the operation sequence are the same described for the installation of devices, in section 5.4.2.

5.5.5. Emergency situations

Throughout the lifetime of a wave energy farm it can happen that it incurs into extremely severe storm conditions. There is a limit to the loads the devices can stand in safety and that is represented by a maximum level of wave height. When conditions over the operational limit are forecasted the devices have to be shut and brought back to shore. The maximum wave height limit is considered to be 6 meters. If that wave height is forecasted the emergency procedure should be performed and all the devices should be carried back to shore. Using the scatter diagram for the site location, as described in section 5.1, it is possible to give an approximate probability of the threshold value to be reached within the lifetime of the farm.

Since severe storm conditions can occur at any time of the year, even if they are more likely to occur in winter time, the annual average length of weather windows is used for the computation of the waiting time. The equipment used as well as the procedures applied are the same as during the installation phase.

5.5.6. DEG system maintenance

As already mentioned in section 5.2.2, the DEG system is composed by a total of 12 modules of elastomer material. Each of them is assumed to have a failure rate of 0.2, meaning that every module has a life expectancy of about 5 years. Due to the high total number of modules for the whole farm, a lot of ruptures are expected to happen throughout the farm lifetime. Since every one of them has a rated power of 10 kW and they are independent from each other, meaning that if one module breaks the device will continue to produce electricity with a nominal power equal to 11/12 of the rated power of the device (150 kW), it is not worth to go for a repair every time there is a failure. Therefore it is assumed that annual maintenance is performed two times throughout the year. It is carried out as an inspection but the specific goal is to repair all the modules that suffered failures from the previous check performed. The number of failures every six months is computed through the failure rate and the modules are considered, as an approximation, to have an average downtime corresponding to the middle point from two consecutive maintenance operations, corresponding to three month, as they all broke together at the same time.

The methodology described applies just to the PTO system, for which minor and major repairs are not considered, while for the other systems described in section 5.5 the procedures are the same as for the other cases, as defined in sections 5.5.2 and 5.5.3.

6. Results

The next four sections, namely *CAPEX*, *OPEX*, *Energy* and *LCOE*, present the results derived from the data presented in the *Description of the model* (section 5). The first three sections are related with the corresponding parameters of the LCOE equation, as described in section 4.2. The LCOE is the final result and the desired outcome of the model, used to assess the effectiveness, from an economic point of view, of the breakthrough concepts, compared to the reference case.

6.1. CAPEX

The capital expenditures are represented as a summary of all the capital costs involved in the farm installation, from the surveys in the desired location to the construction of the devices and their deployment at sea. The main sub-sections of the CAPEX are:

- Project development: includes all the expenses for the project management, as well as for the surveys required to assess in depth the characteristic of the selected location, such as sea bed composition, geotechnical and environmental conditions, wind and wave climates, traffic and navigation. Moreover a complete environmental impact analysis (EIA) is taken into account and its cost appears in the CAPEX. Finally there are the legal and financial costs, related with insurances, leases from authorities, legal and financial expenditures.
- WEC manufacturing: collects all the cost items in the construction phase of the devices. The data are taken from the *WEC design* tab and include all the structural costs (section 5.2.1) and the expenditures for the PTO system and related equipment (section 5.2.2). The mooring system is also taken into account and the information needed to assess its total manufactural price is found in the *Farm design* tab (section 5.3.3).
- Electrical connection equipment: considers both the offshore and onshore electrical systems. The offshore part is described in section 5.3.2. For the onshore electrical system part the items on the list are: onshore collection point, onshore cable to the grid connection and, if not already existing close to the collection point, onshore substation.
- Assembly, installation and commissioning: is the summary of the costs listed in the *Logistic* tab for the installation procedure of the wave energy farm.
- Monitoring and miscellaneous equipment: the monitoring system is based on marker buoys. Their costs together with all the support services infrastructures are taken into account in this sub-section.

A summary of the value of the cost items composing the capital expenditures of the project, including the final value of the CAPEX, is listed in Table 17.

Table 17: CAPEX cost components for a farm composed of reference case devices, installed in Leixões deployment site.

Data	Unit	Reference case
Project development	€/kW	1866
WEC manufacturing	€/kW	15319
Electrical connection equipment	€/kW	1897
Assembly, installation & commissioning	€/kW	3878
Monitoring & miscellaneous equipment	€/kW	170
CAPEX	€/kW	23130

The chosen location greatly affects the final CAPEX since both the length of the export cable and the time needed for the installation operation depend on the distance between the deployment site and respectively the shoreline and the closest large port. Moreover, the electrical configuration chosen has a considerable impact on the electrical connection equipment cost. It is important to underline that in Table 17 the location considered is Leixões and the arrays are electrically connected in strings.

The percentage variations of the capital expenditures, divided in the aforementioned categories, for each breakthrough compared to the reference case is presented in Table 18.

Table 18: Percentage variations in the CAPEX cost components for the five analyzed breakthrough cases compared to the reference case, referring to Leixões deployment site.

Data	EAM	NS	SS	SM	DEG
Project development	-1%	-5%	27%	-8%	-1%
WEC manufacturing	-4%	-8%	38%	-10%	-2%
Electrical connection equipment	0%	0%	0%	0%	0%
Assembly, installation & commissioning	0%	0%	21%	-10%	0%
Monitoring & miscellaneous equipment	0%	0%	0%	0%	0%
CAPEX	-1%	-6%	31%	-9%	-1%

As it is possible to notice from Table 18, the electrical connection equipment has the same cost as the reference case for all the other cases because, the way the concepts were formulated in the present study (i.e. no in-depth study of the impact of the breakthroughs on the electric system was carried out), none of the breakthrough concepts involves changes in the electrical system configuration and the lengths of the electric cables. Moreover, the monitoring and miscellaneous equipment cost remains always constant because it is mainly based on the total number of devices deployed at sea. Since the rated power of the OWC spar-buoy is the same for the reference case and all the breakthrough concepts, the total number of devices is the same as well and thus the cost does not vary.

It is important to know that the project development costs are assessed as a percentage of the sum of the other capital expenditures and thus they follow the variation in the CAPEX.

Considering the breakthrough concepts individually, it is possible to say that:

- The enhanced added mass breakthrough has a slightly positive effect on the CAPEX because of the reduced dimensions of the structure, as explained in section 5.2.1, that affect the cost for materials and thus the total device manufacturing cost.
- The negative spring concept has the same effect as the enhanced added mass but a greater cost reduction because of the even smaller dimensions of the structure.

- The only breakthrough that has a considerably negative effect on the CAPEX is the survivability submergence concept. In fact, the submergence process requires an extra set of mooring lines to be connected to the lower part of the structure. Therefore, the total cost for manufacturing increases, because of the increased number of mooring lines, and the installation process becomes longer, because a greater number of anchoring points have to be deployed on the sea bottom, affecting the cost for the farm deployment at location. Moreover, since the water pumps need to be installed inside the device structure, the assembly time per device is assumed to be longer compared to a reference OWC spar-buoy.
- The greatest positive impact on the CAPEX is achieved through the application of the shared moorings concept. The cost for the mooring system decreases, as explained in section 5.3.3, as well as the installation costs, since the total number both of lines and anchoring points is reduced.
- The DEG PTO system has a slightly positive effect on the CAPEX due to the lower procurement cost of the energy conversion equipment compared to the reference bi-radial turbine.

6.2. OPEX

The operational expenditures are represented as a summary of all the costs encountered throughout the operational lifetime of the farm, divided by the lifetime and thus expressed as annual expenditures. The main cost components of the total OPEX are:

- Management and administration: consists of all the expenses related with the farm management, the insurance of the devices and the lease of the deployment area.
- Annual monitoring and maintenance: takes into account all the inspection procedures described in section 5.5.1 and the costs related with them, such as vessel rental and personnel salary.
- Onsite replacements and works offshore: includes all the small repairs that can be performed offshore, described in section 5.5.2, and all the related costs for vessels and personnel as well as for components when replacements are needed.
- Major replacements and works onshore: considers all the major repairs that have to be conducted onshore, bringing the whole device back to port in order to perform maintenance, as described in section 5.5.3. The costs are related with vessels, personnel and spare components.
- Midlife overhaul: represents the expense related with the check-up that has to be carried out around the midlife of the farm. All the devices have to be brought back to shore, as explained in section 5.5.4, controlled, repainted and eventually adjusted.
- Emergency situations: consists in the expenses related with the emergency procedures to be applied when rough storms are forecasted, as described in section 5.5.5.

A summary of the value of the cost items composing the operational expenditures of the project, including the final value of the OPEX, is listed in Table 19.

Table 19: OPEX cost components for a farm composed of reference case devices, installed in Leixões deployment site.

Data	Unit	Reference case
Management & administration	€/kW	304
Annual monitoring & maintenance	€/kW	36
Onsite replacements & works offshore	€/kW	347
Major replacements & works onshore	€/kW	938
Midlife overhaul	€/kW	53
Emergency situations	€/kW	32
OPEX	€/kW	1710

The chosen location largely influences all the offshore operations related with the maintenance of the devices composing the wave energy farm. In fact, the distance from port and the wave climate are two critical parameters in order to assess the total time needed to perform both the planned and the unplanned maintenance procedures. In turn, the total operational time influences the total operation and maintenance cost because the vessels are rented specifically for offshore operations.

The percentage variations of the operational expenditures, divided in the aforementioned categories, for each breakthrough compared to the reference case is presented in Table 20.

Table 20: Percentage variations in the OPEX cost components for the five analyzed breakthrough cases compared to the reference case, referring to Leixões deployment site.

Data	EAM	NS	SS	SM	DEG
Management & administration	-3%	-6%	28%	-8%	-1%
Annual monitoring & maintenance	0%	0%	35%	-17%	0%
Onsite replacements & works offshore	-2%	-5%	8%	-6%	72%
Major replacements & works onshore	-2%	-4%	-11%	0%	-53%
Midlife overhaul	0%	0%	0%	0%	0%
Emergency situations	0%	0%	-100%	0%	0%
OPEX	-2%	-4%	-1%	-3%	-14%

It is important to know that the insurance of the devices, which is the cost item with the greatest influence on the overall management and administration, is assessed as a percentage of the WEC manufacturing cost and thus the trend follows the variation in the procurement cost for structure, PTO and mooring systems.

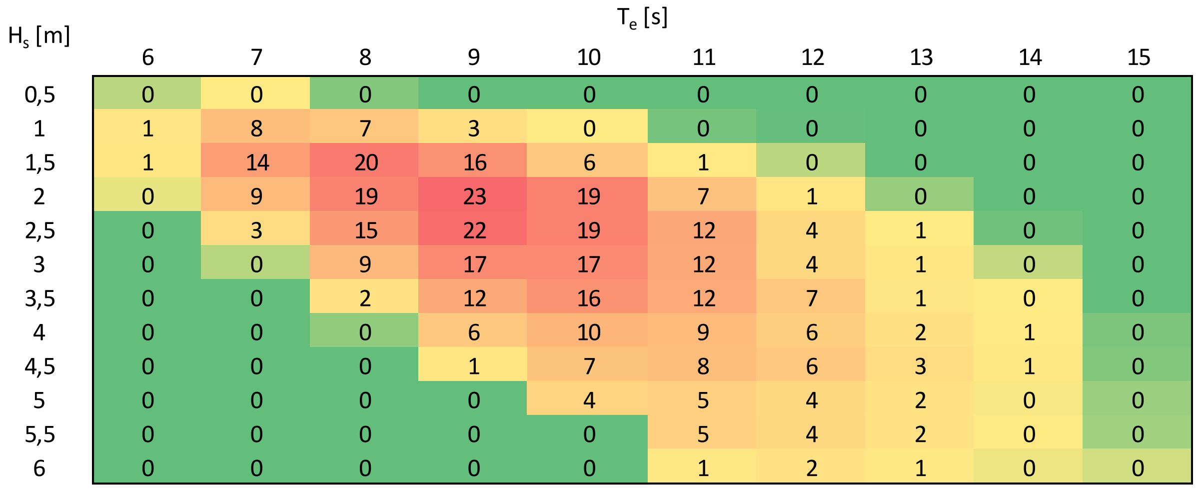
As it possible to notice from Table 20, the cost related with the midlife overhaul are equal for all the cases since the procedures applied are the same and the number of devices to be carried to shore is the same as well.

Considering the breakthrough concepts individually, it is possible to say that:

- The enhanced added mass breakthrough improves slightly the operational expenditures of the project because of a lower insurance of the devices and a reduction in both offshore and onshore replacements. The latter cost items are reduced because of the lower structural cost of the device in the EAM case. In fact, the costs for spare components needed for structural damages are assessed as a percentage of the total procurement cost for the device structure.
- The negative spring concept has the same effect as the enhanced added mass but the final result is better, meaning that the OPEX reduction is greater, because of the lower procurement cost of the device structure.
- The survivability submergence concept is the most complicated case because there are different opposing effects. In fact, the double set of mooring lines causes both a higher WEC manufacturing cost, and thus a higher management and administration cost, and a higher cost for inspections (annual monitoring and maintenance) since the number of anchoring points to be checked is doubled. Moreover, the small repairs offshore are more frequent because a greater number of mooring lines arouse a greater probability of failure per year. On the other hand, the device structure is supposed to suffer fewer damages because of the survivability system and thus the onshore repairs are reduced and the emergency procedure costs are completely avoided because it is not necessary to bring the devices onshore in case of rough storm conditions since they can be submerged instead.
- The reduced number of anchoring points and, in general, the lower amount of wires and chains cause a reduction in the inspection time and in the need for maintenance for the mooring system when the shared moorings breakthrough is applied.
- The DEG PTO system has a different maintenance, compared with the air turbines used in all the other cases, that causes a consistent increase of the minor repairs offshore, due to the characteristic feature of the energy conversion equipment which is divided in independent modules, as explained in section 5.5.6. On the other hand, since the whole PTO system maintenance is performed offshore, there is a remarkable decrease in the expenditures associated with onshore repairs. The effect of the two opposite trends results in an overall decrease of the OPEX for the DEG breakthrough case.

6.3. Energy

The computation of the annual energy production is performed by multiplying the corresponding values for the same intervals of wave height and energy period of the scatter diagram of the chosen location and the power matrix of the device. In fact, the scatter diagram offers the amount of hours in a year for which there are the conditions specified by each wave height and energy period coupling and the power matrix expresses the power output that is possible to achieve with the same conditions. The result is expressed in MWh per year. The energy production for the reference case device (power matrix in Figure 17) deployed in Leixões (scatter diagram in Figure 16) is shown in Figure 23.



H_s [m] \ T_e [s]	6	7	8	9	10	11	12	13	14	15
0,5	0	0	0	0	0	0	0	0	0	0
1	1	8	7	3	0	0	0	0	0	0
1,5	1	14	20	16	6	1	0	0	0	0
2	0	9	19	23	19	7	1	0	0	0
2,5	0	3	15	22	19	12	4	1	0	0
3	0	0	9	17	17	12	4	1	0	0
3,5	0	0	2	12	16	12	7	1	0	0
4	0	0	0	6	10	9	6	2	1	0
4,5	0	0	0	1	7	8	6	3	1	0
5	0	0	0	0	4	5	4	2	0	0
5,5	0	0	0	0	0	5	4	2	0	0
6	0	0	0	0	0	1	2	1	0	0

Figure 23: Energy production matrix, values in MWh/year, for a reference case device, installed in Leixões deployment site.

As it is possible to notice comparing Figure 16 and Figure 17, the most frequent sea-states of the chosen location correspond to low power outcomes of the device, meaning that the geometry of the device is not optimized for the deployment sites analyzed in the study. This effect has a greater impact on the DEG breakthrough case (power matrix in *Annex*, Figure 27) because its power outcome trend that goes increasing sharply with both wave height and energy period and being maximum for very energetic sea-states that are almost never reached for both the locations chosen in the model.

The combination of scatter diagram and power matrix results in the energy production matrix and the sum of all the values in the matrix represents the theoretical electricity production for one device. In fact, the inter-array interactions and both the mechanical and electrical losses have to be considered in order to reach the final energy production.

There are two parameters strictly connected with the energy production: the capacity factor and the availability factor.

The capacity factor of the farm is computed as the ratio between the real annual electricity production and the total amount of energy that the device would be producing if it would work at his rated power throughout the whole year:

$$capacity\ factor = \frac{electricity\ production}{rated\ power \times 8760} \qquad (10)$$

The capacity factor represents the percentage of time during which the device is working at his maximum capacity throughout the year.

The availability factor is a parameter that affects the electricity production, together with the characteristic wave climate of the chosen location, the WEC power matrix and the losses in the electrical system, respectively discussed in sections 5.1, 5.2 and 5.3.2.

The availability factor represents the percentage of time throughout the year during which the device is effectively working, meaning that the rest of the time it is considered to be completely unproductive. The availability depends mainly on the failures and maintenance procedures adopted. In fact, when a failure occurs it affects, partially or totally, the energy production until the moment it is fixed. In the model the maintenance strategy is based on individual repairs every time a failure happens, thus the downtime of the devices is limited to the time needed to obtain the vessels and the spare components, reach the farm and repair the damage.

Table 21 presents the values of the availability and the capacity factors and of the annual electricity production for a farm composed of reference case devices.

Table 21: Availability factor, capacity factor and electricity production for a farm composed of reference case devices, installed in Leixões deployment site.

Data	Unit	Reference case
Availability factor	%	95%
Farm capacity factor	%	31%
Farm electricity production	MWh/y	14105

Since the availability of the farm depends on the operation and maintenance, in turn it also depends on the chosen locations. In fact, the operational time needed to perform a repair depends on the distance to port and on the characteristic wave climate of the deployment site. Moreover, also the electrical configuration has an influence on the availability, when the electrical system suffers for a failure. In fact, the number of devices that are disconnected due to a failure to the dynamic cables is different whether the electrical configuration is string or star: in the first case the same dynamic cable conveys the power output of a whole array and thus all the production of the five devices is unavailable when there is a failure, while in the second case every device is individually connected to a connector and thus the failure would just affect the single device.

Table 22 presents the percentage variations in both availability and capacity factors and in the annual electricity production of a wave energy farm when the five analyzed breakthrough concepts are applied individually compared to a farm composed of reference case devices.

Table 22: Percentage variations in the availability factor, capacity factor and electricity production of the wave energy farm for five breakthrough cases compared to the reference case, referring to Leixões deployment site.

Data	EAM	NS	SS	SM	DEG
Availability factor	0.0%	0.0%	0.2%	0.1%	-3.6%
Farm capacity factor	2.6%	0.4%	0.2%	0.1%	-45.1%
Farm electricity production	2.6%	0.4%	0.2%	0.1%	-45.1%

Considering the breakthrough concepts individually, it is possible to say that:

- When the enhanced added mass concept is applied the device has an improved power outcome (power matrix in *Annex*, Figure 26) compared to the reference case spar-buoy. Therefore, the annual electricity production is higher and consequently the capacity factor.
- Because of the lack of available data regarding the power outcome of the device for the negative spring case, the annual energy production was assessed using the same power matrix as the reference case. The slight increase in the farm electricity production is due to a better inter-array interaction. In fact, the ratio between the distance of the devices within the arrays and the device diameter is higher compared to the other cases because the diameter of the device is smaller (9 meters instead of 12 meters) but the distances are kept constant. The effect of the mutual interactions that the devices have within the arrays, due to the radiation waves produced by the heave motions, is improved when the negative spring concept is applied. It is important to underline the fact that the power matrix used for the computation does not show the real energy production of the negative spring case. In fact this concept is expected to induce a substantial increase in the power outcome of the devices, improving considerably the final LCOE value of the wave energy farm project. For the lack of data the analysis could not show this effect and thus the computation was performed through the approximation of the energy production considered equal to the reference case.
- The survivability submergence concept affects the availability factor, thus both the electricity production and the capacity factor in the same proportion, because the long downtime due to emergency situations is avoided since the devices are unavailable just for the time of the rough storm event and not also for the whole time needed to bring them to port and back to site.
- The shared moorings breakthrough has a similar effect compared to the survivability submergence case. The gain in availability in this case is due to the lower number of mooring lines and anchoring points that reduces the probability of failure events. Even if the devices are not totally unavailable in case of rupture of a mooring line, for instance, their energy production is partially affected, in turn decreasing the availability of the farm. When the shared mooring concept is applied the maintenance procedures are decreased and the total downtime is lower.
- The DEG PTO system has a different maintenance protocol compared to the other cases, as mentioned in section 5.5.6. The unavailable modules are substituted all together every six months but it is impossible to know when the failure happens between two consecutive global PTO system repairs,

thus the modules that suffer a failure are considered to be all unavailable for half of the time, meaning for three months. Due to the high number of failures per year and to the long period of unavailability of the modules before the repair, the availability of the farm results to be lower when the breakthrough is applied. Moreover, as already mentioned in this section, the selected locations are not adequate to match with the power matrix of the DEG PTO system. Therefore, the energy production and the capacity factor are considerably lower compared to the reference case.

6.4. LCOE

The final LCOE value is obtained as the sum of three main components:

- Investment costs: represent the part of the price for energy, expressed by the LCOE, intended to compensate for the capital expenditures, defined in section 6.1. The total CAPEX is computed as if all the expenses were paid in the same time, meaning as if the wave energy farm was built, assembled and installed overnight. In order to have a more realistic result the project is assumed to reach the operational phase in three years. Therefore, all the capital expenditures are equally divided in the three years of construction period and the total investments are discounted, using the discounting factor expressed in equation 1 and considering a discount rate of 10%. The investment costs are computed as the ratio of the sum of the total investments discounted over the construction period and the sum of the farm annual energy production of each year, assumed to be constant, discounted over its lifetime. In order to have a common starting point for the computation, both the total investments and the energy production are discounted to a “time zero” that coincides with the beginning of the operation of the farm. Considering the LCOE formula expressed in section 4.2 (equation 2), the investment costs can be defined as:

$$Investment\ costs = \frac{\sum_{t=0}^{n} \frac{I_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{AEP_t}{(1+r)^t}} \qquad (11)$$

- Operation and maintenance costs: represent the part of the LCOE value intended to compensate for the operational expenditures of the farm, defined in section 6.2. The OPEX is expressed as cost per kW of farm capacity per year. The operation and maintenance costs are computed as the ratio between the sum of the annual operational expenditures and the sum of the annual energy production over the lifetime of the project, both discounted to the beginning of the farm operation. Considering equation 2, the operation and maintenance costs can be defined as:

$$O\&M\ costs = \frac{\sum_{t=0}^{n} \frac{O\&M_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{AEP_t}{(1+r)^t}} \qquad (12)$$

- Decommissioning costs: represent the part of the LCOE value intended to compensate for the decommissioning of the farm. Since there is no record of wave farm decommissioning procedures, the costs related with the end of life are largely unknown. It is a common procedure to assess the decommissioning costs as a percentage of the CAPEX. In the study this expense is assumed to be equal to 5% of the CAPEX value. The decommissioning costs are computed as the ratio between the decommissioning expense and the total energy produced over the lifetime of the project, both discounted to the beginning of the farm operation. Considering equation 2, the decommissioning costs can be defined as:

$$Decommissioning\ costs = \frac{\sum_{t=0}^{n} \frac{D_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{AEP_t}{(1+r)^t}} \qquad (13)$$

Table 23 presents the values of investment, operation and maintenance and decommissioning costs for a farm composed of reference case devices. The sum of the three cost components gives the final LCOE value. Moreover, in Table 23 the three costs components of the LCOE are presented as percentages of the LCOE.

Table 23: LCOE cost components and their percentages of contribution to the total LCOE value for a farm composed of reference case devices, installed in Leixões deployment site.

Data	Unit	Reference case	Percentage of LCOE
Investment costs	c€/kWh	111.6	63.4%
O&M costs	c€/kWh	63.6	36.2%
Decommissioning costs	c€/kWh	0.8	0.4%
LCOE	c€/kWh	176.0	-

As already mentioned, the investment costs and the operation and maintenance costs are computed respectively through the CAPEX and the OPEX and thus they can be divided in the sub-sections described in sections 6.1 and 6.2. Figure 24 shows a graph presenting the percentages of contribution to the total LCOE value for the extended set of cost components. In fact, the investment and operational costs are represented as divided in all the CAPEX and OPEX sub-categories described respectively in sections 0 and 0.

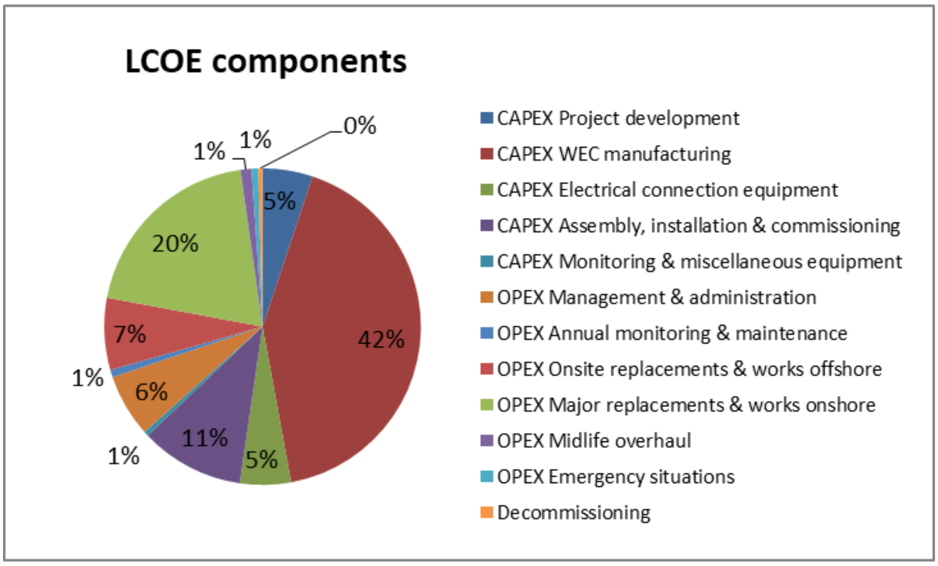


Figure 24: Extended percentage composition of the LCOE value for a farm composed of reference case devices, installed in Leixões deployment site.

Table 24 presents the percentage variations of the five analyzed breakthrough cases in the aforementioned components of the LCOE value compared to the reference case.

Table 24: Percentage variations in the LCOE cost components for the five analyzed breakthrough cases compared to the reference case, referring to Leixões deployment site.

Data	EAM	NS	SS	SM	DEG
Investment costs	-5.1%	-6.0%	30.6%	-9.0%	79.6%
O&M costs	-4.6%	-4.9%	-0.9%	-3.0%	55.7%
Decommissioning costs	-5.1%	-6.0%	30.6%	-9.0%	79.6%
LCOE	-4.9%	-5.6%	19.2%	-6.8%	71.0%

As it can be noticed from Table 24, the variation in the decommissioning is the same as the variation in the investment costs for each case. In fact, as already mentioned, the decommissioning costs are computed as a percentage of the total CAPEX of the project and thus when the capital expenditures are reduced, the decommissioning costs decreases proportionally.

Considering the breakthrough concepts individually, it is possible to say that:

- The enhanced added mass has a positive impact on every component of the LCOE. In fact, the WEC manufacturing cost is reduced (Table 18, section 6.1) as well as the costs for both offshore and onshore maintenance (Table 20, section 6.2). Moreover, the overall energy production is higher compared to the reference case (Table 22, section 6.3) and thus the LCOE components are lower because the AEP is the denominator of the LCOE equation (equation 2, section 4.2).

- The negative spring concept implies the same effects as described for the enhanced added mass case. Both the procurement cost for the structure (Table 18, section 6.1) and the costs related with maintenance procedures (Table 20, section 6.2) are lower compared to the enhanced added mass case and thus compared to the reference case. On the other hand, the increase in the energy production (Table 22, section 6.3) is lower compared to the enhanced added mass case. The final LCOE value is improved when the negative spring concept is applied rather than the enhanced added mass.
- The survivability submergence causes an overall increase in the final LCOE value. There is a slight decrease in the operation and maintenance costs, mainly due to the reduction in the major repairs and the absence of expenses related with emergency situation procedures (Table 20, section 6.2). Nevertheless, the variation in the WEC manufacturing costs (Table 18, section 6.1), due to the extra set of mooring lines per device needed for the submergence process, causes a dramatic raise in the CAPEX of the project, thus in both the investment and decommissioning costs, that cannot be counterbalanced by the low gain in the operation and maintenance costs. Moreover, the energy production increases just slightly, because of the increased availability of the farm (Table 22, section 6.3), and thus the final LCOE value is considerably higher compared to the reference case.
- The shared moorings concept has a positive effect on all the components of the LCOE of the project. In fact, the reduced number of both mooring lines and anchoring points causes a decrease in the WEC manufacturing and installation costs, concerning the CAPEX (Table 18, section 6.1), and in the annual monitoring and offshore maintenance, concerning the OPEX (Table 20, section 6.2). Therefore, respectively the investment costs and the operation and maintenance costs are reduced and the energy production remains practically equal to the reference case (Table 22, section 6.3).
- The DEG PTO system produces a dramatic increase in the LCOE value. Although both CAPEX (Table 18, section 6.1) and OPEX (Table 20, section 6.2) are lower when the breakthrough is applied, the consistent decrease in the energy production (Table 22, section 6.3) causes the three terms of the LCOE equation (equation 2, section 4.2) to be considerably higher compared to the reference case. As already mentioned in section 6.3, the OWC spar-buoy equipped with a DEG PTO system has a power matrix that is not tuned on the more frequent sea-states for the chosen locations of the model. The breakthrough should be validated in different locations, possibly with scatter diagrams showing higher frequencies of occurrence of more energetic sea-states, in order to establish better its potential because the result obtained in this study is highly compromised by the low energy production, while in all the other parameters composing the LCOE it performs better than the reference case device.

7. Future work

The analysis of the effects of the five analyzed breakthroughs on the economics of a wave energy farm project compared to the reference case, as described in section 6.4, shows that the single concepts have a limited positive impact on the final LCOE value. Therefore, the idea of combining together different concepts arose naturally as a potential improvement. Three combinations have been assessed:

- Shared moorings and enhanced added mass (SM & EAM);
- Survivability submergence and negative spring (SS & NS);
- Dielectric elastomer generator and shared moorings (DEG & SM).

The analysis of the three combinations is based on the study of the single concept cases and the three pairs of breakthroughs have been chosen for the fluency of the assessment starting from the model described in section 5. The percentage variations in CAPEX, OPEX, AEP and LCOE of these cases compared to the reference case is presented in Table 25.

Table 25: Percentage variations in CAPEX, OPEX, AEP and LCOE values for three combinations of breakthroughs compared to the reference case, referring to Leixões deployment site.

Data	SM & EAM	SS & NS	DEG & SM
CAPEX	-11.1%	25.7%	-10.2%
OPEX	-4.7%	-4.0%	-16.7%
AEP	2.7%	0.6%	-45.0%
LCOE	-11.2%	14.3%	59.1%

Considering the three combinations individually, it is possible to say that:

- The best result, concerning the final LCOE of the wave energy farm project, is obtained when the shared moorings and the enhanced added mass breakthroughs are combined together. In fact, the LCOE for the SM & EAM combination has a lower value compared to all the single breakthrough cases. The joint benefits of the two concepts, mainly related with the WEC manufacturing for the reduced costs of mooring system (SM) and device structure (EAM), provoke a consistent decrease in the CAPEX value that in turn reflects in a reduction of the LCOE. Moreover, the increase in the energy production, caused by the EAM concept, further lowers the final LCOE value.
- The combination of the survivability submergence and the negative spring concepts results in an overall increase of the LCOE. The WEC manufacturing cost reduction induced by the smaller dimensions of the devices in the NS case is not sufficient to counterbalance the increase in the costs related with the mooring system in the SS case. The operational costs are decreased and the annual energy production is slightly improved but the effect of the increase in the CAPEX is dominant. Nevertheless, it is important to notice that the increase in the LCOE value compared to the reference

case passes from 19.2% (Table 24, section 6.4), when only the SS breakthrough is applied, to 14.3% (Table 25) when the SS is combined with the NS concept.

- The combination of the DEG PTO system with the shared moorings concept has a considerably higher LCOE compared to the reference case. The benefits related with both capital and operational expenditures, due to the lower expenses related to the PTO system (DEG) and the mooring system (SM), are countered by the low annual energy production, almost half compared to the reference case, due to the DEG PTO system characteristic power outcome, not optimized for the chosen locations. Nevertheless, the variation in the LCOE compared to the reference case decreases to 59.1% (Table 25) while when only the DEG breakthrough is applied it corresponds to 71.0% (Table 24, section 6.4).

It was not possible to assess the impacts of other pairs of breakthroughs on the LCOE of a wave energy farm project because of technical reasons. For instance, the combination of the NS concept with the DEG PTO system implies changes in both structure and energy conversion equipment that might not combine in a linear way. Therefore, specific computations would be needed in order to assess the power outcome.

Nevertheless, combinations of two or more breakthroughs appear to have a good potential for a further improvement in the effectiveness of wave energy farm project and thus they should be analyzed in dedicated assessments.

The future work would consist in refining the analysis and exploring the possibility of combining befits from the different breakthroughs, trying to minimize at the same time the less positive aspects of the single concepts (e.g. integrating one breakthrough that reduces CAPEX with another that reduces OPEX) and trying to have a deeper understanding not only of how the combination reflects on the techno-economic analysis, but also on the technical aspects alone.

8. Conclusions

Three of the five analyzed breakthroughs proved to be effective in the reduction of the LCOE value for a wave energy farm project: the enhanced added mass, the negative spring and the shared moorings concepts. In fact, the NS and the SM are the two cases with the greatest reduction in the capital expenditures, as shown in Table 18 (section 6.1), while the EAM case has the greatest increase in the annual energy production, as shown in Table 22 (section 6.3). Since the cost component that has the most relevant impact on the LCOE value is the WEC manufacturing, as it is possible to notice from Figure 24, a reduction of the procurement costs for device structure, PTO and mooring systems results to be very effective in order to improve the economics of the project. Moreover, an increase in the energy production of the farm causes a reduction in the LCOE because the cost of electricity can be lower if there is a greater amount of energy available to be sold.

On the other hand, the survivability submergence and the dielectric elastomer generator concepts caused an increase in the final LCOE value. In the SS case the cost reduction related with the operational expenditures (Table 20, section 6.2) is not sufficient to counterbalance the great increase in the capital expenditures (Table 18, section 6.1). It is important to notice that the SS breakthrough can result to be more effective when the wave energy farm is assumed to be installed in a location that presents a more energetic wave climate compared to the two sites chosen for this study. In fact, if the emergency situations are more frequent, the benefits related with the SS concept can be more relevant in the feasibility assessment of the project. It is important to highlight that further research and development will be required to find more efficient, less expensive processes to carry out the submergence. Regarding the DEG PTO system case, the low energy production (Table 22, section 6.3) causes a considerable increase in the LCOE value, despite the benefits of the DEG energy conversion equipment, related with both capital and operational expenditures (respectively Table 18, section 6.1, and Table 20, section 6.2). It is important to remember that the geometry was not optimized for the chosen locations and the low values of energy production affected dramatically the final LCOE value. Therefore, keeping the same geometry used for the study, the breakthrough needs to be analyzed for locations with more energetic wave climates in order to have a more reliable comparison with the reference case.

In general, all the analyzed breakthroughs seem to have a good potential for the improvement of the economics of a wave energy project. They all need further development and more accurate assessment, especially the tetra-radial turbine concept that, according to the graph presented in Figure 15 (section 3.6), is supposed to increase consistently the energy production of the devices but it needs to be proved effective for that target. Moreover, it is important to underline the effect of the assumptions used for the computations on the final results obtained for some of the breakthrough cases. In fact, for the negative spring case the energy production was assessed using the same power matrix of the reference case while it is supposed to have a considerably higher power outcome that would reflect in a substantial decrease of the final LCOE value. Moreover, the water depth value given for Leixões deployment site, corresponding to 106 m, affects the analysis of both the shared moorings and the survivability submergence breakthroughs. Specifically, for the survivability submergence case, since an extra set of mooring lines is needed, the lengths of the lines have a great impact on the economics of the project. The analysis related to Wave Hub pilot zone, where a water depth of 50 m is considered for the deployment location, is reported in *Annex* and it can be used as reference for a comparison with the case of Leixões, in order to understand the effect of the water depth on the cost for the mooring system and its variation for the five analyzed breakthrough cases.

The possibility of integration of different breakthroughs in the same wave energy farm project deserves a specific insight. The assessment of three of the possible combinations is briefly described in the short analysis of section 7. The lower LCOE value of the whole set of results presented in the study is attained when the shared moorings and the enhanced added mass are combined together. Just a few combinations are presented because of the specific and time-demanding computations needed to assess the effects on the economics of a project when various concepts are integrated.

All the presented breakthroughs show interesting features that can potentially contribute to make the wave energy sector overcome the challenges and barriers it is facing nowadays. The combination of different concepts appears to be the most promising way to achieve competitiveness for wave energy devices through the increase of the energy production and of the reliability of the farms and the reduction of the costs associated with both investment and operation.

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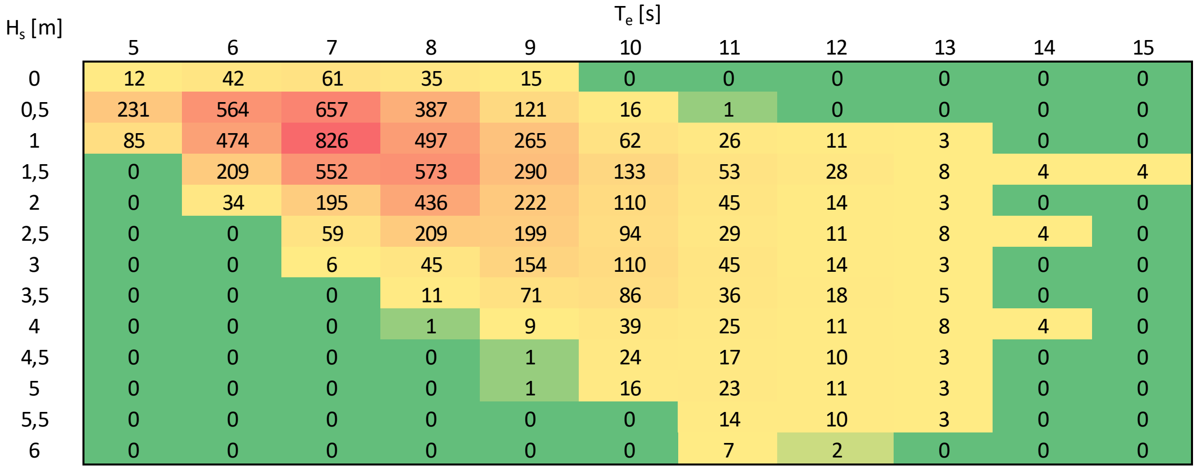
Annex

This section is intended to show the data that were not presented in the report, such as the scatter diagram of Wave Hub pilot zone and the power matrices of the breakthrough concept cases. The results that would be obtained when the farm is considered to be installed in Wave Hub, and the consequent variations in the LCOE parameters for the different breakthroughs, are also reported in this section.

A.1. Location

Figure 25 presents the scatter diagram representing the wave climate of Wave Hub pilot zone.

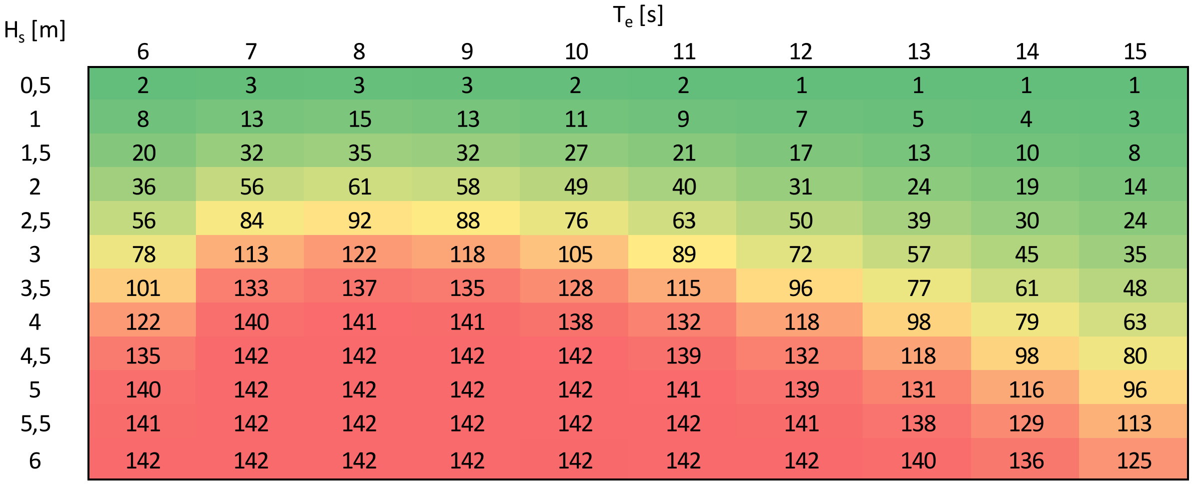


H_s [m]						T_e [s]					
	5	6	7	8	9	10	11	12	13	14	15
0	12	42	61	35	15	0	0	0	0	0	0
0,5	231	564	657	387	121	16	1	0	0	0	0
1	85	474	826	497	265	62	26	11	3	0	0
1,5	0	209	552	573	290	133	53	28	8	4	4
2	0	34	195	436	222	110	45	14	3	0	0
2,5	0	0	59	209	199	94	29	11	8	4	0
3	0	0	6	45	154	110	45	14	3	0	0
3,5	0	0	0	11	71	86	36	18	5	0	0
4	0	0	0	1	9	39	25	11	8	4	0
4,5	0	0	0	0	1	24	17	10	3	0	0
5	0	0	0	0	1	16	23	11	3	0	0
5,5	0	0	0	0	0	0	14	10	3	0	0
6	0	0	0	0	0	0	7	2	0	0	0

Figure 25: Scatter diagram, expressed in hours per year, for Wave Hub pilot zone, Cornwall (internal WavEC data)**.**

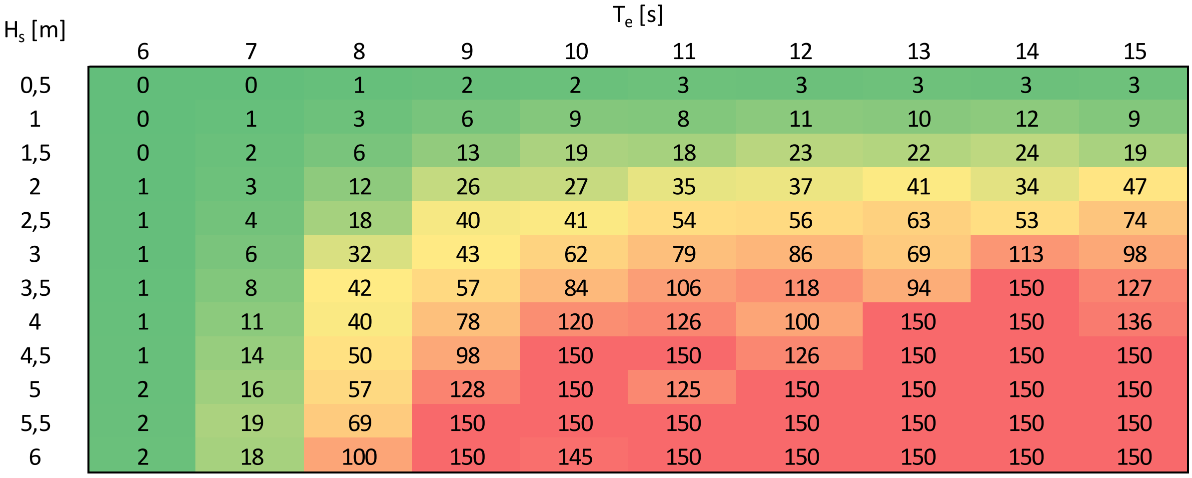
A.2. WEC design

The only two cases that have been assessed using a different power matrix are the EAM and the DEG breakthroughs while for all the others (namely NS, SS and SM) the same power outcome of the reference case has been considered. Their energy power matrices are presented respectively in Figure 26 and Figure 27, in order to make a comparison with the matrix of the reference case presented in Figure 17 (section 5.2).



H_s [m] \ T_e [s]	6	7	8	9	10	11	12	13	14	15
0,5	2	3	3	3	2	2	1	1	1	1
1	8	13	15	13	11	9	7	5	4	3
1,5	20	32	35	32	27	21	17	13	10	8
2	36	56	61	58	49	40	31	24	19	14
2,5	56	84	92	88	76	63	50	39	30	24
3	78	113	122	118	105	89	72	57	45	35
3,5	101	133	137	135	128	115	96	77	61	48
4	122	140	141	141	138	132	118	98	79	63
4,5	135	142	142	142	142	139	132	118	98	80
5	140	142	142	142	142	141	139	131	116	96
5,5	141	142	142	142	142	142	141	138	129	113
6	142	142	142	142	142	142	142	140	136	125

Figure 26: Power matrix, values expressed in kW, of the EAM case device (internal IST data)**.**

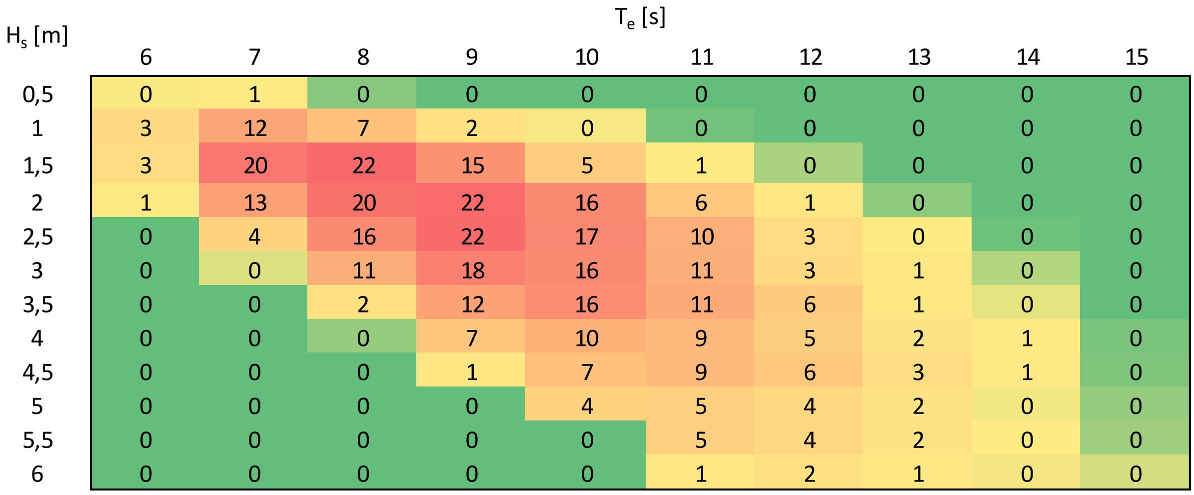


H_s [m] \ T_e [s]	6	7	8	9	10	11	12	13	14	15
0,5	0	0	1	2	2	3	3	3	3	3
1	0	1	3	6	9	8	11	10	12	9
1,5	0	2	6	13	19	18	23	22	24	19
2	1	3	12	26	27	35	37	41	34	47
2,5	1	4	18	40	41	54	56	63	53	74
3	1	6	32	43	62	79	86	69	113	98
3,5	1	8	42	57	84	106	118	94	150	127
4	1	11	40	78	120	126	100	150	150	136
4,5	1	14	50	98	150	150	126	150	150	150
5	2	16	57	128	150	125	150	150	150	150
5,5	2	19	69	150	150	150	150	150	150	150
6	2	18	100	150	145	150	150	150	150	150

Figure 27: Power matrix, values expressed in kW, of the DEG case device (internal WavEC data)**.**

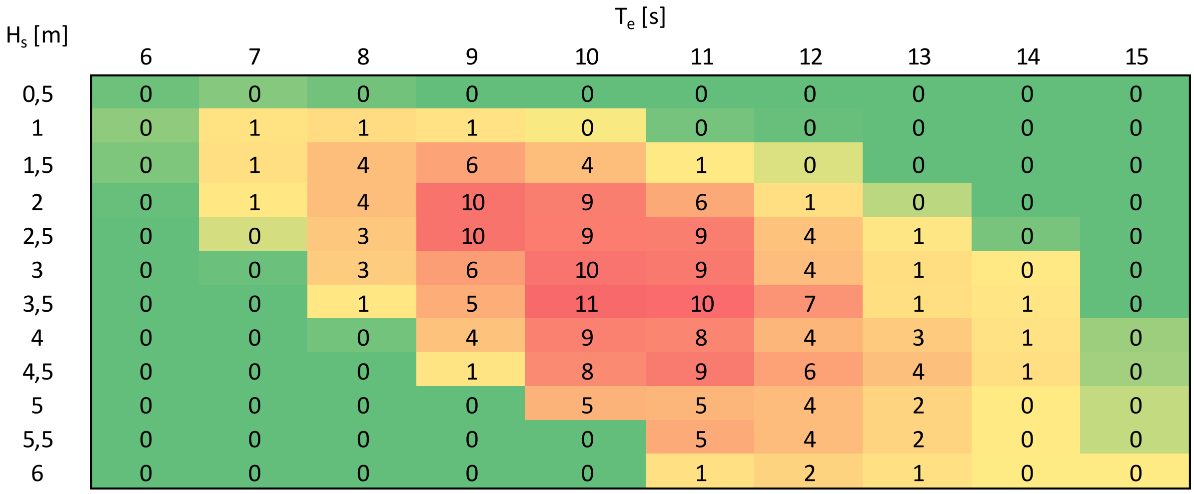
A.3. Energy

As it can be noticed from Table 22 (section 6.3), the only two breakthroughs that induce a consistent variation in the annual energy production of the wave energy farm are the EAM and the DEG concepts. Their energy production matrices are presented respectively in Figure 28 and Figure 29, in order to make a comparison with the matrix of the reference case presented in Figure 23 (section 6.3).



H_s [m]	T_e [s]									
	6	7	8	9	10	11	12	13	14	15
0,5	0	1	0	0	0	0	0	0	0	0
1	3	12	7	2	0	0	0	0	0	0
1,5	3	20	22	15	5	1	0	0	0	0
2	1	13	20	22	16	6	1	0	0	0
2,5	0	4	16	22	17	10	3	0	0	0
3	0	0	11	18	16	11	3	1	0	0
3,5	0	0	2	12	16	11	6	1	0	0
4	0	0	0	7	10	9	5	2	1	0
4,5	0	0	0	1	7	9	6	3	1	0
5	0	0	0	0	4	5	4	2	0	0
5,5	0	0	0	0	0	5	4	2	0	0
6	0	0	0	0	0	1	2	1	0	0

Figure 28: Energy production matrix, values in MWh/year, for an EAM case device deployed in Leixões deployment site.



H_s [m]	T_e [s]									
	6	7	8	9	10	11	12	13	14	15
0,5	0	0	0	0	0	0	0	0	0	0
1	0	1	1	1	0	0	0	0	0	0
1,5	0	1	4	6	4	1	0	0	0	0
2	0	1	4	10	9	6	1	0	0	0
2,5	0	0	3	10	9	9	4	1	0	0
3	0	0	3	6	10	9	4	1	0	0
3,5	0	0	1	5	11	10	7	1	1	0
4	0	0	0	4	9	8	4	3	1	0
4,5	0	0	0	1	8	9	6	4	1	0
5	0	0	0	0	5	5	4	2	0	0
5,5	0	0	0	0	0	5	4	2	0	0
6	0	0	0	0	0	1	2	1	0	0

Figure 29: Energy production matrix, values in MWh/year, for a DEG case device deployed in Leixões deployment site.

As it is possible to notice from Figure 23, Figure 28 and Figure 29, the energy production when the DEG breakthrough is applied is considerably lower compared to both reference and EAM cases. This is the main reason for its high value of LCOE.

A.4. LCOE components

The percentages of contribution to the final LCOE value for the extended set of cost components of the EAM, NS, SS, SM and DEG cases, referring to Leixões deployment site, are presented respectively in the graphs of Figure 30, Figure 31, Figure 32, Figure 33 and Figure 34. The percentages vary with the breakthrough applied. It is interesting to notice that the greatest part of the LCOE value is represented by the WEC manufacturing and the cases that show the lowest share of influence in that cost component are the most effective in the improvement of the economics of the wave energy farm project.

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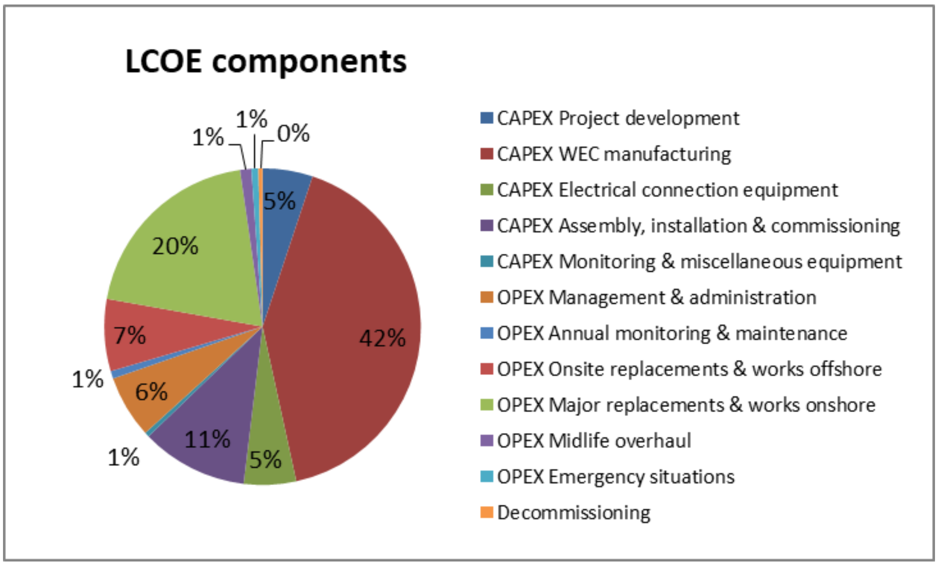


Figure 30: Extended percentage composition of the LCOE value for a farm composed of EAM case devices, installed in Leixões deployment site.

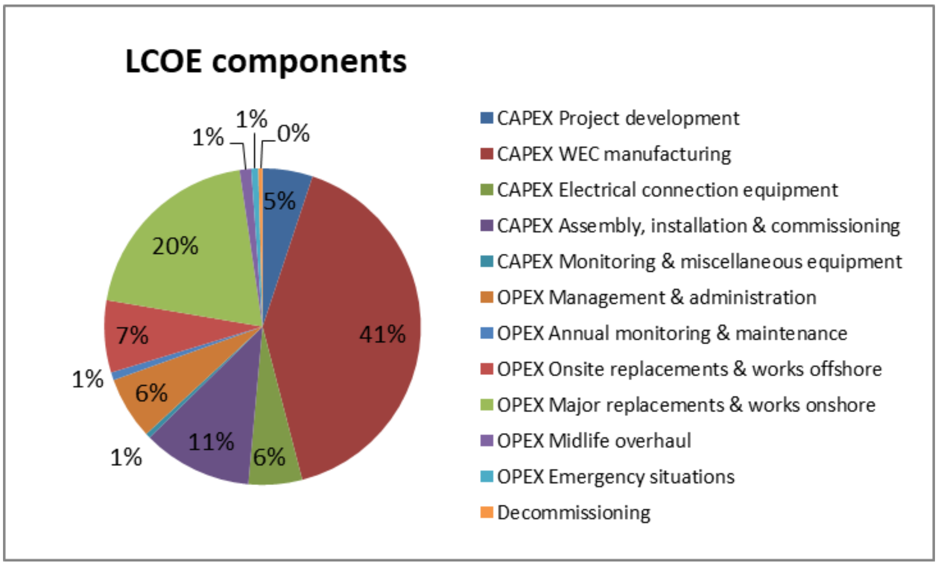


Figure 31: Extended percentage composition of the LCOE value for a farm composed of NS case devices, installed in Leixões deployment site.

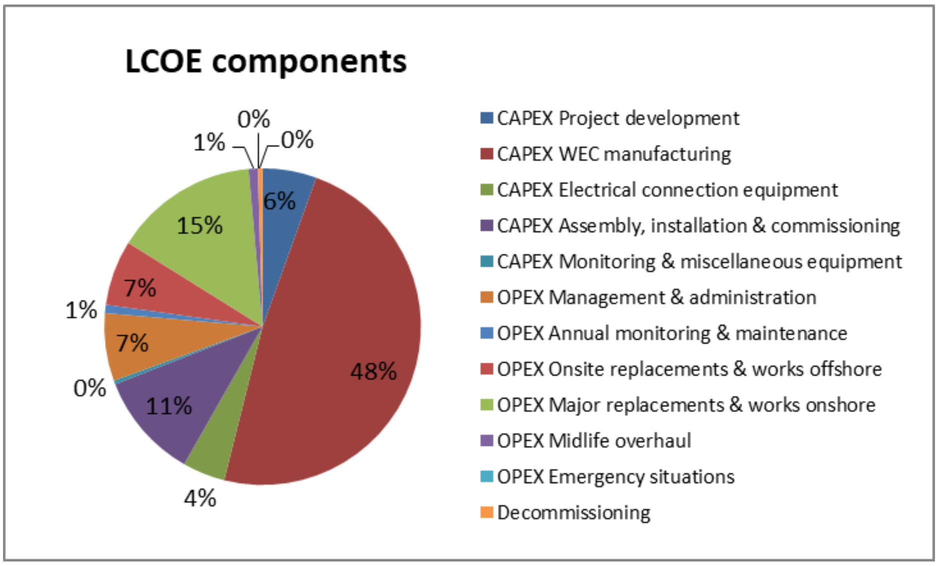


Figure 32: Extended percentage composition of the LCOE value for a farm composed of SS case devices, installed in Leixões deployment site.

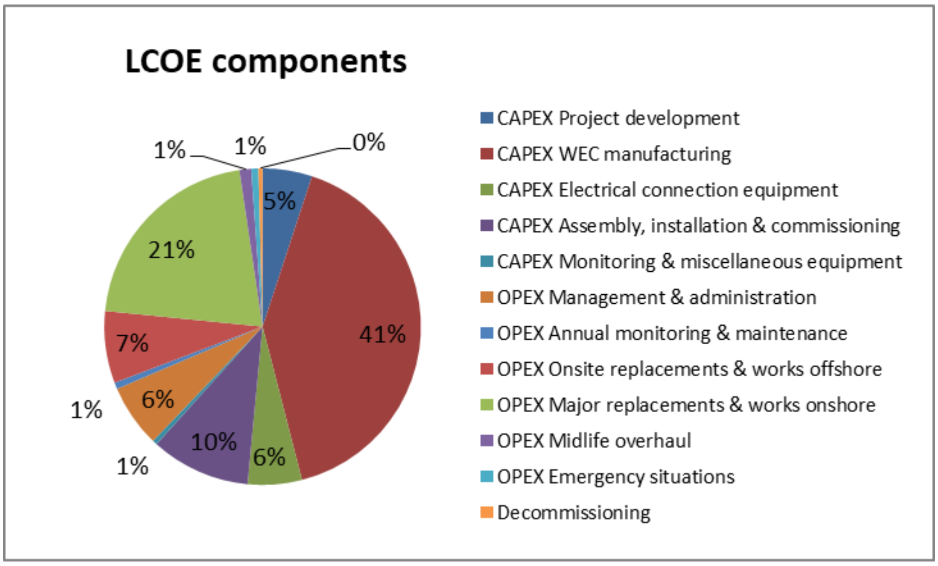


Figure 33: Extended percentage composition of the LCOE value for a farm composed of SM case devices, installed in Leixões deployment site.

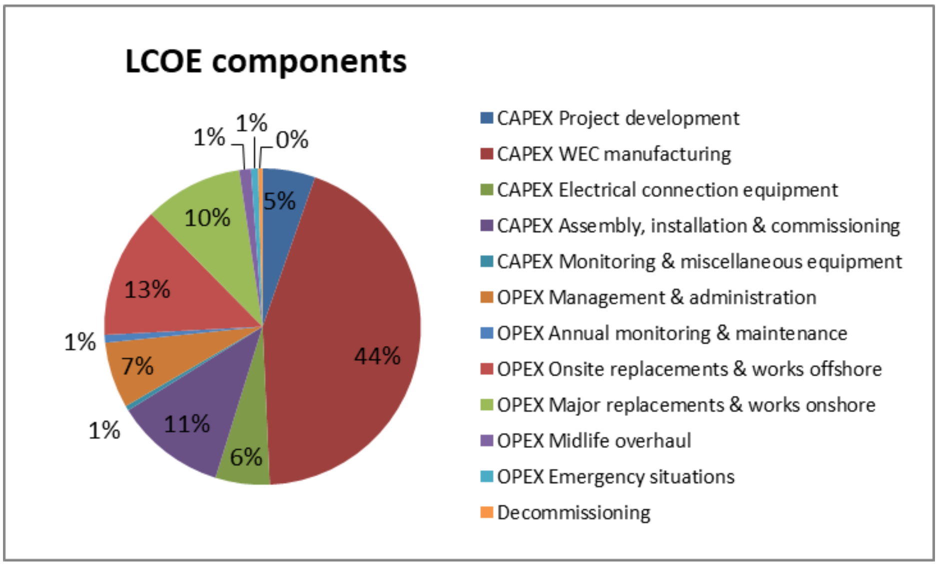


Figure 34: Extended percentage composition of the LCOE value for a farm composed of DEG case devices, installed in Leixões deployment site.

A.5. Wave Hub

This section is intended to report the results obtain from the model when the Wave Hub pilot zone was selected as deployment location. The purpose is to allow the comparison of the changes that the choice of the installation site induces on the economic assessment.

A.5.1. Electrical system configuration

Table 26 presents a comparison of the total cost for the electric system and the effect it has on the LCOE value, when the farm is considered to be installed in Wave Hub pilot zone, for the two different electrical configurations described: string and star. It can be compared to Table 10 (section 5.3.2), referring to Leixões deployment site.

Table 26: Electric system cost, losses and influence on the overall LCOE value for the two electrical configurations considered (string and star) referring to Wave Hub pilot zone.

Data	Unit	String	Star
Total cost of the electrical system	k€	5301	5122
Total electrical losses	%	2.0%	2.6%
Total LCOE	c€/kWh	221.6	224.9

A.5.2. Mooring system configuration

The costs for the mooring system, considering a farm composed of reference case devices installed in Wave Hub pilot zone, are presented in Table 27. It can be compared to Table 13 (section 5.3.3) that refers to Leixões deployment site.

Table 27: Mooring system costs for a farm composed of reference case devices, installed in Wave Hub pilot zone.

Data	Unit	Reference case
Mooring Lines	k€	11558
Anchors	k€	840
Total mooring system	k€	12398

Table 28 presents the percentage variation of the mooring system cost for the five analyzed breakthrough cases compared with the reference case.

Table 28: Percentage variation in the mooring system costs for the five analyzed breakthroughs compared to the reference OWC spar-buoy, referring to Wave Hub pilot zone.

Data	EAM	NS	SS	SM			DEG
				B	C	D	
Mooring lines	0%	0%	91%	29%	-8%	-12%	0%
Anchors	0%	0%	100%	-47%	-73%	-73%	0%
Total mooring system	0%	0%	92%	23%	-12%	-17%	0%

For Wave Hub pilot zone the most effective configuration for the shared moorings breakthrough is configuration D while for Leixões deployment site it was configuration C, as shown in Table 14, section 5.3.3. The difference in the most cost-effective solution for the two locations is related with the lengths of wires and chains and their cost functions expressed by equations 8 and 9, in section 5.3.3. When the distance to the sea bottom is lower, as in Wave Hub pilot zone, the reduction in the number of interconnection lines of configuration D, as described in section 3.4, results to be more effective since there is just a low increase in the length of the chains, in order to keep the same station-keeping performance, compared to configuration C.

For the survivability submergence case the percentage variation compared to the reference case does not change for the two locations but for Wave Hub pilot zone the total cost of the mooring system is considerably lower compared to Leixões deployment site and it reflects on the final increase in the LCOE value (expressed in Table 36, section A.5.6) that is lower when the breakthrough is applied in a location with a lower water depth.

A.5.3. CAPEX

The same analysis of the CAPEX for the reference case and its variations for the different breakthroughs, as presented in section 6.1 (Table 17 and Table 18) for Leixões deployment site, is reported in Table 29 and Table 30, referring to Wave Hub pilot zone.

Table 29: CAPEX cost components for a farm composed of reference case devices, installed in Wave Hub pilot zone.

Data	Unit	Reference case
Project Development	€/kW	1390
WEC Manufacturing	€/kW	12111
Electrical Connection Equipment	€/kW	1033
Assembly, Installation & Commissioning	€/kW	2775
Monitoring & Miscellaneous Equipment	€/kW	170
CAPEX	€/kW	17479

Table 30: Percentage variations in the CAPEX cost components for the five analyzed breakthrough cases compared to the reference case, referring to Wave Hub pilot zone.

Data	EAM	NS	SS	SM	DEG
Project development	-3%	-7%	20%	-5%	-2%
WEC manufacturing	-5%	-10%	23%	-4%	-2%
Electrical connection equipment	0%	0%	0%	0%	0%
Assembly, installation & commissioning	0%	0%	21%	-11%	0%
Monitoring & miscellaneous equipment	0%	0%	0%	0%	0%
CAPEX	-3%	-7%	21%	-5%	-2%

A.5.4. OPEX

The same analysis of the OPEX for the reference case and its variations for the different breakthroughs, as presented in section 6.2 (Table 19 and Table 20) for Leixões deployment site, is reported in Table 31 and Table 32, referring to Wave Hub pilot zone.

Table 31: OPEX cost components for a farm composed of reference case devices, installed in Wave Hub pilot zone.

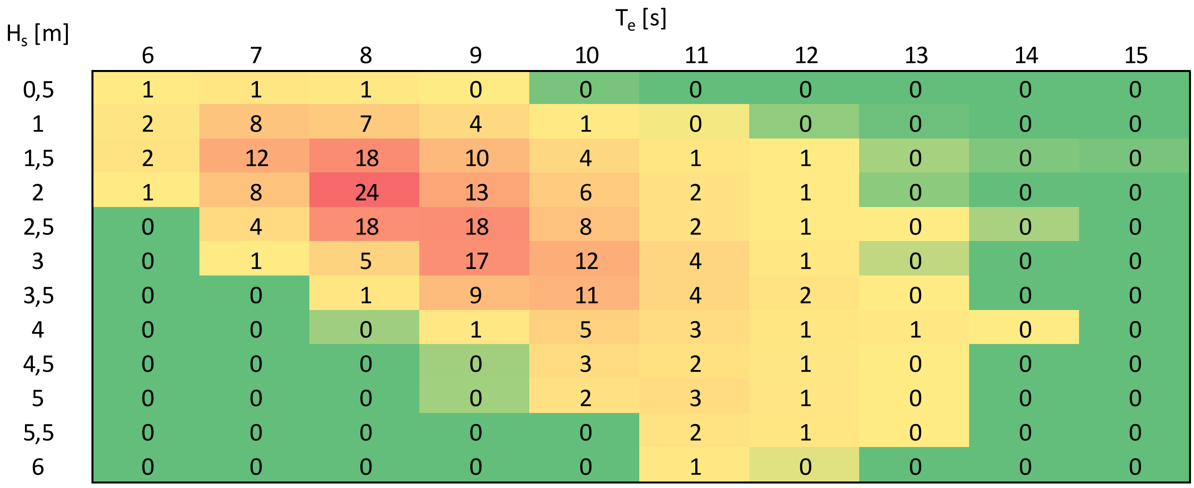
Data	Unit	Reference case
Management & administration	€/kW	255
Annual monitoring & maintenance	€/kW	36
Onsite replacements & works offshore	€/kW	282
Major replacements & works onshore	€/kW	938
Midlife overhaul	€/kW	73
Emergency situations	€/kW	2
OPEX	€/kW	1586

Table 32: Percentage variations in the OPEX cost components for the five analyzed breakthrough cases compared to the reference case, referring to Wave Hub pilot zone.

Data	EAM	NS	SS	SM	DEG
Management & administration	-3%	-7%	17%	-3%	-2%
Annual monitoring & maintenance	0%	0%	17%	-17%	0%
Onsite replacements & works offshore	-3%	-6%	5%	-5%	85%
Major replacements & works onshore	-2%	-4%	-11%	0%	-53%
Midlife overhaul	0%	0%	0%	0%	0%
Emergency situations	0%	0%	-100%	0%	0%
OPEX	-2%	-5%	-3%	-2%	-16%

A.5.5. Energy

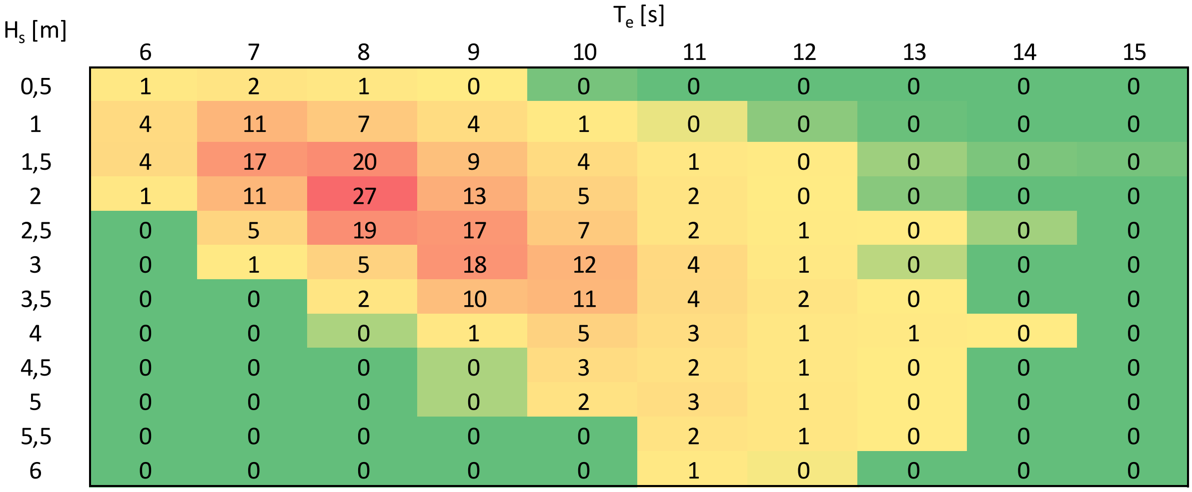
The annual energy production of a reference case device installed in Wave Hub pilot zone is shown in Figure 35 and it can be compared to the energy production matrix for Leixões deployment site reported in Figure 23 (section 6.3).



H_s [m]	T_e [s]									
	6	7	8	9	10	11	12	13	14	15
0,5	1	1	1	0	0	0	0	0	0	0
1	2	8	7	4	1	0	0	0	0	0
1,5	2	12	18	10	4	1	1	0	0	0
2	1	8	24	13	6	2	1	0	0	0
2,5	0	4	18	18	8	2	1	0	0	0
3	0	1	5	17	12	4	1	0	0	0
3,5	0	0	1	9	11	4	2	0	0	0
4	0	0	0	1	5	3	1	1	0	0
4,5	0	0	0	0	3	2	1	0	0	0
5	0	0	0	0	2	3	1	0	0	0
5,5	0	0	0	0	0	2	1	0	0	0
6	0	0	0	0	0	1	0	0	0	0

Figure 35: Energy production matrix, values in MWh/year, for a reference case device deployed in Wave Hub pilot zone.

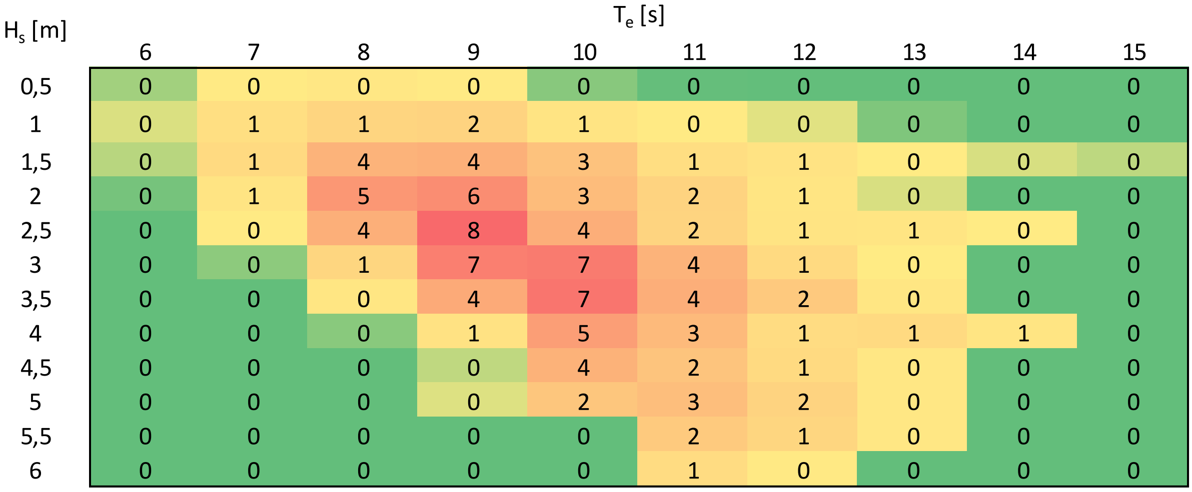
The energy production matrices for the EAM and DEG cases are presented respectively in Figure 36 and Figure 37, referring to Wave Hub pilot zone. They can be compared with the matrices of Figure 28 and Figure 29, reported in section 0 of the *Annex* and referring to Leixões deployment site.



T_e [s]

H_s [m]	6	7	8	9	10	11	12	13	14	15
0,5	1	2	1	0	0	0	0	0	0	0
1	4	11	7	4	1	0	0	0	0	0
1,5	4	17	20	9	4	1	0	0	0	0
2	1	11	27	13	5	2	0	0	0	0
2,5	0	5	19	17	7	2	1	0	0	0
3	0	1	5	18	12	4	1	0	0	0
3,5	0	0	2	10	11	4	2	0	0	0
4	0	0	0	1	5	3	1	1	0	0
4,5	0	0	0	0	3	2	1	0	0	0
5	0	0	0	0	2	3	1	0	0	0
5,5	0	0	0	0	0	2	1	0	0	0
6	0	0	0	0	0	1	0	0	0	0

Figure 36: Energy production matrix, values in MWh/year, for an EAM case device deployed in Wave Hub pilot zone.



T_e [s]

H_s [m]	6	7	8	9	10	11	12	13	14	15
0,5	0	0	0	0	0	0	0	0	0	0
1	0	1	1	2	1	0	0	0	0	0
1,5	0	1	4	4	3	1	1	0	0	0
2	0	1	5	6	3	2	1	0	0	0
2,5	0	0	4	8	4	2	1	1	0	0
3	0	0	1	7	7	4	1	0	0	0
3,5	0	0	0	4	7	4	2	0	0	0
4	0	0	0	1	5	3	1	1	1	0
4,5	0	0	0	0	4	2	1	0	0	0
5	0	0	0	0	2	3	2	0	0	0
5,5	0	0	0	0	0	2	1	0	0	0
6	0	0	0	0	0	1	0	0	0	0

Figure 37: Energy production matrix, values in MWh/year, for a DEG case device deployed in Wave Hub pilot zone.

The same analysis of the annual energy production for the reference case and its variations for the different breakthroughs, as presented in section 6.3 (Table 23 and Table 24) for Leixões deployment site, is reported in Table 33 and Table 34, referring to Wave Hub pilot zone.

Table 33: Availability factor, capacity factor and electricity production for a farm composed of reference case devices, installed in Wave Hub pilot zone.

Data	Unit	Reference case
Availability factor	%	96%
Farm capacity factor	%	20%
Farm electricity production	MWh/y	9158

Table 34: Percentage variations in the availability factor, capacity factor and electricity production of the wave energy farm for five breakthrough cases compared to the reference case, referring to Wave Hub pilot zone.

Data	EAM	NS	SS	SM	DEG
Availability factor	0.0%	0.0%	0.0%	0.1%	-3.6%
Farm capacity factor	7.5%	0.4%	0.0%	0.1%	-57.2%
Farm electricity production	7.5%	0.4%	0.0%	0.1%	-57.2%

A.5.6. LCOE

The same analysis of the LCOE for the reference case and its variations for the different breakthroughs, as presented in section 6.4 (Table 23 and Table 24) for Leixões deployment site, is reported in Table 35 and Table 36, referring to Wave Hub pilot zone.

Table 35: LCOE cost components for a farm composed of reference case devices, installed in Wave Hub pilot zone.

Data	Unit	Reference case
Investment costs	c€/kWh	129.9
O&M costs	c€/kWh	90.9
Decommissioning costs	c€/kWh	0.9
LCOE	c€/kWh	221.6

Table 36: Percentage variations in the LCOE cost components for the five analyzed breakthrough cases compared to the reference case, referring to Wave Hub pilot zone.

Data	EAM	NS	SS	SM	DEG
Investment costs	-10.2%	-7.8%	21.1%	-4.9%	129.6%
O&M costs	-9.1%	-5.2%	-3.0%	-1.9%	95.8%
Decommissioning costs	-10.2%	-7.8%	21.1%	-4.9%	129.6%
LCOE	-9.8%	-6.7%	11.2%	-3.6%	115.7%

A.5.7. LCOE components

Figure 38 presents the percentages of contribution to the final LCOE value of the various cost components (CAPEX, OPEX and decommissioning) for a wave energy farm composed of reference case devices, installed in Wave Hub pilot zone. It can be compared to the graph of Figure 24 (section 6.4) that refers to Leixões deployment site.

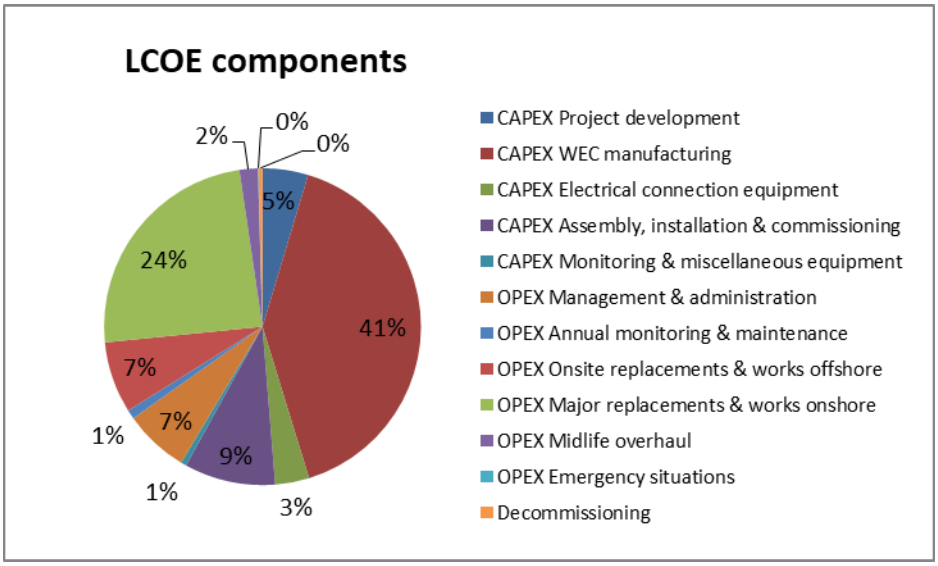


Figure 38: Extended percentage composition of the LCOE value for a farm composed of reference case devices, installed in Wave Hub pilot zone.

The percentages of contribution to the final LCOE value for the extended set of cost components of the EAM, NS, SS, SM and DEG cases, referring to Wave Hub pilot zone, are presented respectively in the graphs of Figure 39, Figure 40, Figure 41, Figure 42 and Figure 43.

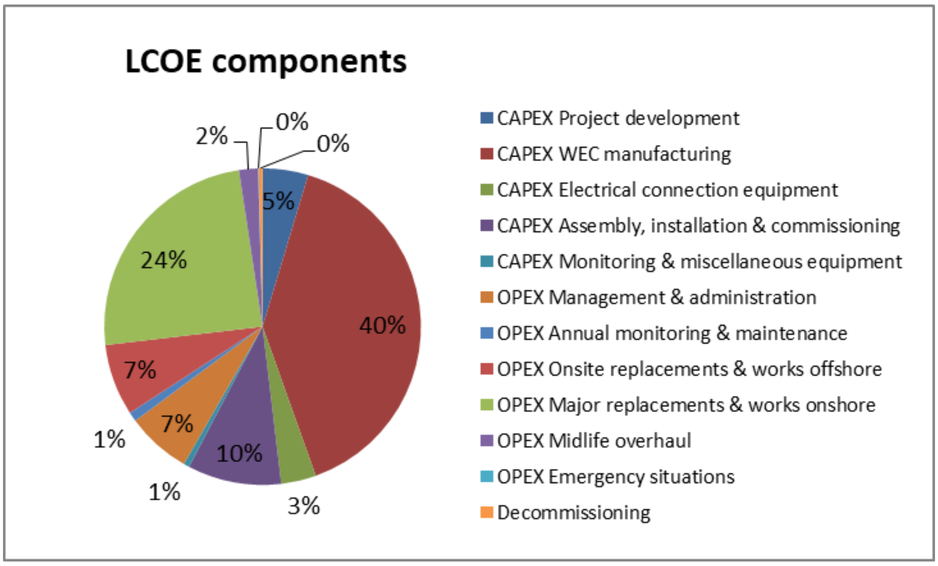


Figure 39: Extended percentage composition of the LCOE value for a farm composed of EAM case devices, installed in Wave Hub pilot zone.

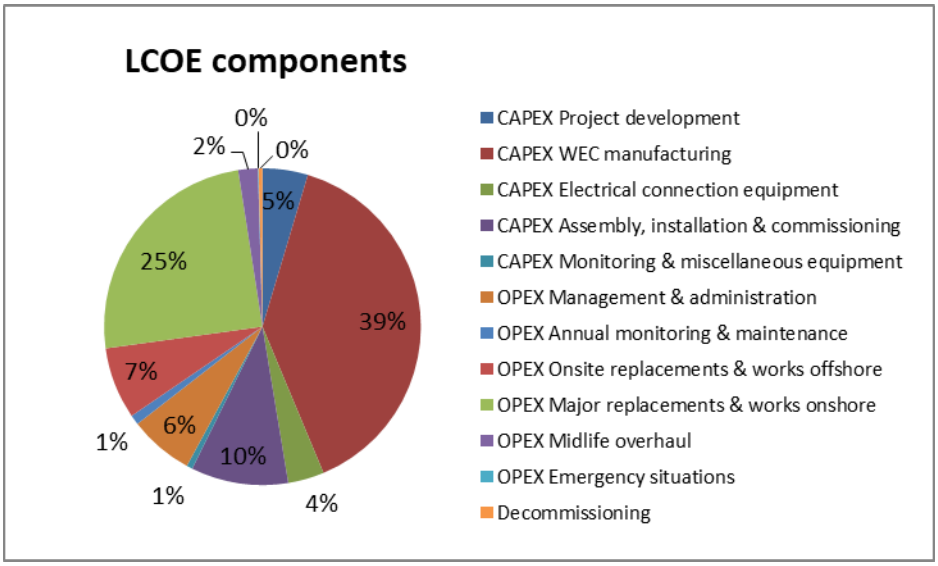


Figure 40: Extended percentage composition of the LCOE value for a farm composed of NS case devices, installed in Wave Hub pilot zone.

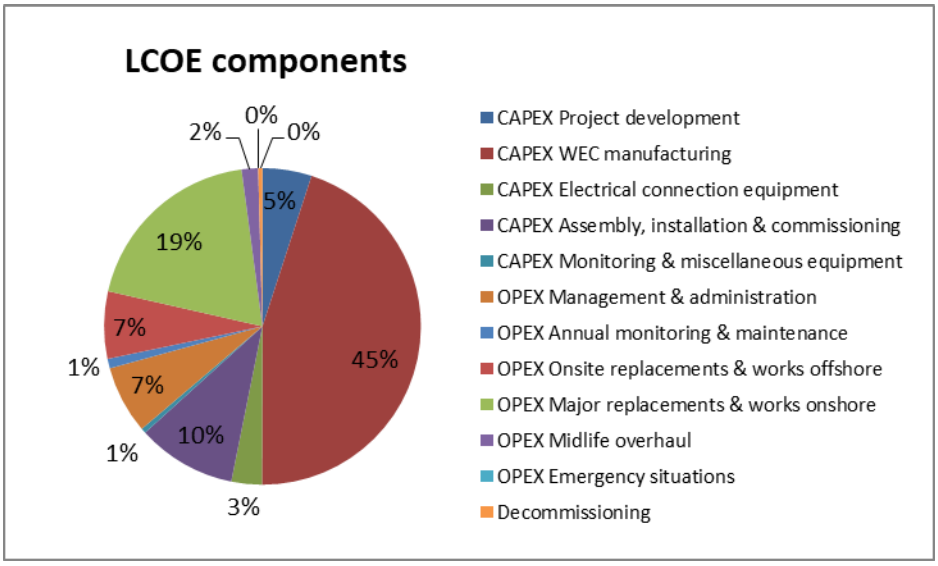


Figure 41: Extended percentage composition of the LCOE value for a farm composed of SS case devices, installed in Wave Hub pilot zone.

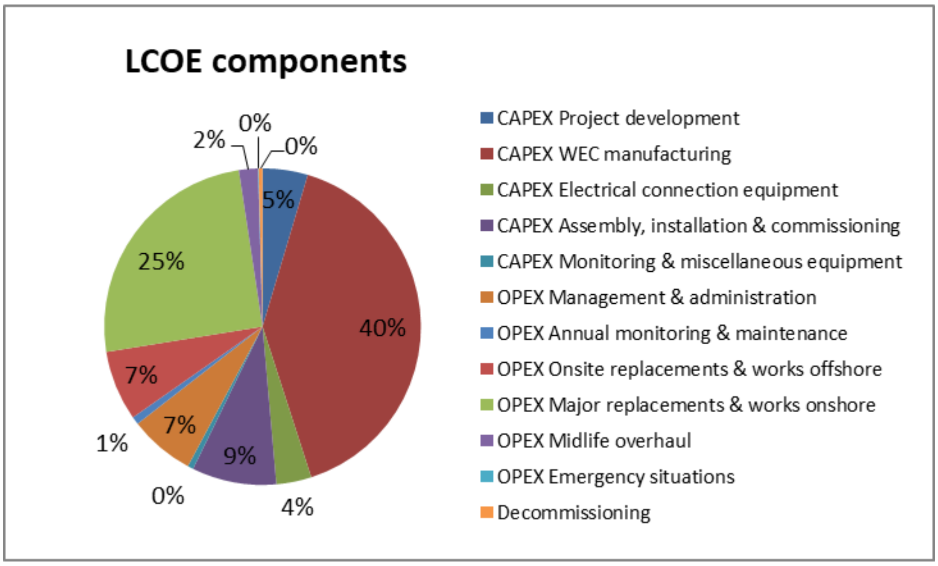


Figure 42: Extended percentage composition of the LCOE value for a farm composed of SM case devices, installed in Wave Hub pilot zone.

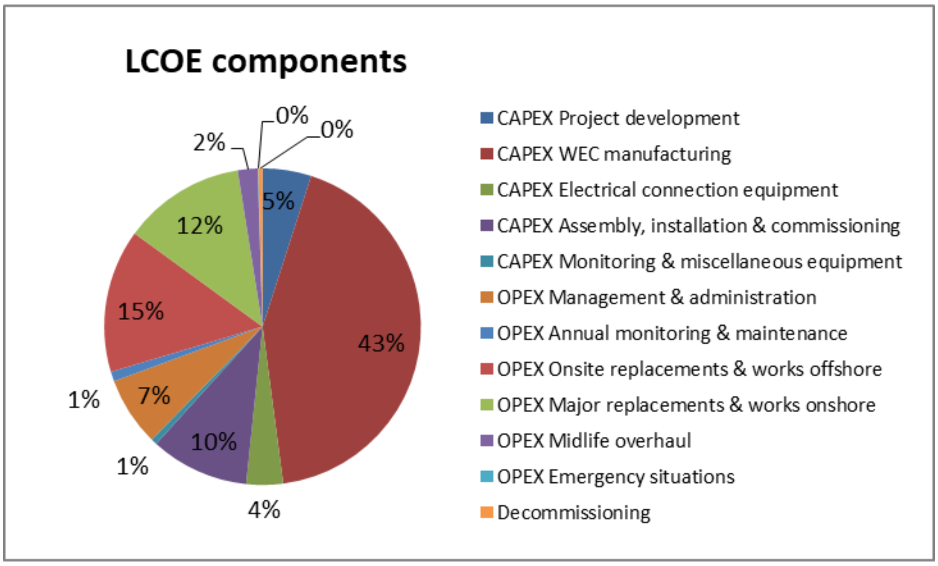


Figure 43: Extended percentage composition of the LCOE value for a farm composed of DEG case devices, installed in Wave Hub pilot zone.

In general, it is possible to say that when the devices are installed in Leixões deployment site all the cost components related with the capital expenditures, apart from the monitoring and miscellaneous equipment that is considered to be the same, have a slightly more relevant impact on the LCOE of the wave energy farm project compared to the deployment in Wave Hub pilot zone. Concerning the OPEX, the costs are higher for Wave Hub pilot zone when the devices have to be brought at port for maintenance, so for major repairs and midlife overhaul, due to the considerably larger distance to the closest large port with adequate features to perform such operations. On the other hand, the emergency situations costs are reduced because of the lower probability of occurrence of rough storms, over the operating limit conditions, in Wave Hub pilot zone. The decommissioning costs have a low share in the LCOE value for both Leixões deployment site and Wave Hub pilot zone.

A.5.8. Combinations of breakthroughs

The same analysis of the three combinations of breakthroughs compared to the reference case, as presented in section 7 (Table 25) for Leixões deployment site, is reported in Table 37, referring to Wave Hub pilot zone.

Table 37: Percentage variations in CAPEX, OPEX, AEP and LCOE values for three combinations of breakthroughs compared to the reference case, referring to Wave Hub pilot zone.

Data	SM & EAM	SS & NS	DEG & SM
CAPEX	-6.9%	14.4%	-5.8%
OPEX	-3.6%	-6.5%	-17.2%
AEP	7.6%	0.5%	-57.2%
LCOE	-12.2%	5.3%	109.1%

The benefits of the SM & EAM and the SS & NS combinations are greater compared to the reference case when the devices are installed in Wave Hub pilot zone. The main reason is the lower cost for mooring systems due to the considerable lower water depth in Wave Hub location compared to Leixões deployment site that reduces the total WEC manufacturing cost, which is the greater cost component in the final LCOE value. Moreover, for the SM & EAM case the annual energy production has a greater improvement compared to the reference case when the devices are installed in Wave Hub, due to the better matching between the power matrix of the EAM breakthrough and the scatter diagram of the chosen location. On the other hand, the DEG & SM combination has a considerably worst result compared to the installation in Leixões deployment site case. The main reason is the typical wave climate of Wave Hub pilot zone that is mainly characterized by low-energetic sea-states. Therefore, the drop in the energy production when the DEG PTO system is applied is even lower if the devices are installed in Wave Hub pilot zone compared to Leixões deployment site.