Ref. Ares(2018)4049148 - 31/07/2018

D7.3 Techno-economic assessment of the proposed breakthroughs for large scale deployment

DATE: July 2018

PROJECT COORDINATOR:

WavEC Offshore Renewables

GRANT AGREEMENT NR: 641334

PROJECT: WETFEET

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 No 641334.

Techno-economic assessment of the proposed breakthroughs for large scale deployment			
Project	WETFEET – Wave Energy Transition to Future by Evolution of Engineering and Technology		
WP No.	7	WP Title	Multi-disciplinary Assessment for Large-scale Deployment
Deliverable No.		7.3	
Nature (R: *Report*, P: *Prototype*, O: *Other*)		R	
Dissemination level (PU, PP, RE, CO)		PU	
Lead beneficiary:		WavEC Offshore Renewables	
Contributing partners		WavEC, IST, Teamwork	
Authors List:		Marta Silva (WavEC), Lorenzo Afferni (WavEC), Rui Sebastian (WavEC)	
Quality reviewer			
Status (F: final; D: draft; RD: revised draft):		F	
Due Delivery Date:		30/04/2018	
Actual Delivery Date:		31/07/2018	

Version no.	Dates and comments
1	19-Nov-2017 First draft
2	31-Jul-2018 Final draft
3	
4	
5	

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

EXECUTIVE SUMMARY

Despite the considerable progress witnessed during the past decade in the development of wave energy devices, the sector has struggled to progress towards commercialization. This delay results from barriers and issues which have already been identified:

- 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 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.. 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 submerged point absorber that features a water turbine as PTO equipment.

This deliverable aims to provide a techno-economic assessment of the selected devices & breakthroughs at large scale deployment. To implement the integrated techno-economic model, the technical modelling work carried out from WP2 to WP6 was coupled to an economic module based on a cost database to support the capital and operational costs calculations.

The presented techno-economic assessment of potential wave energy farms of Oscillating Water Column (OWC) spar-buoy and of Symphony devices, based on the Levelized Cost of Energy (LCOE) metric and it is performed using a model developed by WavEC Offshore Renewables.

LIST OF ACRONYMS

AEP	Annual Energy Production
AWS	Archimedes Wave Swing
CAPEX	Capital Expenditures
CF	Capacity Factor
CS	Continuous Submergence
DEG	Dielectric Elastomer Generator
EAM	Enhanced Added-Mass
IEA-OES	International Energy Agency – Ocean Energy Systems
LCOE	Levelized Cost of Electricity
NS	Negative Spring
OPEX	Operational Expenditures
OWC	Oscillating Water Column
PM	Permanent Magnet
PTO	Power Take-Off
SM	Shared Moorings
SMemb	Structural Membrane
SPDD	Submerged Pressure Differential Devices
SS	Survivability Submergence
TPL	Technology Performance Level
TRL	Technology Readiness Level
TRT	Tetra-Radial Turbine
WEC	Wave Energy Converter
WT	Water Turbine

1 INTRODUCTION

1.1 State-of-the art of techno-economic assessment of wave energy devices

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 hydrodynamic response and control system effectiveness point of view, 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, which makes 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 the need to be as small as possible to reduce costs and achieve economic feasibility.

It is important to notice that there is no 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 [1], [2]:

- 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).

For wave energy to reach its full market potential, it needs to become economically competitive with other sources of energy, including fossil fuel power plants. The levelized cost of electricity (LCOE) is a handy tool for comparing the unit costs of different technologies over their economic life.

The LCOE is therefore used as a parameter to assess the economic feasibility of a technology, and it is defined as the sum of total lifetime costs divided by the electricity generation to grid accumulated throughout the technology's lifetime. It corresponds to the cost of an investor assuming the certainty of production costs and the stability of electricity prices. The costs and electricity generated are all discounted to present value, and the discount rate used in LCOE calculation reflects the return on capital for an investor in the absence of specific market or technology risks.

Given that such specific market and technology risks frequently exist, a gap between the LCOE and true financial costs of an investor operating in real electricity markets with their specific uncertainties is usually verified. For the same reason, LCOE is also closer to the real cost of investment in electricity production in regulated monopoly electricity markets with loan guarantees and regulated prices rather than to the real costs of investments in competitive markets with variable prices.

The formula for LCOE calculation is:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{(Investment_t + O\&M_t + Fuel_t + Carbon_t + Decommissioning_t)}{(1+r)^t}}{\sum_{t=0}^{n} \frac{AEP_t}{(1+r)^t}}$$

LCOE	**=**	Levelized Cost of Energy
AEP_t	=	Annual electricity production *(at year t)*
r	=	Discount rate
n	=	Lifetime of the system
t	=	Project year, from the start of the project (*year 0*) to the final year of the project (*year n*)

This equation can be used for different energy systems, and other cost centres can be added as needed. For renewable energy systems, which have no fuel or carbon costs associated, it is common to simplify the equation down to:

- Investment costs, commonly called **CAPEX**: these are assumed to happen all in year 0, for the simplicity of the calculation. However, this value can be adjusted to account the time it takes to develop a project. Investment costs can also be divided into procurement costs (cost of purchasing the elements in a project), installation costs and administrative costs.
- Operational costs, commonly called **OPEX**: all the cost incurred during the operational lifetime of the project. For more simple calculations these are can be assumed as fixed rate throughout the lifetime of the project, sometimes expressed as a percentage of the CAPEX in less mature technologies for which the operational costs are still subject to high uncertainty. However, operational costs are not fixed. There will be a part of fixed costs related to administrative and other recurrent costs, but maintenance operations, especially corrective ones, will add a variable element to the operational costs. Mid-life refit contribution to OPEX is comparable to that of planned or corrective maintenance [3], but happens once during the lifetime of the project. This means that there will be a period with significantly higher costs (and lower production).
- Decommissioning costs are sometimes included in the OPEX. However, like operational costs, in the case of less mature technologies, it may be hard to estimate the actual values for decommission, meaning that it is also common for these costs to be expressed as a percentage of CAPEX or of Installation costs. It is also common that decommissioning cost are not included, as due to the nature of the present value calculation, its impact on the LCOE is very small, especially for long duration projects.

In the large electricity markets, renewables compete with large conventional power plants, which have low costs of energy, and it is required some level of support in order to enable the progressive deployment of new technologies with higher LCOE in the market and enable learning and cost reduction until grid parity is achieved.

The energy sector is very dynamic, and the cost of energy is in constant evolution. Recent analyses show that some renewable energy technologies have achieved grid parity with conventional power plants. The following graph has been extracted from the most recent report from the Annual Energy Outlook 2015 published by the U.S [4], which provides similar outlooks as other reference reports published by other international reference institutions [5]–[8].

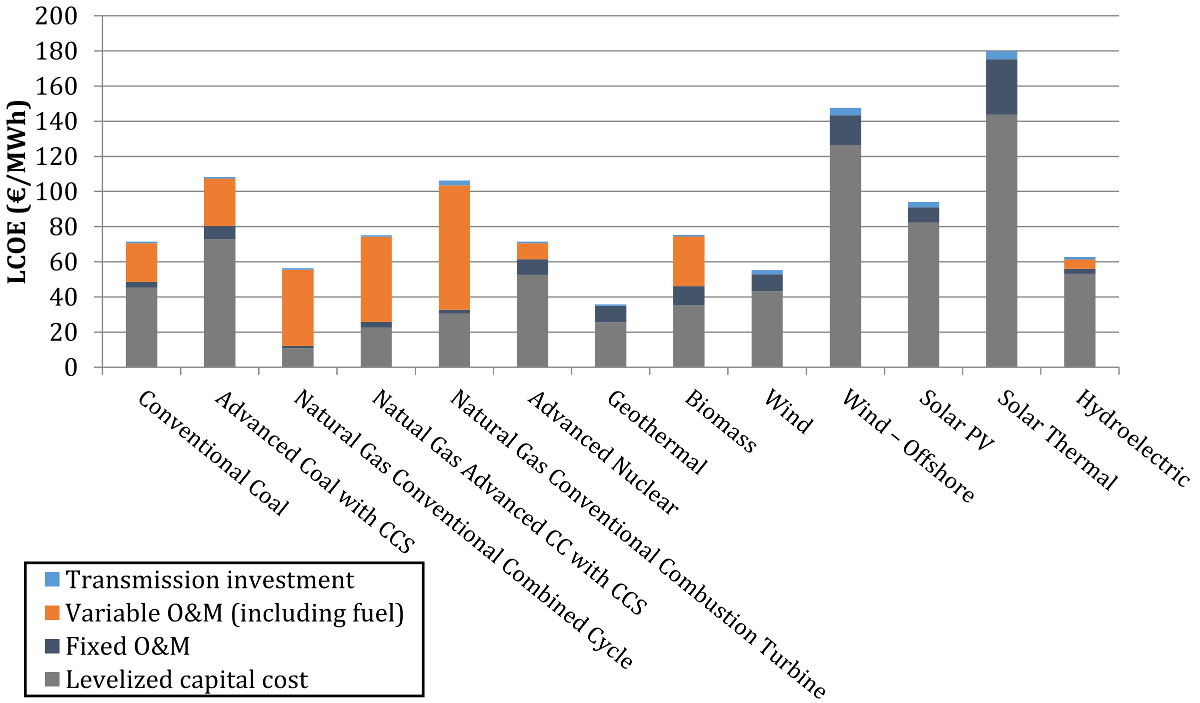


FIGURE 1:1 U.S. AVERAGE LEVELIZED COSTS FOR PLANTS ENTERING SERVICE IN 2020 [9]
Original costs in 2013 $/MWh have been converted to Euros by applying avg. 0.75 EUR/US$.

It can be observed that renewable energy technologies such as geothermal, biomass, onshore wind, hydropower or solar PV are already competing with the conventional coal, gas or nuclear power plants. However, the first arrays of wind and solar power plants had significantly higher prices, only a few decades ago. New energy technologies typically offer higher energy prices at the start of the learning curve, which typically decrease over time after learning and experience is gained with the manufacture, deployment, and production, as well as with R&D effort (Figure 1:2). This cost reduction is also expected for the marine energy industry and arrays will follow a similar path as explained in the following sections.

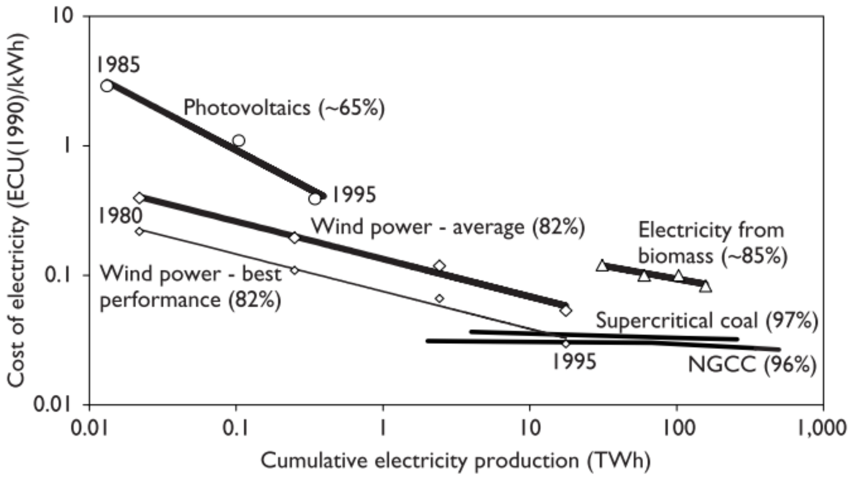


FIGURE 1:2 OBSERVED LEARNING CURVES IN ENERGY TECHNOLOGIES [10]

It is also important to mention that LCOE varies from project to project, especially depending on the site resource levels and characteristics that influence the energy production as well as some of the costs (e.g. installation) and many of these factors can only be fully understood at array level.

Capital costs are usually presented in relation to the power capacity of the technology or farm (e.g. 1.5 €/kW for an onshore wind farm unitary CAPEX). The CAPEX represents a significant share for the LCOE for marine renewable, but before accounting for operation costs and energy production no conclusion should be taken. For example, today offshore wind farms have higher capital costs than onshore (e.g. ≈3-4 €/kW *vs.* 1.5-2 €/kW) but they also have higher capacity factors (35-40% vs. 25-35%) due to the higher resource that is available.

This use of unitary values can be artefactual, as some companies may overrate their technologies, thus apparently reducing the initial costs. This, however, has the downside that the capacity factor (CF) will also decrease, as well as PTO efficiency (with a small increase in costs due to higher rating generators being used). There is an optimal rating that minimizes the LCOE, but at this early stage with very small operational experience and a large diversity of technologies there is no convergence. It is expected capacity factors for wave energy to be around 30-40%.

The most recent analysis of ocean energy costs was published by the IEA-OES in 2015 [11], which analysed previous reports from Europe and the US and adding an international context, by including responses from questionnaires sent to leading developers across the world.

The expected CAPEX values plotted against project capacity are presented on Figure 1:3. Although for small scale projects values vary widely, the trend for higher capacity projects from the different sources of information were shown to converge at levels comparable to those of offshore wind.

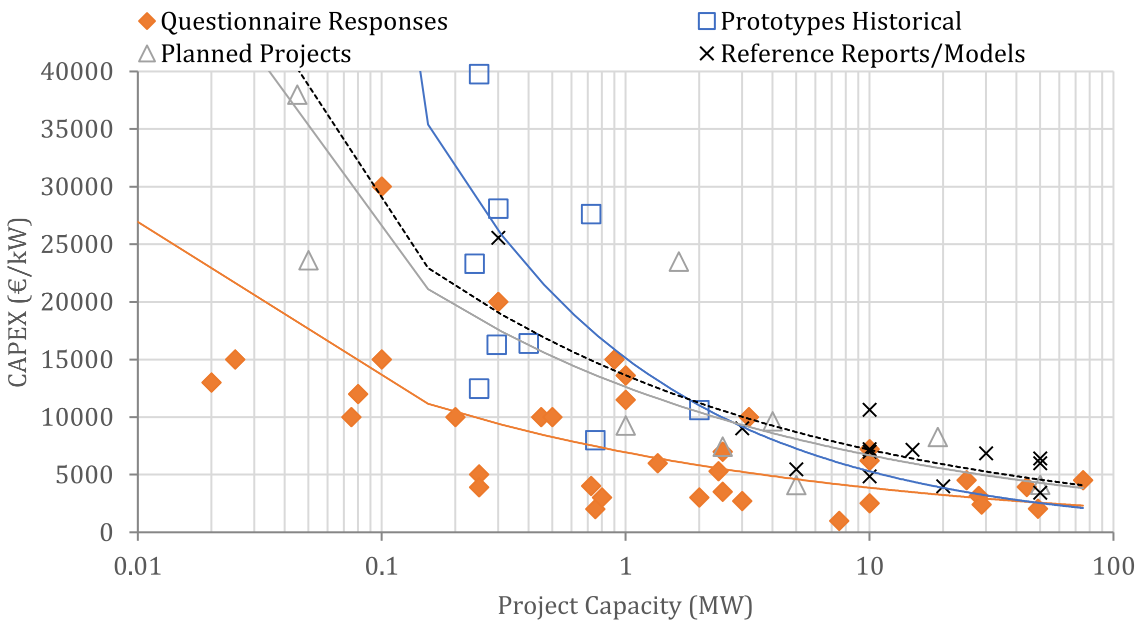


FIGURE 1:3 UNITARY CAPEX VARIATION WITH PROJECT CAPACITY [11]

The contribution of each subsystem or cost centre towards the total CAPEX will depend on technology and project characteristics, including size. But from previous studies some values can be extracted as 'expected', in order to benchmark future analysis. Figure 1:4 presents one of such cost breakdowns. While grid connection and project management cost are not expected to vary much from project to project; structural, PTO systems and moorings or foundations costs are intimately linked to the characteristics of a specific device. The installation operations are also linked to the technology, as well as the location in relation to shore/port.

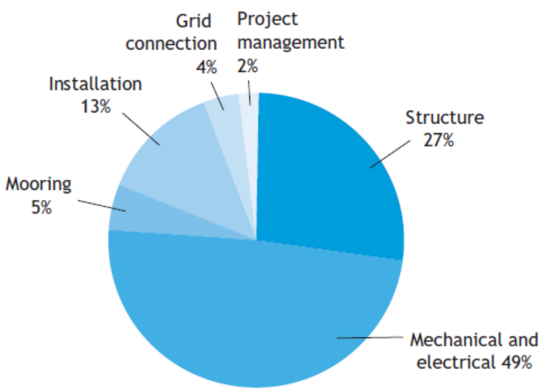


FIGURE 1:4 CAPEX BREAKDOWN ACCORDING TO [12]

Furthermore, the scale of the project also has impact on the total cost of the project. Project development costs can be expected to remain more or less constant. The cost of the devices however, is expected to be reduced due to both economies of scale and learning from the industry. The electrical connection equipment, however, is less likely to see big cost reductions from learning. In the past, there have been cost reductions associated with learning that resulted from the development of the offshore wind

market. These will be beneficial to wave energy projects, but further reductions are likely to be fewer and in a smaller scale than those expected for wave devices.

Considering economies of scale alone, Figure 1:5 presents the breakdown of CAPEX for similar projects of different capacity, and the expected reduction in unitary CAPEX.

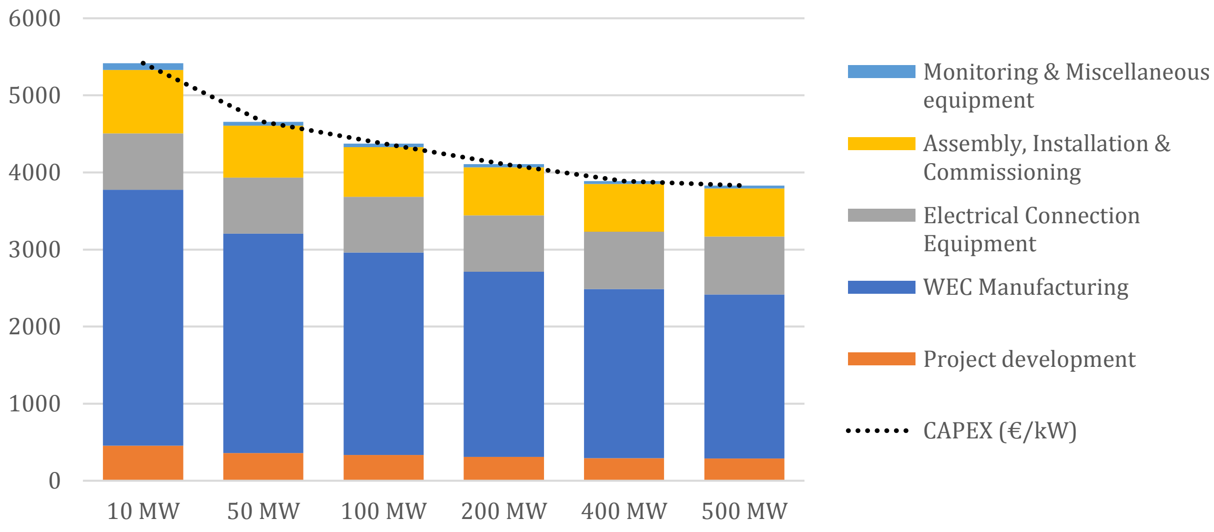


FIGURE 1:5 CAPEX AND CAPEX BREAKDOWN BY PROJECT SIZE, ACCOUNTING FOR ECONOMIES OF SCALE ONLY

Operational costs of array projects are still not fully understood, as few projects have full scale operational experience. Furthermore, the operational expenditures of prototype testing and small-scale arrays are not indicative of the cost expected for commercial projects. Often estimates of operational costs for wave energy comes from experience from more mature technologies, such as onshore wind, offshore wind or hydropower, as the data is considered more reliable.

The O&M costs can vary greatly from technology to technology, and even from concept to concept, depending on the maintenance strategy for the project and even the selected location. The use of expertise from other energy sectors must then be taken with care, analysing what can be extrapolated to the marine energy sector and what can't. For instance, most offshore wind maintenance occurs on site, as the cost of removing a wind turbine to take to shore is high. However, most marine energy devices will be easily towed to shore and may not allow for maintenance operations on site due to Health & Safety reasons.

It is common to show OPEX values as a % of CAPEX. This is obtained from other technologies (typically 3-5%, following the trend of offshore wind) but will then be depending on the assumed CAPEX. Ideally, OPEX values should be presented in terms of €/kWh, but at this stage it is still unrealistic as production is small, and there are a lot of inspection actions that wouldn't occur in a commercial scale project.

Figure 1:6 shows the range of OPEX estimations presented on [11], for first, second and commercial arrays.

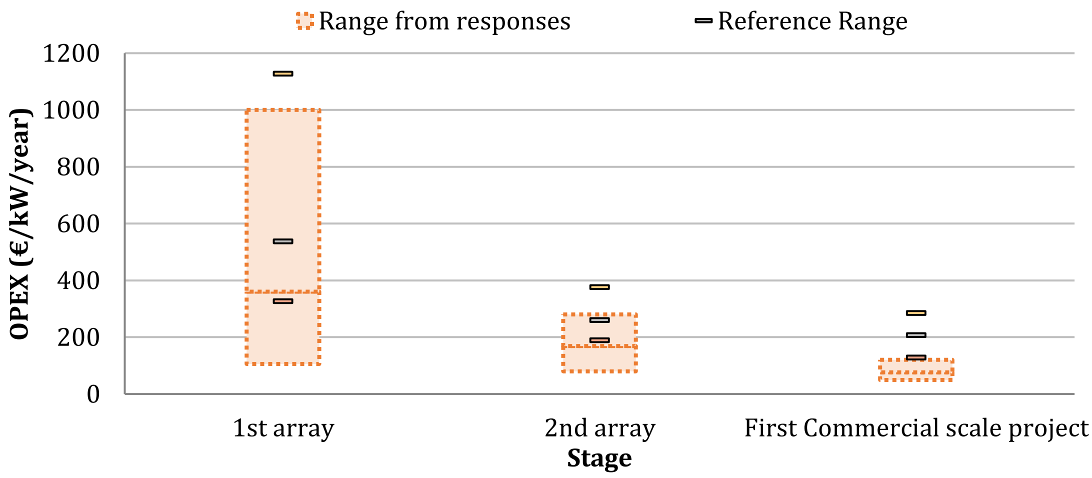


FIGURE 1:6 OPEX COST RANGES AT DIFFERENT STAGES OF DEVELOPMENT [11]

While CAPEX and OPEX values are important and require reductions in order to make wave energy competitive, it is the Levelized Cost of Energy, which also considers the energy production, that is used to compare technologies and to measure its economic feasibility. Results from wave energy developers in the study by OES provide a very high range for the first pre-commercial array, due to the variety of concepts as well as large uncertainties and different assumptions in costs but especially in capacity and availability factors for different developers. The expected costs in the future reduce significantly and tend to converge between developers. In the long term, forecasts indicate that the LCOE of wave energy could achieve 100€/MWh or lower as shown in the forecasts from SI Ocean (see Figure 1:7 and Figure 1:8).

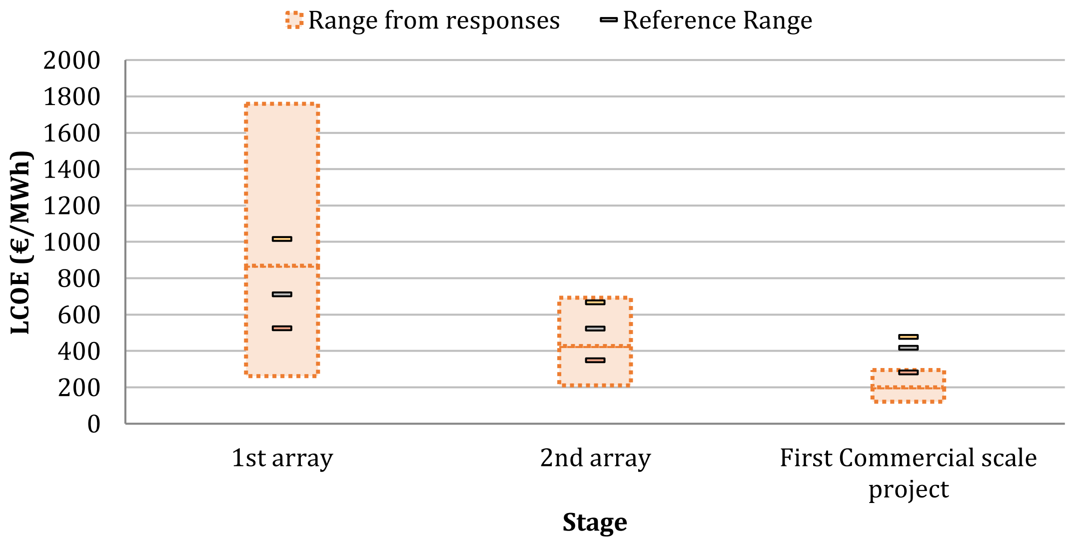


FIGURE 1:7 LCOE EVOLUTION AT THE THREE STAGES BASED ON DEVELOPER ESTIMATES AND INTERNATIONAL ANALYSIS [11].

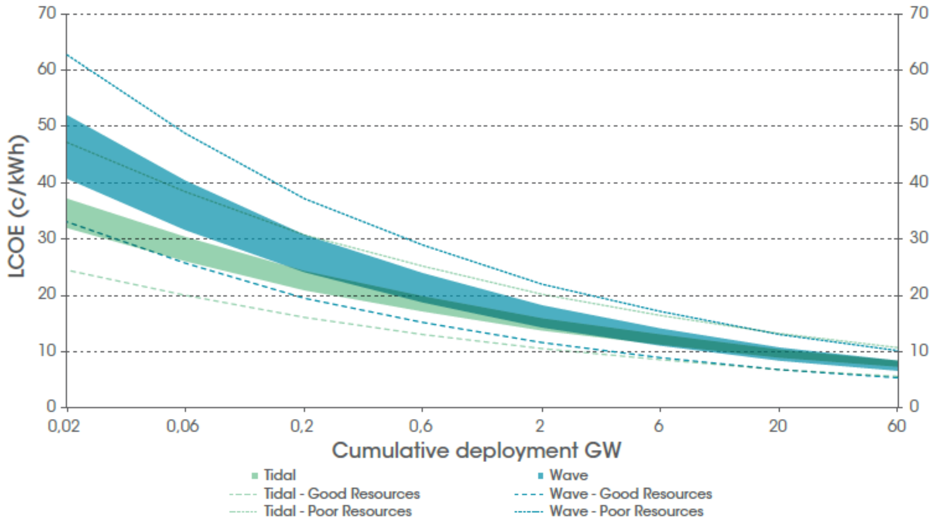


FIGURE 1:8 LCOE PREDICTIONS FOR 10MW ARRAYS, AFTER 10MW HAS ALREADY BEEN INSTALLED [13]

A large share of the LCOE is related to the device CAPEX (both structural and PTO). Estimates of device CAPEX are based on developers' responses as well as on the historical costs of wave energy prototypes published in the OES report. The CAPEX of these prototypes ranged between 7.5-40 k€/KW installed, depending on the type and scale (the higher the scale the lower the cost per kW). In addition to the device CAPEX, the balance of plant CAPEX (other array sub-component such as moorings & foundations and electrical infrastructure), the installation CAPEX as well as the O&M costs typically represent more than 50% of the overall LCOE [14]. Furthermore, the energy production (both capacity factor and availability) is the most critical factor for which there are more differences and uncertainties among developers.

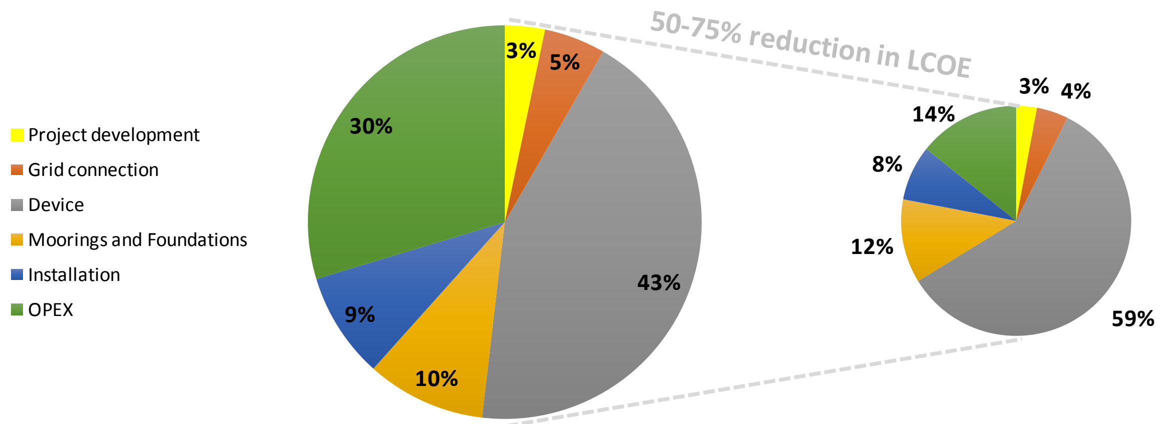


FIGURE 1:9: WAVE LCOE PERCENTAGE BREAKDOWN BY COST CENTRE VALUES AT CURRENT STAGE OF DEPLOYMENT (LEFT) AND THE COMMERCIAL TARGET (RIGHT) [11]

Note: the area of the chart represents the LCOE

The LCOE of ocean energy arrays depends on many factors and varies from project to project depending on the type and number of devices in the array, level of resource, water depth, geophysical characteristics of the site, distance to shore and ports, among others. Figure 1:10 shows the variation of the LCOE in relation to distance to shore, accounting to changes in the depth profile and in the resource level. These results are just an approximation and will differ from site to site and for different technologies.

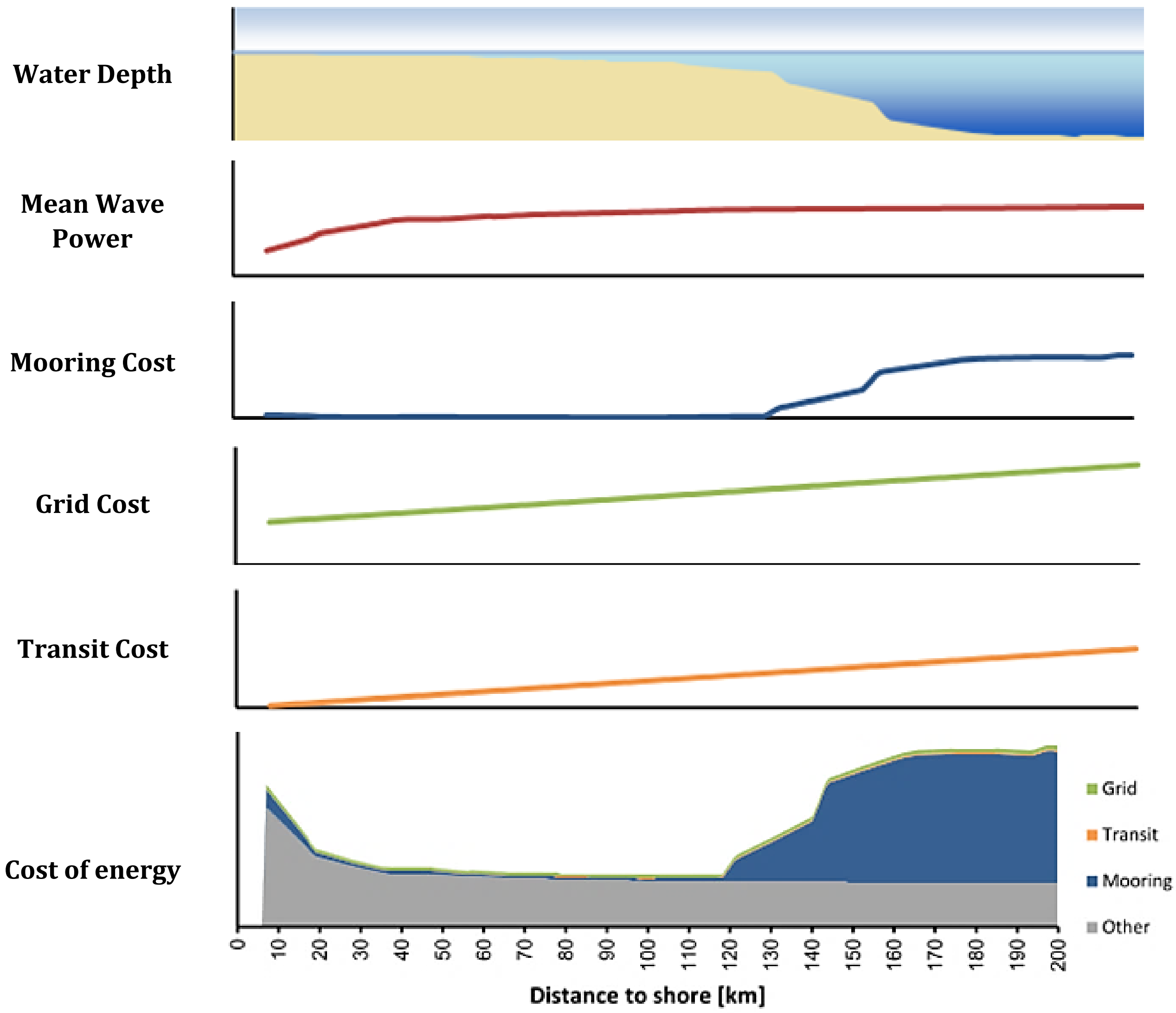


FIGURE 1:10 TRADE-OFF BETWEEN COST OF ENERGY AND DISTANCE TO SHORE FOR A SPECIFIC EXAMPLE IN THE UK [15]

The following table summarizes the expected economics for the first wave energy arrays based on the study published in 2015 by the IEA-OES [11].

TABLE 1:1 SUMMARY OF ECONOMIC DATA FOR WAVE ENERGY ARRAYS AVERAGED FOR EACH STAGE OF DEPLOYMENT [11]. VALUES CONVERTED TO EUROS (0.75 EUR/US$ 2014)

Deployment Stage	Variable	Wave	
		Min	Max
First array/First Project	Project Capacity (MW)	1	3
	CAPEX (€/kW)	3000	13575
	OPEX (€/kW per year)	105	1125
Second array/Second Project	Project Capacity (MW)	1	10
	CAPEX (€/kW)	2700	11475
	OPEX (€/kW per year)	75	375
	Availability (%)	85%	98%
	Capacity Factor (%)	30%	35%
	LCOE (€/MWh)	157,5	502,5
First Commercial Scale Project	Project Capacity (MW)	2	75
	CAPEX (€/kW)	2025	6825
	OPEX (€/kW per year)	52,5	285
	Availability (%)	95%	98%
	Capacity Factor (%)	35%	40%
	LCOE (€/MWh)	90	352,5

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. 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 WETFEET project 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 submerged point absorber that features a water turbine as PTO equipment.

This deliverable aims to provide a techno-economic assessment of the selected devices & breakthroughs at large scale deployment. To implement the integrated techno-economic model, the technical modelling work carried out from WP2 to WP6 was coupled to an economic module based on a cost database to support the capital and operational costs calculations.

The presented techno-economic assessment of potential wave energy farms of Oscillating Water Column (OWC) spar-buoy and of Symphony devices, based on the Levelized Cost of Energy (LCOE) metric and it is performed using a model developed by WavEC Offshore Renewables.

1.3 Technologies

1.3.1 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.

For the OWC spar-buoy some new features intended to increase its performances have undergone research and development processes. These new features comprise the breakthrough variants which will be assessed in relation to the basic converter without innovative features applied, named as reference case.

The breakthrough concepts are innovative ideas to improve the effectiveness of the OWC spar-buoy device. While these are at an early stage of development, they have been identified as potential solutions for the challenges described before and as potential ways for improving the performances and reducing the costs associated with the OWC spar-buoy technology, and wave energy in general.

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, as defined on deliverable D2.1, can be divided in the cost-reduction pathways they belong to:

- 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 [16].

The main inputs required for the techno-economic analysis will be presented in section 2, and a full description of the OWC Spar Buoy technology and the intended breakthroughs can be found in deliverables 2.1 [16] and 2.3 [17].

1.3.2 Symphony

In order to enable an evaluation of the breakthrough components on an at least partially quantitative basis using the TPL approach (Technology Performance Level), it was decided to reconstruct a hypothetical reference case for a submerged pressure differential device of 6m diameter, using a combination of publicly available data, and in-house knowhow partly being generic, partly generated in the context of the Symphony development (which by all means is a system with several physical similarities to the reference system). The chosen reference design resembles the 'original' concept of the Archimedes Wave Swing (AWS): an air volume and a gas spring are used as spring, an air gap (internal over-pressure) is used as seal, a hydraulic (water) brake serves as end stop, and a linear generator converts movements into electricity.

The submerged pressure differential devices (SPDD) concept resembles an underwater buoy of which the upper part (floater) moves up and down in the wave while the lower part (basement) stays in position. The periodic changing of hydrostatic pressure beneath a wave initiates these cyclic up- and downward motions of the upper part.

The concept bases on the physical property of waves, where the diameter of the circular water particle motion for deep water waves is equal to the wave height at the surface and reduces with depth. An underwater body experiences two forces from a passing wave:

- the acceleration force of the circulating water that must move (accelerate) around the body;

- the pressure of the water column above the body.

As swell waves have large wave lengths (100 – 500m), WECs of the size of 2-12m can be seen as relative small bodies. Nevertheless, if they start to move and convert energy, they will have an effect on the wave and the forces from the waves to the bodies are reduced (hydrodynamic damping).

There is a physical limitation in the construction to obstruct the motion going beyond a certain limit. Such a physical limitation must be included in any heaving WEC, and it is generally referred to as 'end stop'.

For the energy conversion from linear relative motion into useful (electrical) energy a PTO is used, which requires bearings to guide the system and seals to keep the water separated from the inside.

Finally, the motion has to react against a reference frame, e.g. a foundation. Similar to the hydrodynamics however, there are no implicit differences between a Symphony WEC with incorporated breakthrough components and a reference design case.

For the Symphony device, different breakthrough concepts have been proposed. Unlike the OWC Spar Buoy, these will be all included into the new device. The breakthroughs developed are:

- Dielectric elastomer generator (DEG);
- Water turbine (WT);
- The structural membrane (SMemb);
- Control Cocoon – Continuous Submergence (CS).

The breakthrough concepts, as defined on deliverable D2.1, can be divided in the cost-reduction pathways they belong to:

- Optimized structural design and device profile: the **structural membrane** and the **control cocoon** concepts are implemented to obtain a more efficient and resilient structural design;
- Increased system reliability: the **structural membrane**, the **control cocoon** and the **dielectric elastomer generato**r 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 generator** and the **water turbine** are new PTO concepts that aim at enhancing the overall energy production.

The main inputs required for the techno-economic analysis will be presented in section 2, and a full description of the Symphony device and the intended breakthroughs can be found in deliverables 2.2 [18] and 2.3 [17].

2 TECHNO-ECONOMIC ANALYSIS

The techno-economic assessment of breakthroughs performed in this task is based on the LCOE metric and it is performed using a model developed by WavEC Offshore Renewables. The model aims to reduce as much as possible the uncertainties and the approximations made during the economic assessment of a wave energy project, by being comprehensive in all the input data.

One techno-economic model was developed, based on WavEC's own model, to account for the specificities of the WETFEET analysis. This model incorporates the logistics analysis that was presented on deliverable 7.1 [19], and was coupled with the macro-economic model presented on deliverable 7.5 [20].

The model was subsequently ported into two versions, one for the analysis of the OWC Spar Buoy, and another for the Symphony device. In this section, the general layout of the model will be presented with the analysis-specific inputs used.

2.1 Location

For the performed study two different locations where taken into account: the EMEC test centre in Scotland, UK, and Leixões deployment site in Portugal. These two sites were considered as adequate for possibly hosting wave energy farms composed of OWC spar-buoy devices or Symphony 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, water depth at the farm central deployment location, and the resource available. The information needed to fill the model were extracted from sources [21]–[24].

The data used for both locations is presented on the table below, and the scatter diagrams for both locations are shown on Figure 2:1.

TABLE 2:1 GEOPHYSICAL INPUTS AND DATA OF THE TECHNO-ECONOMIC MODEL

	Leixões	EMEC
Distance from nearest large port to site	25	13
Distance from nearest small O&M port to site	25	13
Distance from site to shore	26	3.7
Distance from shore to substation/grid	2	0.25
Water depth at central farm location	80	60

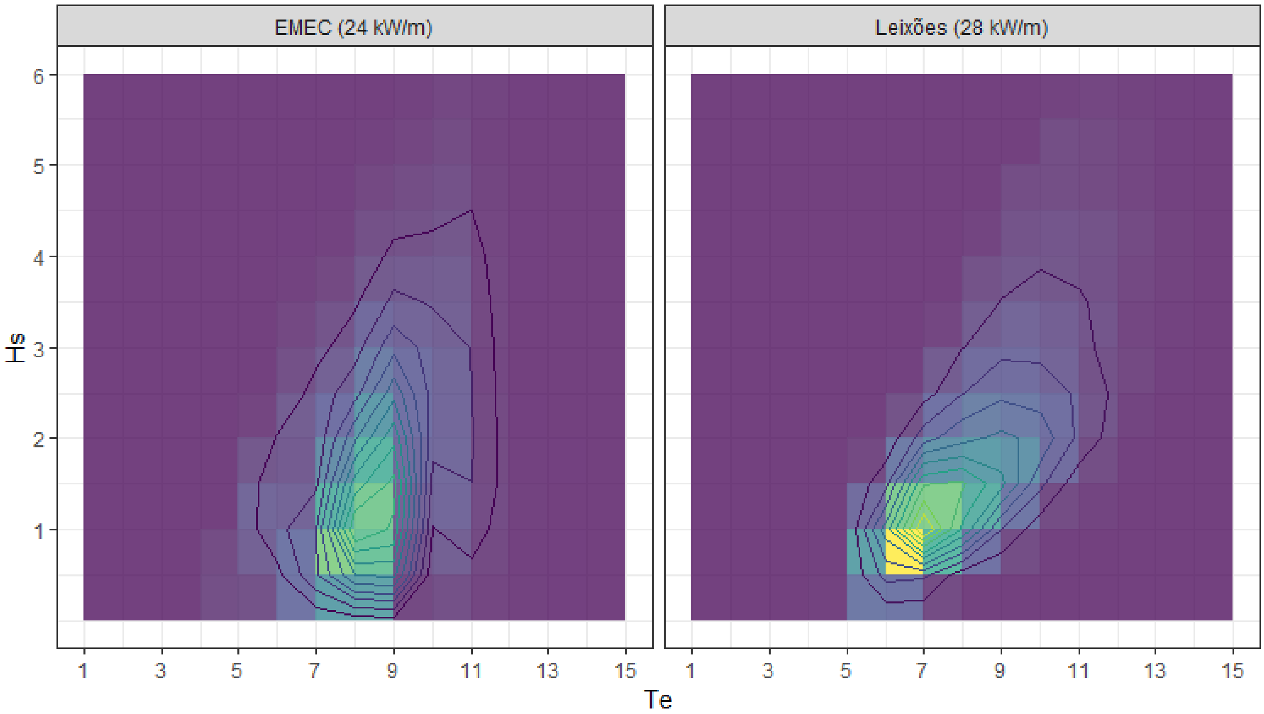


FIGURE 2:1 SCATTER DIAGRAMS FOR THE TWO LOCATIONS USED

2.2 WEC design

The WEC design section of the techno-economic model works similarly for the OWC Spar Buoy and the Symphony device, with only changes on the underlying assumptions. The main characteristics of the device structure and PTO are described, for the reference case and the breakthrough options.

In the WEC design module the choice of which breakthrough to analyse is made. Depending on the choice of the case under focus, some of the characteristics of the device might change all over the model. The major changes will be in terms of:

- **Power output**: by selection of the corresponding power matrix, the overall energy production will change.
- **Structural cost**: Different breakthroughs may have impact on the overall size of the device, which will change the structural cost of the device.
- **PTO and ancillary systems cost:** Different breakthroughs may use different PTO systems, or use extra ancillary systems, which will be reflected on the PTO costs.

The structural cost is made 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 PTO costs are based on typical values, either from literature or from the breakthrough developers.

2.2.1 OWC Spar Buoy

For the OWC Spar Buoy the model incorporates one reference case, and five breakthroughs:

- Reference Case (1. REF)
- Enhanced added mass (2. EAM)
- Negative spring (3. NS)
- Survivability submergence (4. SS)
- Shared moorings (5. SM)
- Dielectric elastomer generator (6.DEG)

It is important to underline that in the presented model, for the OWC Spar buoy, each breakthrough is analysed on its own and they cannot be put together in order to apply more than one at the same time.

Regarding the power output, each variant has its own power matrix, with the exception of the SS and SM. In these cases, the substantial changes in the mooring system design can potentially 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, so the power matrix of the reference case was used. All variants have a rated capacity of 150 kW.

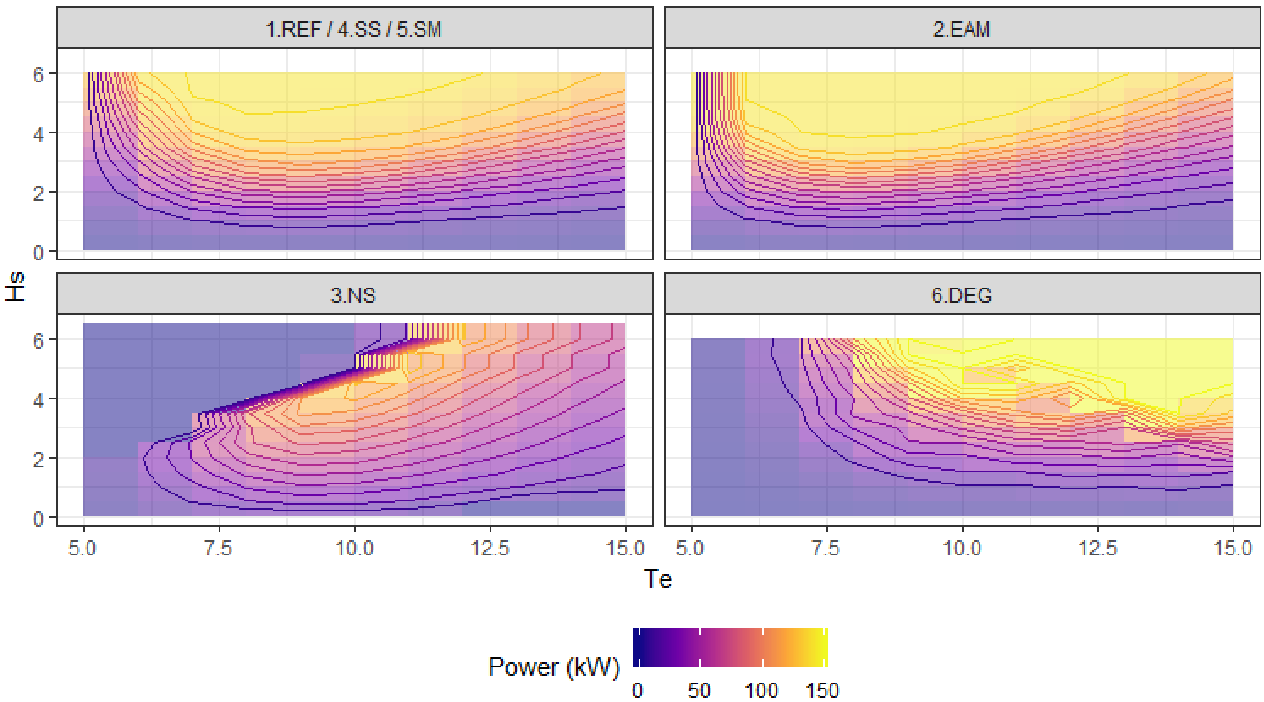


FIGURE 2:2 POWER MATRICES USED IN THE OWC SPAR BUOY ANALYSIS

In terms of structural design, only the EAM and NS variants differ from the reference case.

The EAM breakthrough concept is an optimization of the geometry of the OWC Spar buoy device, namely by changing the large thickness tube, 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 but, as shown in Figure 2:3, 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.

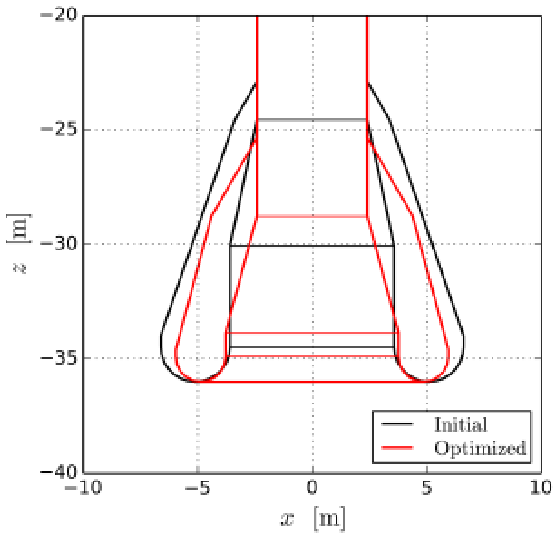


FIGURE 2:3 LARGE THICKNESS TUBE GEOMETRY FOR REFERENCE CASE (BLACK) AND EAM CASE (RED) [17]

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.

In the NS variant, the OWC spar-buoy's inner structure is modified to impact directly on the hydrodynamic properties of the device in order to produce a negative spring effect without requiring any mechanical or electrical component. This is achieved by enlarging the air chamber inside the floater, as shown in Figure 2:4. 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.

The OWC spar-buoy with the negative spring breakthrough applied is considerably smaller than the reference case device, with a reduction of 10 meters in the total height and draft of the device, but keeping the same rated power. 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 40% of the value it has in the reference case in order to make room for the expanded air chamber.

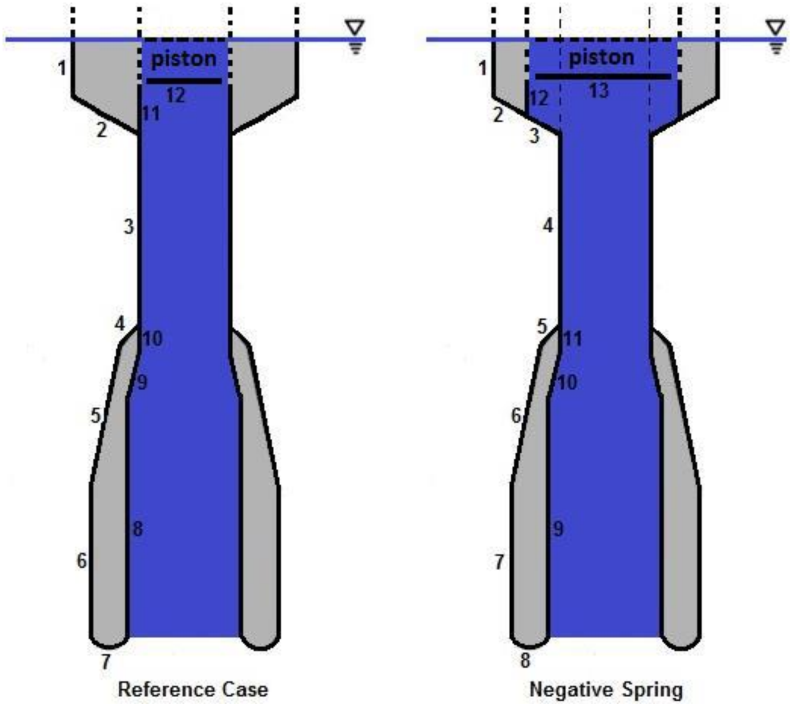


FIGURE 2:4 GEOMETRY SCHEMATIC DESCRIPTION FOR REFERENCE CASE AND NS CASE [25]

The input values for the structural cost computation for all variants are presented on the table below.

TABLE 2:2 STRUCTURAL INPUTS FOR OWC SPAR BUOY

Device Code	**1. REF**	**2. EAM**	**3. NS**	**4. SS**	**5. SM**	**6. DEG**
Device Diameter/Width (m)	12	12	9	12	12	12
Device Length (m)	51	51	41	51	51	51
Draft (m)	36	36	28	36	36	36
Structural mass	248	231	208	248	248	248
Ballast mass	964	799	765	964	964	964
Total mass	1212	1029	973	1212	1212	1212

Concerning the PTO system, in the reference case the spar-buoy is equipped with a bi-radial turbine coupled with a permanent magnet synchronous generator. The breakthroughs that have different equipment for energy conversion are the dielectric elastomer generator and the tetra-radial turbine. However, as no power matrix for the tetra radial turbine was available, it was not included on the analysis.

The PTO cost for the reference case was estimated based on an available correlation for Wells turbines:

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

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. [26]

For the electrical and ancillary equipment another function was adopted, based on the rated power (P_{rated}) of the device [26]:

$$C_{elec} = 3.3P_{rated}^{0.7}$$

The DEG PTO system is composed by three circular membranes located on top of the floater sub-structure is considered, as shown inFigure 2:5. 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.

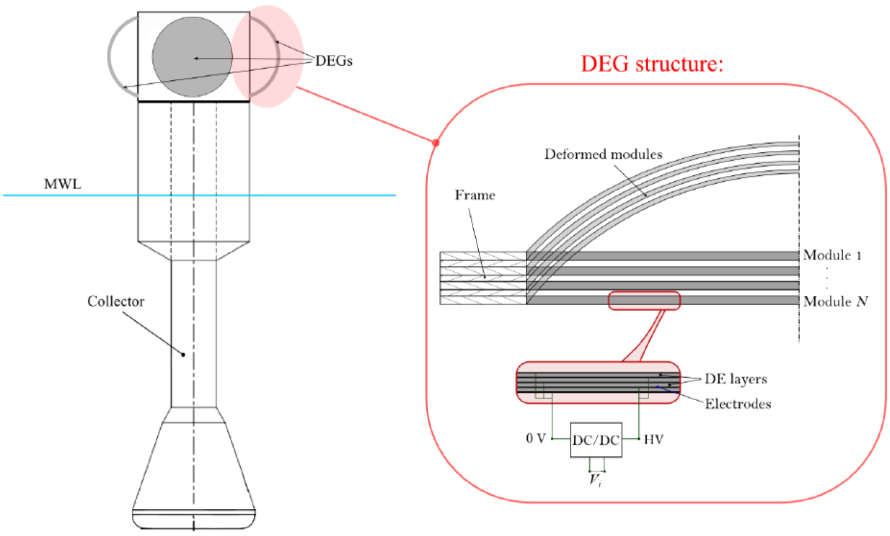


FIGURE 2:5 DEG PTO SYSTEM SCHEMATIC ARCHITECTURE [27]

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 [28]. 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 [16]. 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.

For the DEG system the cost function is based on a cost per weight of dielectric material used, with the price for procurement of the elastomer material of 7.5 k€/ton. Each DEG PTO module is composed by three membranes, each containing 3.21 tons of elastomer material and 0.48 tons of electrodes. The mass of each PTO module weighs 11.07 tons. For a 150 kW device, 12 modules of 12.5 kW are used.

The SS 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 last breakthrough concept related with the PTO system is 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 2:6. The name "tetra-radial" comes from the two inlets and two outlets resulting from the twin turbine rotor configuration.

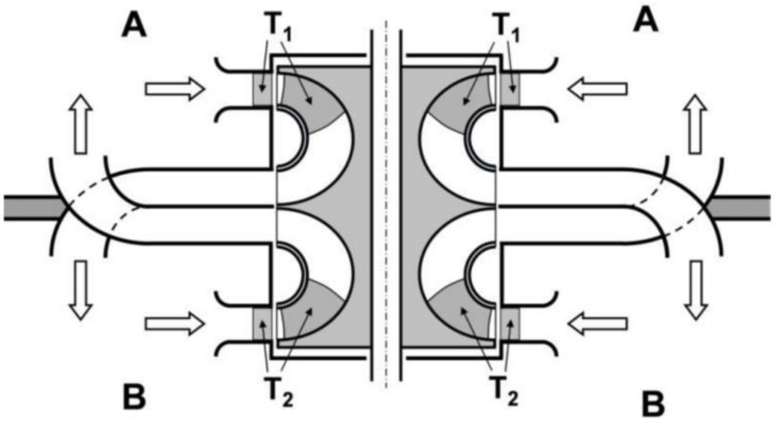


FIGURE 2:6 TETRA-RADIAL TURBINE SCHEMATIC CONFIGURATION [29]

The tetra-radial turbine has been projected 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 2:7, 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 [29].

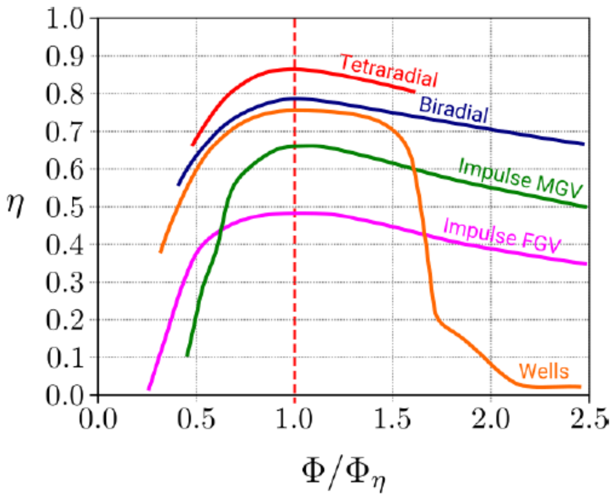


FIGURE 2:7 EFFICIENCIES OF DIFFERENT TYPOLOGIES OF SELF-RECTIFYING AIR TURBINES [29]

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.

The effect of the tetra-radial turbine on the economics of a wave energy project was assessed in this study due of the lack of suitable data regarding the costs and the power outcome of the new generation self-rectifying air turbine.

Table 2:3 presents the percentage variation of cost for the PTO system for the five analysed breakthroughs compared with the reference case.

TABLE 2:3 PERCENTAGE VARIATION IN THE PTO SYSTEM COSTS COMPARED TO THE REFERENCE CASE

	1. REF	2. EAM	3. NS	4. SS	5. SM	6. DEG
Energy conversion equipment cost	0.0%	0.0%	0.0%	0.0%	0.0%	-32.1%
Electrical & ancillary equipment cost	0.0%	0.0%	0.0%	+7.3%	0.0%	0.0%
Total PTO	0.0%	0.0%	0.0%	+3.4%	0.0%	-16.9%

2.2.2 Symphony

For the Symphony device, the analysis is made of a Symphony device comprised of several breakthroughs against and hypothetical reference case for a submerged pressure differential device. The reference case was constructed based on a combination of publicly available data, and in-house know-how. The chosen reference design resembles the 'original' concept of the Archimedes Wave Swing (AWS): an air volume and a gas spring are used as spring, an air gap (internal over-pressure) is used as seal, a hydraulic (water) brake serves as end stop, and a linear generator converts movements into electricity.

The breakthroughs included in the Symphony device are:

- Water turbine (WT);
- The structural membrane (SMemb);
- Control Cocoon – Continuous Submergence (CS).

In terms of energy output, both systems are rated at around 250 kW, although they have different energy extraction profiles, as can be seen by the power matrices (Figure 2:8).

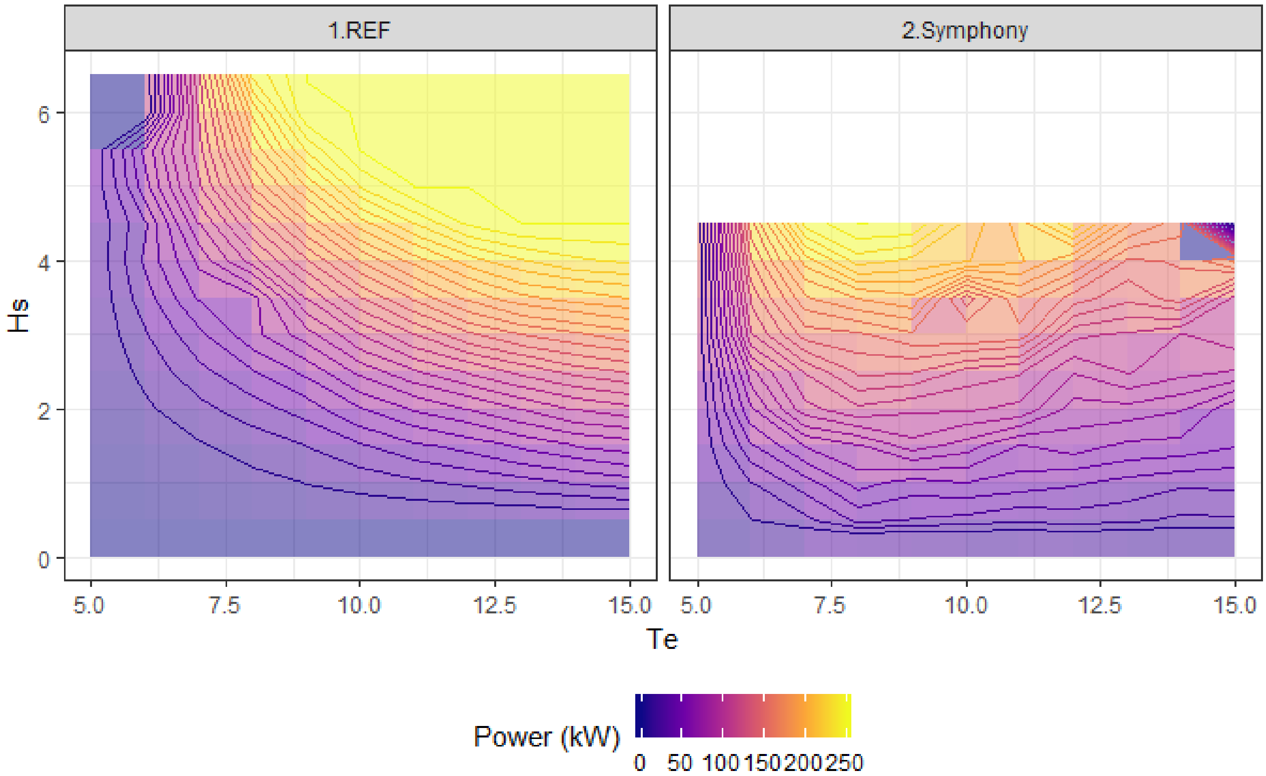


FIGURE 2:8 POWER MATRICES USED IN THE SYMPHONY ANALYSIS

Structurally, the reference case device is larger, with 9.5 m diameter against 6 m of the Symphony. The device is also longer, which overall means that the Symphony is lighter, almost by a factor of 2.

In the Symphony, the structural membrane is used as a multifunctional component. It functions as a bearing, guidance system, end buffer and medium carrier.

The Symphony consists of two parts separated by a membrane. The hydrostatic pressure of passing waves pushes the upper part (outer cylinder) down. This results in a decreasing inner volume of the Symphony. The decreasing volume creates an internal water flow through a turbine driving a generator. At the same time the inner pressure in the Spring Chamber builds up due to the decreasing volume. The counter movement, the Outer Cylinder moves up again, happens under a wave through as the inner pressure is larger than the hydrostatic pressure. The internal water flow is reversed through the turbine.

Although the primary function of the membrane is the separation between the two parts of the Symphony, its overall functionality is much more. While acting as a seal to enclose the inner pressure/volume, it also acts as a bearing for the cylinder. More precisely, the membrane is the variable volume 'breathing' under the waves. The inner volume changes due to the difference in the width in which the upper and lower part of the membrane roll up and down. Due to a specially designed (inner) hull shape, the membrane also acts as end stop.

The following 3 main functions are to be fulfilled by the membrane:

- **Sealing**: the membrane acts as a sealing, protecting the internal components from the ocean water and preventing water to flow in the upper part of the hull;
- **Bearing**: the membrane functions as a bearing in-between the moving hull and the fixed compensation tank. It is important that the membrane centres the hull radially to exclude possible collision between the hull and the compensation tank;
- **End stop**: The membrane will be used as an end stop. The end stop will be realised by narrowing the wall geometry on the inner (static) side of the contact area.

In the reference case, these three functions were solved by:

- **Sealing**: With respect to the role of the seal in the context of evaluating the reference design case, it takes a central role: as a consequence of a (pressurised) air gap fulfilling the vital function of a seal between the two moving bodies, the spring of the device gets pre-tensioned to an extent that it would become dysfunctional, unless an additional component (the hydraulic spring) is introduced. Using an air gap as seal is feasible and straight-forward but has significant impact on other parts of the system, which become more complex and expensive.
- **Bearing**: The movement of the cylinders, the incoming waves and potentially currents, induce significant sideway forces, so there is a need of bearings keeping both parts separated from each other, and guiding the up- and down movement within a certain tolerance. Although the state of the art of bearings with the required characteristics should allow to address the required functions, there exists no significant operational experience for this component, which introduces a grade of uncertainty of its use as reference design case.
- **End stop**: For the reference design case, it is assumed to have water labyrinths near the end of stroke, which can absorb very high forces by successive damping according to floater position. In absence of other convincing end stop systems, such a water brake is suggested for the reference design case. There is no hard data on operational experience, and only rough estimates can be made about material and manufacture costs.

TABLE 2:4 STRUCTURAL INPUTS FOR OWC SPAR BUOY

Device Code	**1. REF**	**2. SYM**
Device Diameter/Width (m)	9.5	6
Device Length (m)	50	30
Draft (m)	70	70
Structural mass	909	552
Ballast mass	1134	426
Total mass	2380	1348

In terms of the PTO, the reference case uses a linear generator. Due to its relatively high force density and efficiency at low speeds, a permanent-magnet (PM) generator is chosen.

The choice of an appropriate PTO for the Symphony wave energy converter, and the decision to use a water turbine (against a spindle drive or similar linear electro-mechanical options) was presented in Deliverable 2.2 [18].

As there were no off-the-shelf solutions for the operational requirements, a novel water turbine for a Symphony WEC had to be developed. In general, the following issues need to be carefully considered for future considerations about the turbine:

The complexity of manufacturing is based on the number of parts and the number of specialized parts or tooling required for the assembly. A complex assembly with a high number of parts which are tailormade, will be more expensive to manufacture.

The Symphony is a device which operates several meters beneath the water surface in a sea or ocean. This makes maintenance to the device a costly and time consuming task. The entire device would benefit from a turbine assembly which requires minimal maintenance to minimize downtime. In addition, it must be guaranteed that the turbine casing fits into the control for ensuring in-situ removal.

The reliability is a term which includes addressing all factors which may compromise the performance of the turbine. Two of the most important questions to assess this criterion are:

(i) how much does the performance degrade and components wear when operating outside the ideal theoretical conditions?
(ii) (ii) how sensitive is this concept to electro-mechanical failure?

Another important feature of the turbine in addition to energy conversion is its pumping function, i.e. the ability to induce a volume flow in order to function as a starter motor for the Symphony. Especially for the early phase of technology implementation, the turbine must be able to pump water (using the generator as an electro-motor) with only minor adjustments.

As one of these breakthroughs for the Symphony device had been identified continuous submergence, and removal of critical components from the device without dismounting the complete wave energy

converter. As a submerged floating structure, the Symphony concept has a potential edge over surface-floating devices, since it is less exposed to extreme loading under storm conditions and to brisk movements in operating conditions. However, the continuous submergence of a wave energy device naturally implies a fail-safe philosophy of sealing elements, as well as a new approach to access. The control cocoon containing the vital parts of PTO and communication is the key to this approach.

The control cocoon contains the critical parts of the Symphony, and can be removed without transporting the complete device to shore. The cocoon, shown in Figure 2:9, includes the following parts (see Deliverable 2.3 [17]):

➢ **Turbine**: a custom dual direction turbine will be used to drive the axis of the generator. The turbine is the interface to the static volume of the device, and the most critical part is the sealing between cocoon and internal water volume.

➢ **Generator**: the axis of the turbine is connected to a permanent magnet generator, which could be used to drive the turbine axis, too. It is sealed in the interior of the cocoon and has no critical interfaces to the outside. The generator will be an off-the-shelf model.

➢ **Electronics and control system**: the electronics will be placed in a sealed box, from which the generator and valves of the pressure systems are controlled (and the winch, in case it is inside the cocoon). This is the core part of the device control, and might be placed closer to the end of the cocoon for easier access. Slight over-pressure is being considered for additional protection. Critical physical interfaces to the outside (unless going through winch).

➢ **Spring adjustment tank**: this unit is required to integrate the tuning of the air spring. If a limited unwanted pressure drop/raise occurs in the spring chamber due to leakage or temperature changes, the spring adjustment tank is used to compensate. The pressure inside the spring adjustment tank will be the same as the neutral pressure of the spring chamber which is around 15 bar. An air connection of the adjustment tank to the spring chamber is another important interface between the cocoon and the static device parts, as well as air and water valves to the outside. The spring adjustment tank is not part of the design steps in this phase, as it is considered an uncritical item, which can be adjusted and manufactured according to available space and configuration inside the cocoon.

➢ **Compressed air tank**: a compressed air tank with control valves is placed in the cocoon in order to pressurise the spring adjustment tank, in order to compensate pressure losses. The pressure inside the compressed air tank will be 100-200 bar, which is in the range of common off-the-shelf pressurised air tank systems. The feeding time is relatively slow which is why all valves, and piping are no significant design challenges.

➢ **Winch or other mechanism**: for tide compensation and survivability mode under severe sea conditions, a winch unit (or alternative mechanism) is placed either on the bottom part of the cocoon, or into an external box. It will equally be used for maintenance removal of the cocoon. Interfaces to upper part of cocoon and/or outside of device.

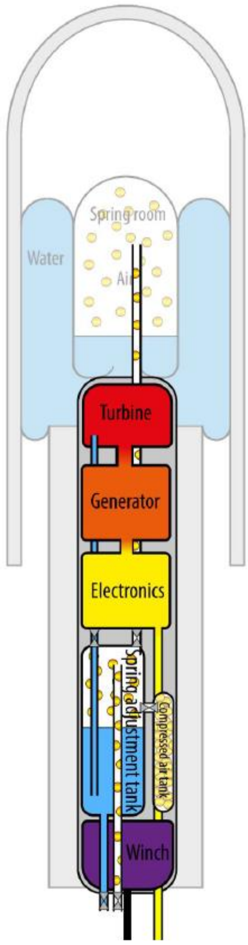


FIGURE 2:9 SCHEMATIC VIEW OF COCOON HOUSING VITAL COMPONENTS AND CONTROLS OF SYMPHONY

2.3 Farm design

2.3.1 Farm layout

In this part of the model, the outline of a farm composed of spar-buoy or symphony 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.

2.3.1.1 OWC Spar Buoy

For the OWC Spar Buoy, in order to properly compare with the shared mooring breakthrough, 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. 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.

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 2:10.

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.

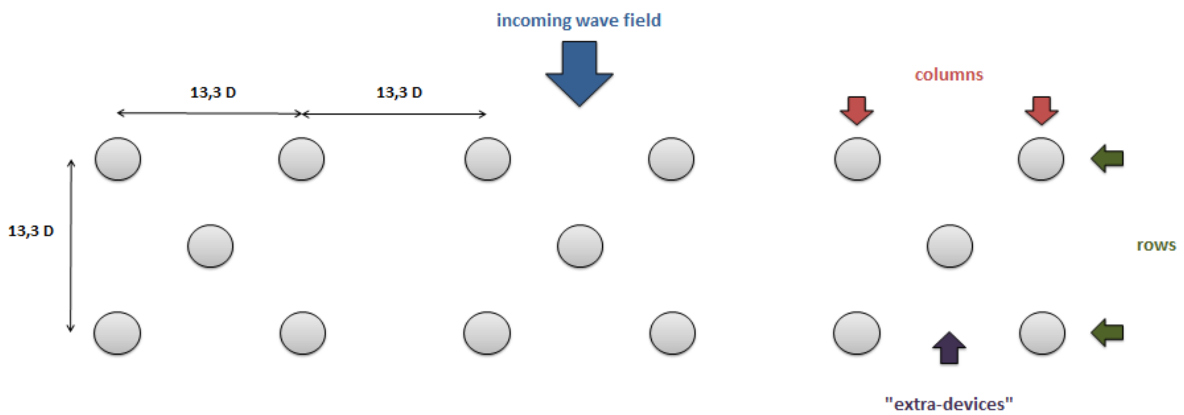


FIGURE 2:10 SCHEMATIC LAYOUT OF A WAVE ENERGY FARM COMPOSED OF OWC SPAR-BUOY DEVICES

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.

2.3.1.2 Symphony

For the Symphony device a more standard layout has been assumed, with the devices in two rows of 10 devices. The distance between rows is 300m and 90m between columns.

2.3.2 Electrical system configuration

The electric system is composed by electric cables, connectors and collection points. The definition of the farm layout is very important for the computations related with the lengths of the electric cables. The positions of the devices on the water surface define the distances that have to be covered by the cables, and the electric configuration employed is a relevant element to assess the final cost of the system. The two typologies of electric 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. The cables have to be sized so that they can support the power output of the whole array (0.75 MW);
- **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.

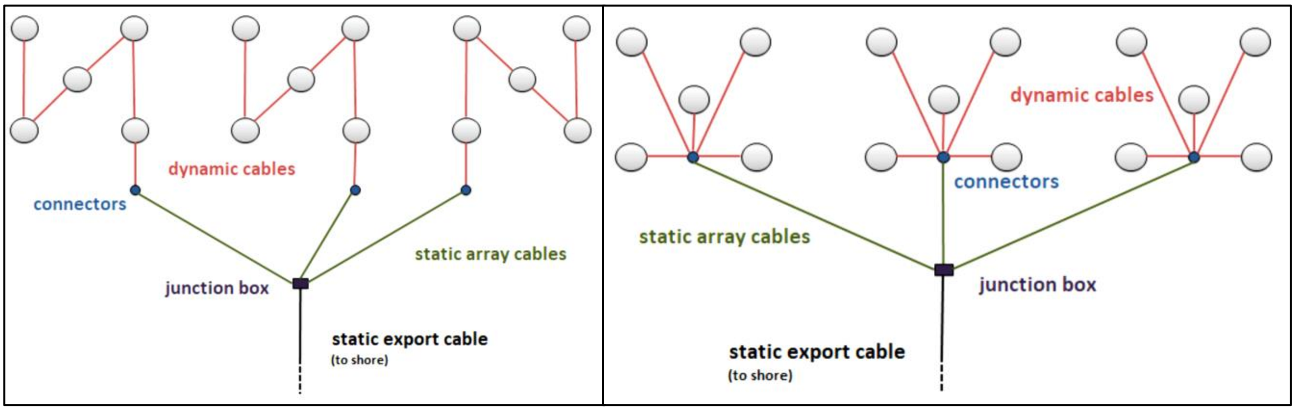


FIGURE 2:11 SCHEMATIC REPRESENTATION OF THE STRING ELECTRIC CONNECTION (LEFT) AND THE STAR ELECTRIC CONNECTION (RIGHT) FOR THE OWC SPAR BUOY

The different sizing of the dynamic cables in the two different configurations has impact on both the capital costs and losses in the system. The cost and loss functions are taken from sources [30], [31] and internal WavEC data. 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%. The lengths of the cables in the two configurations are presented in Table 2:5.

TABLE 2:5 CABLE LENGTHS FOR THE TWO ELECTRICAL CONFIGURATIONS CONSIDERED FOR LEIXÕES SITE

	OWC Spar Buoy		Symphony	
Configuration	**Star**	**String**	**Star**	**String**
Dynamic Cables (m/device)	239	323	365	45462
Static intra-array (m/array)	708	634	1331	1192
Export (km)	30.9	30.9	30.7	30.7
Total cable length (km)	44.2	46.6	43.3	44,5
LCOE	132.1	132.5	114.9	115

By adjusting the safety factors of the cables and minimizing losses, the impact of the configuration chosen is minimal on the LCOE, and in favour of the star configuration. This configuration was kept equal to all cases.

2.3.3 Mooring system configuration

The mooring system analysis considers the mooring line configuration, supplied by project partners, and anchoring system. The mooring configuration differs between the two technologies, and across some of the breakthroughs. The mooring lines design updates with changes in depth, however it does not substitute a full mooring analysis.

2.3.3.1 OWC Spar Buoy

As a floating device, the OWC Spar Buoy requires a mooring system to ensure station-keeping. The connection with the sea bottom for the reference case is designed as a slack-mooring system with two sets of four equally-spaced mooring lines, connecting at the bottom of the device and at the bottom of the top substructure.

The mooring lines are a combination of nylon rope and steel chain.

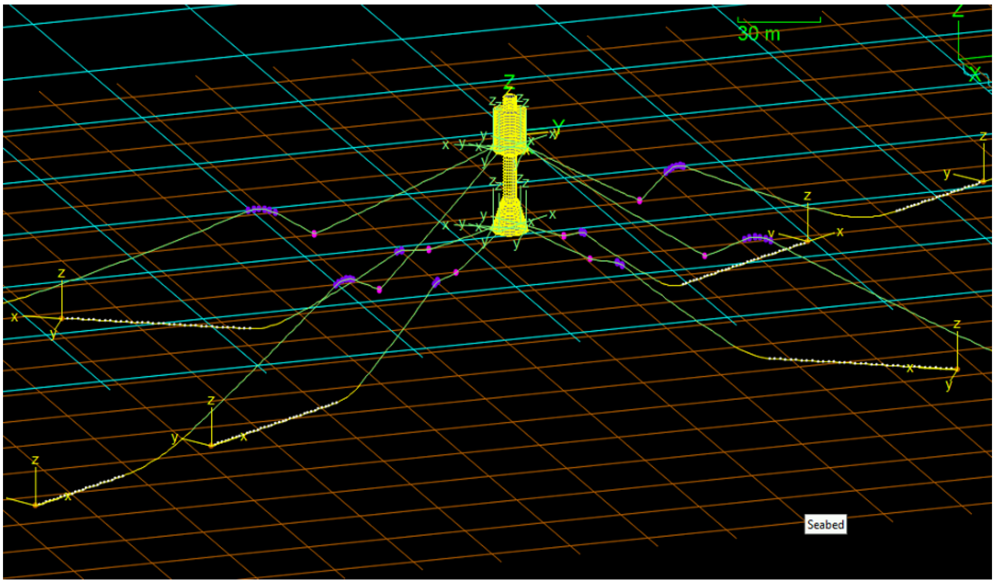


FIGURE 2:12 MOORING SYSTEM SCHEMATIC DESCRIPTION

The survivability submergence breakthrough aims to solve the survivability issues associated with wave energy by temporarily submerging the device during extreme events. A consequence of submerging the device a few meters below the water free surface is that structural loads are significantly lower. This means that the mooring system can be designed to withstand lower loads, achieving some cost reductions.

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. 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, the system makes use of the two sets of moorings defined on the reference case, which allow dragging down the device and keep it in the desired final position: lying almost horizontally under the water surface, as shown in Figure 2:13.

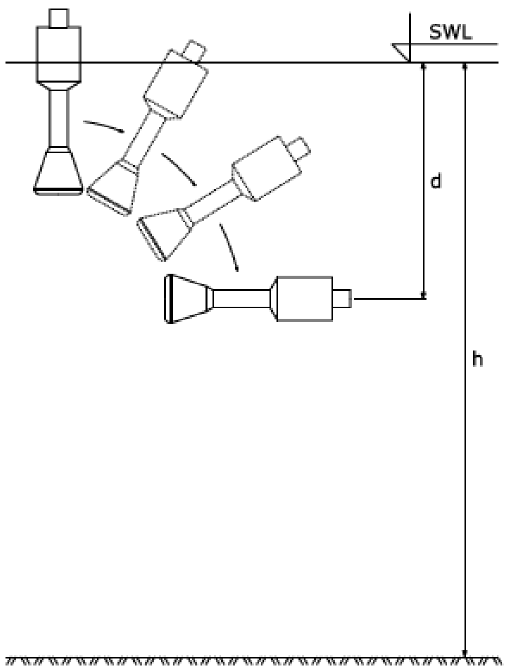


FIGURE 2:13 FINAL SUBMERGED POSITION OF THE OWC SPAR-BUOY [17]

Although the concept would be very effective for the survivability of floating devices, as proven by hydrodynamic computation in sources [17] and [32], there are some critical engineering issues associated with the submergence strategy, such as:

- Submergence and position restoring procedures and their hydrodynamic analysis;
- Hydrodynamic behaviour 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 required holding capability of the mooring system, and potential reduction of maintenance cost of a farm composed of OWC spar-buoy devices.

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.

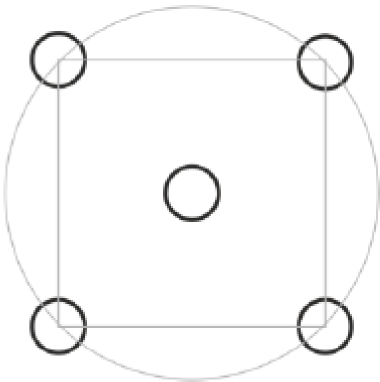


FIGURE 2:14 DISPOSITION OF FIVE DEVICES IN A CLUSTER TO FORM AN ARRAY [33]

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 2:14.

In the first configuration (configuration B, since configuration A refers to the situation where the breakthrough is not applied, Figure 2:15 on the left) for shared moorings each of the four corner devices (Dev. 1-4 in Figure 2:15) has two mooring lines anchored on the seabed. Those lines have the same

features as 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 2:15 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.

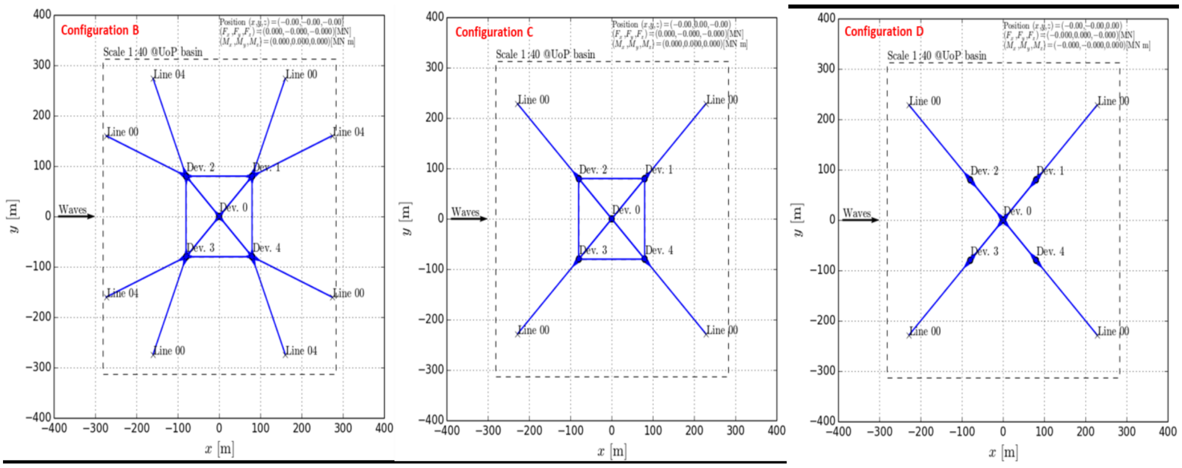


FIGURE 2:15 SCHEMATIC DEFINITION OF THE THREE POSSIBLE CONFIGURATIONS FOR THE SM BREAKTHROUGH

Finally, in the third configuration (configuration D, Figure 2:15 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.

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.

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 2.3.1.1.

Table 2:6 shows lengths and diameters of lines for the reference case, the shared moorings and the survivability submergence breakthroughs.

TABLE 2:6 MOORING SYSTEM CHARACTERISTICS FOR REFERENCE, SM AND SS CASES REFERRING TO LEIXÕES DEPLOYMENT SITE.

	Unit	Reference case	Shared moorings			Submergence
			Conf. B	Conf. C	Conf. D	
N° anchoring points/device	n	8	1.6	0.8	0.8	6
Avg. rope length/device	m	863.8	501.5	343.4	200.2	833.1
Avg. chain length/device	m	676.0	123.5	85.7	108.8	343.2
Rope cost/length	€/m	123.1	41.6	31.4	39.9	67.3
Chain cost/length	€/m	142.2	246	246	246	112.6
Array mooring system cost	k€	1012.2	256.5	159.4	174	473.6
Total mooring system cost	k€	7086	1795	1116	1217	3318

The cost functions for the mooring lines were taken from source [31], [34] and from internal sources at WavEC. They are empirical correlations based on the diameters of wires and chains.

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 2:6, and the cost of each anchor is computed assuming a cost of 200 €/ton of material.

Table 2:7 and Table 2:8 present the percentage variation of the mooring system cost for the five analysed breakthrough cases compared with the reference case.

TABLE 2:7 PERCENTAGE VARIATION IN THE MOORING SYSTEM COSTS FOR THE FIVE ANALYSED BREAKTHROUGHS COMPARED TO THE REFERENCE CASE (LEIXÕES)

	1. REF	2. EAM	3. NS	4. SS	5. SM			6. DEG
					Conf. B	Conf. C	Conf. D	
Mooring Lines	0%	0%	0%	-53%	-75%	-84%	-83%	0%
Anchors	0%	0%	0%	-25%	-50%	-50%	-50%	0%
Total	0%	0%	0%	-46%	-69%	-76%	-75%	0%
LCOE					101.1	99.8	99.8	

TABLE 2:8 PERCENTAGE VARIATION IN THE MOORING SYSTEM COSTS FOR THE FIVE ANALYSED BREAKTHROUGHS COMPARED TO THE REFERENCE CASE (EMEC)

	1. REF	2. EAM	3. NS	4. SS	5. SM			6. DEG
					Conf. B	Conf. C	Conf. D	
Mooring Lines	0%	0%	0%	-53%	-73%	-83%	-82%	0%
Anchors	0%	0%	0%	-25%	-50%	-50%	-50%	0%
Total	0%	0%	0%	-46%	-66%	-73%	-73%	0%
LCOE					83.0	82.1	82.1	

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 lower mooring system cost due to the fewer mooring lines (3 point spread instead of 4 point), and lower holding capacity.

All three shared mooring configurations offer a better performance than the reference mooring system, with configurations C and D offering the best LCOE. Since configuration C has the best LCOE (albeit with minimal difference to configuration D), it is going to be considered as the reference for the shared mooring breakthrough in the future comparisons.

2.3.3.2 Symphony

The mooring system for both the reference case and the Symphony future was assumed as described in D2.2 [18], adapted for different depth locations. The preliminary mooring system (Figure 2.4-1), consists of a tension leg for keeping the device vertically in the water column, a floating box envisaged for tidal adjustments, and placed at a sufficient distance to allow an easy removal of the control cocoon, and a slack mooring for station keeping. When transposing this tentative mooring design to a future 6m reference device, the following mooring setup results:

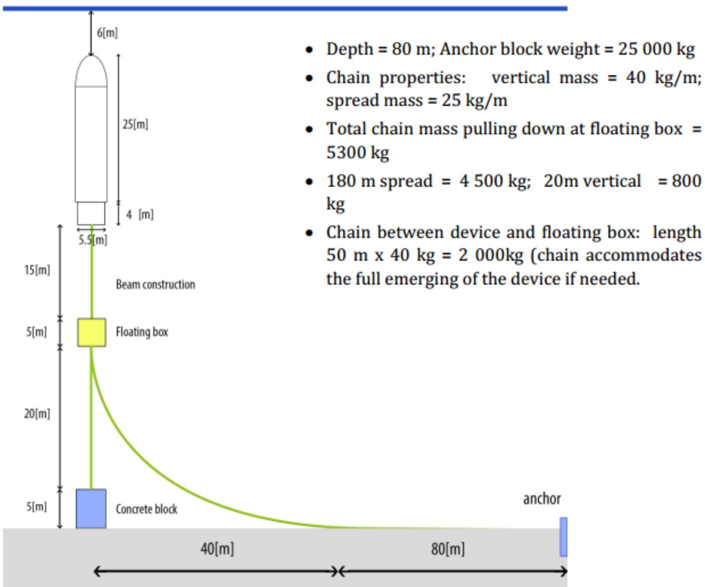


FIGURE 2:16 INDICATIVE MOORING LAYOUT FOR A 6M SYMPHONY IN 80M DEPTH [18]

2.4 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. The logistics section of the model was also used for the deliverable D7.1 [19] , and is based on the methodology developed in the DTOcean project [35], [36].

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.

The anchors are the first item to be installed, together with the mooring lines, so that when the devices are brought to the deployment site they can be immediately secured and kept in position. The operation can be carried out through anchor handling tug supply (AHTS) vessels, or multicat vessels.

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.

The choice of the most adequate vessel was done considering the lifting capacity of the crane, the deck dimensions and the cargo capacity. 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.

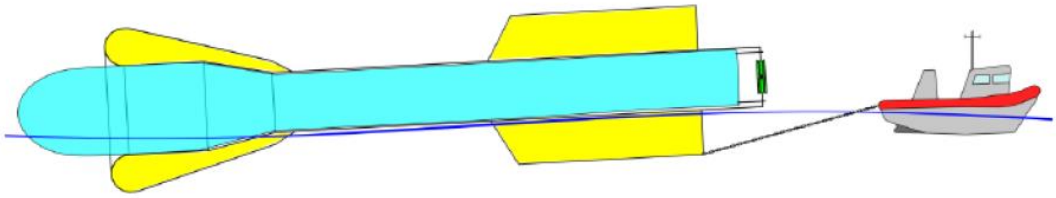
For the OWC Spar Buoy an AHTS vessel was chosen for the mooring installation, using a Multicat vessel and a remotely operated vehicle (ROV) of the inspection typology to provide support during the marine operations.

For the Symphony device a suitable Multicat was selected, with the support of a tug boat, and an inspection ROV.

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.

For both the OWC Spar Buoy and the Symphony, and all the variants a tow strategy was assumed for installation.



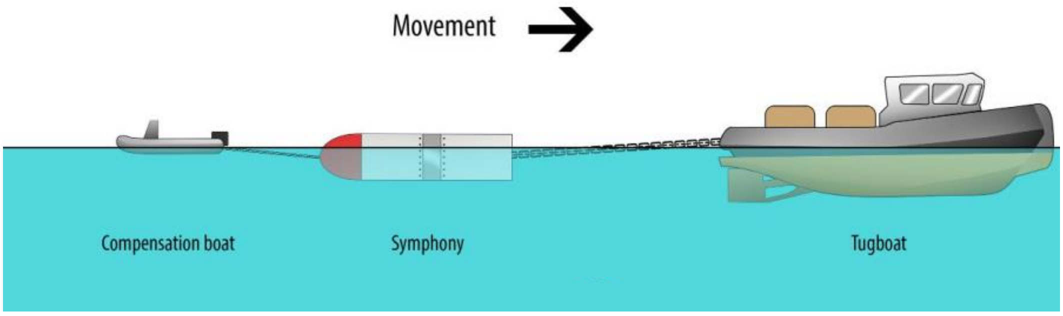


FIGURE 2:17 REPRESENTATION OF THE TOWING POSITION FOR DEVICES DURING INSTALLATION PROCEDURES [16], [18]

For the OWC Spar Buoy, the use of AHTS vessels is recommended for the towing task. For the Symphony a tugboat with the appropriate bollard pull could be used. In order to minimize the mobilization costs, the same vessels used for the mooring system installation have been chosen for 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).

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.

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 [36].

Dynamic cables have a slightly different installation procedure, due to their different characteristics compared with static ones. 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.

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.

2.5 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.

2.5.1 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 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.

For the OWC device, extra inspections are added for all variant with the exception of the survivability submergence, directly connect to the number of storms that occur.

2.5.2 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 2:9.

TABLE 2:9 COMPONENTS MINOR FAILURE RATES, FOR REFERENCE CASE DEVICE, FROM SOURCES [31], [31] AND INTERNAL WAVEC DATA.

<table>
<tr><th></th><th></th><th colspan="6">OWC Spar Buoy</th><th colspan="2">Symphony</th></tr>
<tr><th></th><th></th><th>1. REF</th><th>2. EAM</th><th>3. NS</th><th>4. SS</th><th>5. SM</th><th>6. DEG</th><th>1. REF</th><th>2. SYM</th></tr>
<tr><td rowspan="4">Electrical System</td><td>Electric dynamic cable (MV)</td><td colspan="8">9.12E-03</td></tr>
<tr><td>Electric static cable (MV)</td><td colspan="8">9.12E-03</td></tr>
<tr><td>Electric export cable (HV)</td><td colspan="8">1.52E-01</td></tr>
<tr><td>Transformer</td><td colspan="8">2.16E-02</td></tr>
<tr><td rowspan="4">Mooring System</td><td>Chain</td><td colspan="3">3.78E-03</td><td>2.84E-03</td><td>1.11E-03</td><td>3.78E-03</td><td colspan="2">3.78E-03</td></tr>
<tr><td>Rope</td><td colspan="3">2.44E-03</td><td>1.83E-03</td><td>3.31E-06</td><td>2.44E-03</td><td></td><td></td></tr>
<tr><td>Moorings (gen/unknown)</td><td colspan="3">2.22E-04</td><td>1.67E-04</td><td>3.85E-07</td><td>2.22E-04</td><td></td><td></td></tr>
<tr><td>Anchor</td><td colspan="3">8.09E-03</td><td>6.07E-03</td><td>7.71E-05</td><td>8.09E-03</td><td>8.09E-03</td><td>8.09E-03</td></tr>
<tr><td rowspan="3">Device</td><td>Device structure</td><td colspan="3">0.05</td><td>0.075</td><td>0.05</td><td>0.05</td><td colspan="2">0.1</td></tr>
<tr><td>PTO system</td><td colspan="5">0.1</td><td>0*</td><td colspan="2">0.1</td></tr>
<tr><td>Generator</td><td colspan="6">0.0546</td><td>0.0546</td><td>0.01</td></tr>
</table>

** The DEG analysis is done separately*

All the failures are supposed to happen separately and repaired individually. As it happens for the installation procedures, 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.

2.5.3 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 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 exception is the case of the Symphony, where only the control cocoon is removed, without the need of towing a device.

The failure rates referring to major failures are listed in Table 2:10.

TABLE 2:10 COMPONENTS MAJOR FAILURE RATES, FOR REFERENCE CASE DEVICES, FROM INTERNAL WAVEC DATA.

	OWC Spar Buoy						Symphony	
	1. REF	2. EAM	3. NS	4. SS	5. SM	6. DEG	1. REF	2. SYM
Device structure	0.025	0.025	0.025	0.0375	0.025	0.025	0.05	0.05
PTO system	0.05	0.05	0.05	0.05	0.05	0*	0.05	0.05

** The DEG analysis is done separately*

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.

2.5.4 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.

2.5.5 DEG system maintenance

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.

3 RESULTS

3.1 OWC SPAR-Buoy

The LCOE of the first 5.25 MW OWC Spar buoy array farm, for the reference case, assessed through techno-economic analysis, was of 131 c€/kWh for the Leixões site and 106 c€/kWh for EMEC. These values are higher than the target, but not learning assumptions have been made, as the goal of this task was to assess the improvements of the breakthroughs in relation to the reference case. The analysis presented forward in this deliverable will use normalized LCOE values, in which the LCOE for each case is divided by LCOE for the reference case, matching the location.

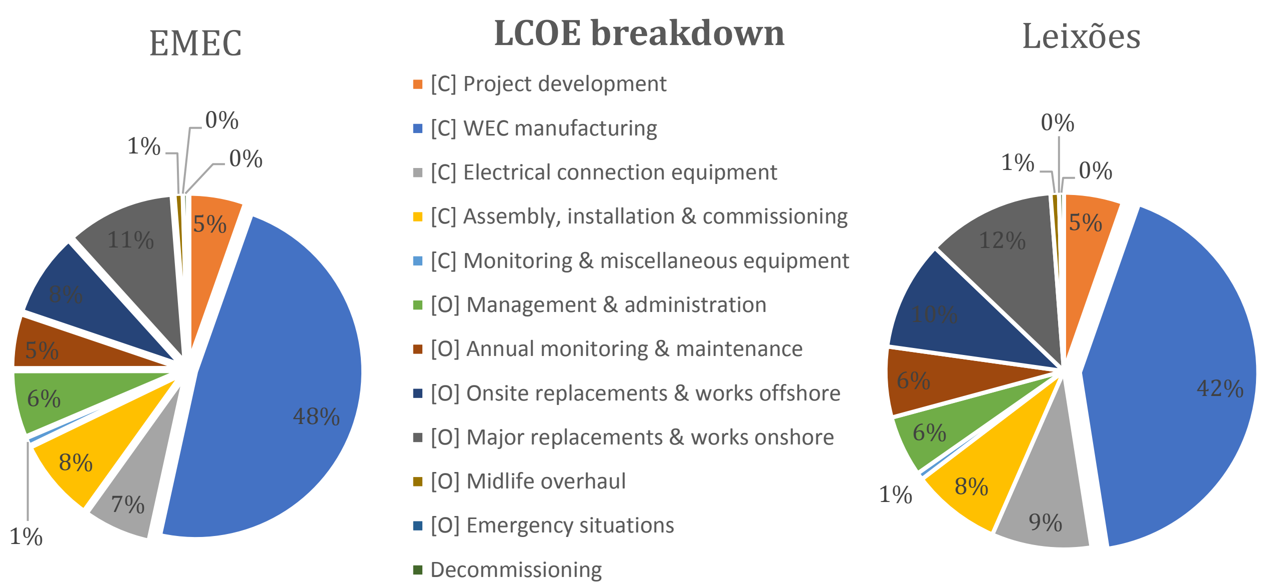


FIGURE 3:1 LCOE BREAKDOWN FOR REFERENCE CASE

The majority of the LCOE is due to the device CAPEX, which is inline with what is expected for first wave energy arrays, as was presented in section 1.1.

Looking at the LCOE averaged for both locations and comparing breakthroughs (Table 3:1), it can be seen that, except for the DEG breakthrough, all variants show positive improvements in relation to the reference case. The table below presents the ratio of breakthrough and reference case, for CAPEX, OPEX, energy extraction and the LCOE.

TABLE 3:1 AVERAGE RESULTS OF BREAKTHROUGHS IN RELATION TO REFERENCE CASE

		1. REF	2. EAM	3. NS	4. SS	5. SM	6. DEG
CAPEX	**Total**	**1,00**	**0,95**	**0,91**	**0,94**	**0,89**	**0,98**
	Device	*1,00*	*0,95*	*0,89*	*0,93*	*0,87*	*0,97*
OPEX	**Total**	**1,00**	**0,92**	**0,90**	**0,97**	**0,89**	**1,23**
	Inspection/Maintenance	*1,00*	*0,91*	*0,89*	*0,97*	*0,88*	*1,29*
AEP	**Farm Capacity Factor**	**1,00**	**1,02**	**1,00**	**1,00**	**1,16**	**0,50**
	Device Capacity Factor	*1,00*	*1,02*	*1,00*	*1,00*	*1,00*	*0,56*
	Availability	*1,00*	*1,00*	*1,00*	*1,00*	*1,00*	*0,90*
LCOE	**Total**	**1,00**	**0,92**	**0,91**	**0,94**	**0,77**	**2,12**
	CAPEX	*1,00*	*0,93*	*0,91*	*0,93*	*0,77*	*1,95*
	OPEX	*1,00*	*0,90*	*0,90*	*0,96*	*0,77*	*2,45*

The breakthrough which shows more promise is the flexible shared moorings, with LCOE reductions of the order of 20-25%. The benefits in this case are two-fold: there is a reduction of costs due to fewer mooring lines and anchoring points, and there is an improvement of energy capture, as detailed in deliverable 6.5 [37].

The enhanced added-mass, negative spring and survivability submergence variants show similar results, with LCOE improvement of between 5-10%, and most cost reduction coming from a reduction of initial costs. For the survivability submergence case there is also improvements in O&M costs.

The DEG breakthrough performs worse than the reference case, however in this case there is a significant reduction of the energy capture (about 50% reduction).

In terms of location, the Leixões site outperforms EMEC in terms of improvement relative to the reference case. However, the analysed project achieves lower LCOE values at EMEC.

3.1.1 Sensitivity Analysis

For the different breakthroughs and the reference case, sensitivity analysis was conducted. For each of the cases, a sensitivity analysis for seven components was done through semi-random sampling of four location inputs: depth, distance to shore, distance to large port and distance to small port. The latter three variables are loosely related, in which the distance to small port cannot be larger than the distance to large to port, and distance to shore is also related to the distance to the ports.

The seven components analysed, divided into CAPEX and OPEX categories, were:

- CAPEX
  - Wave Energy Converter CAPEX
  - Electrical grid CAPEX
  - Installation CAPEX
  - Logistics duration
- OPEX
  - Total OPEX
  - Vessel related OPEX
  - Availability

Figures Figure 3:2 and Figure 3:3 show the CAPEX related variables, for the different variants. The values have been normalized to the reference value in terms of location and variant.

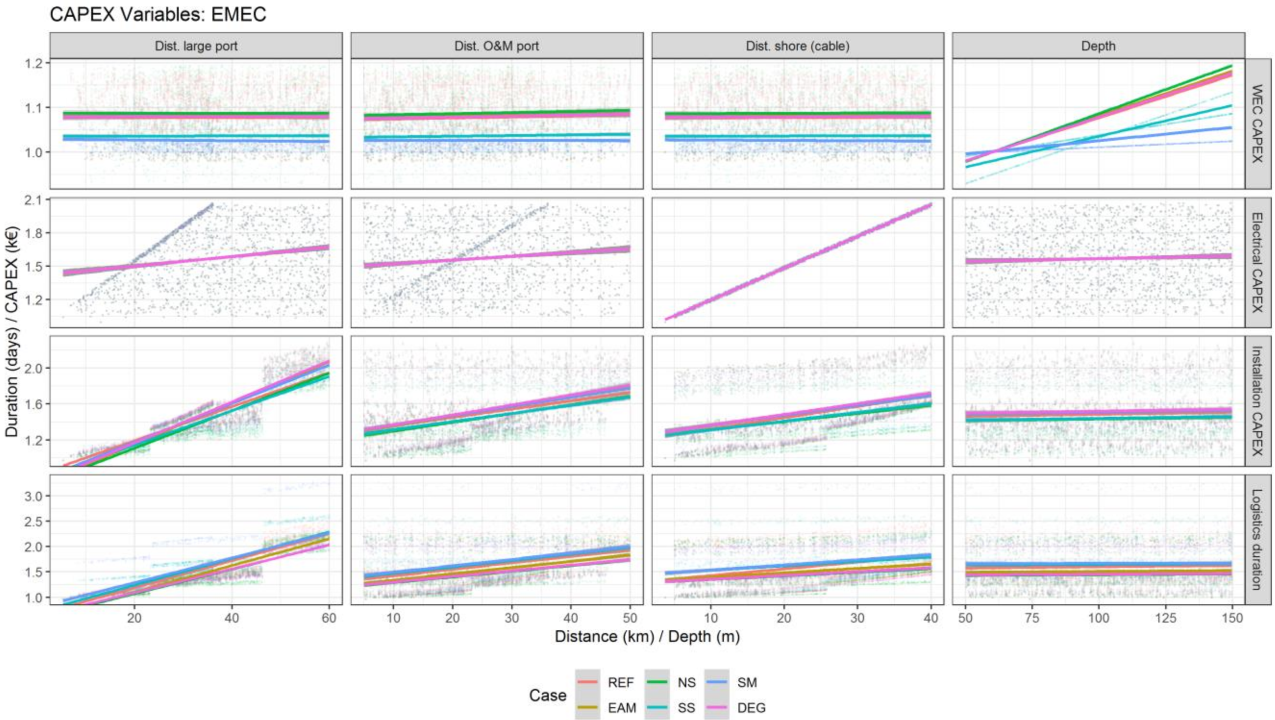


FIGURE 3:2 CAPEX VARIABLES VARIATION FOR THE EMEC SITE

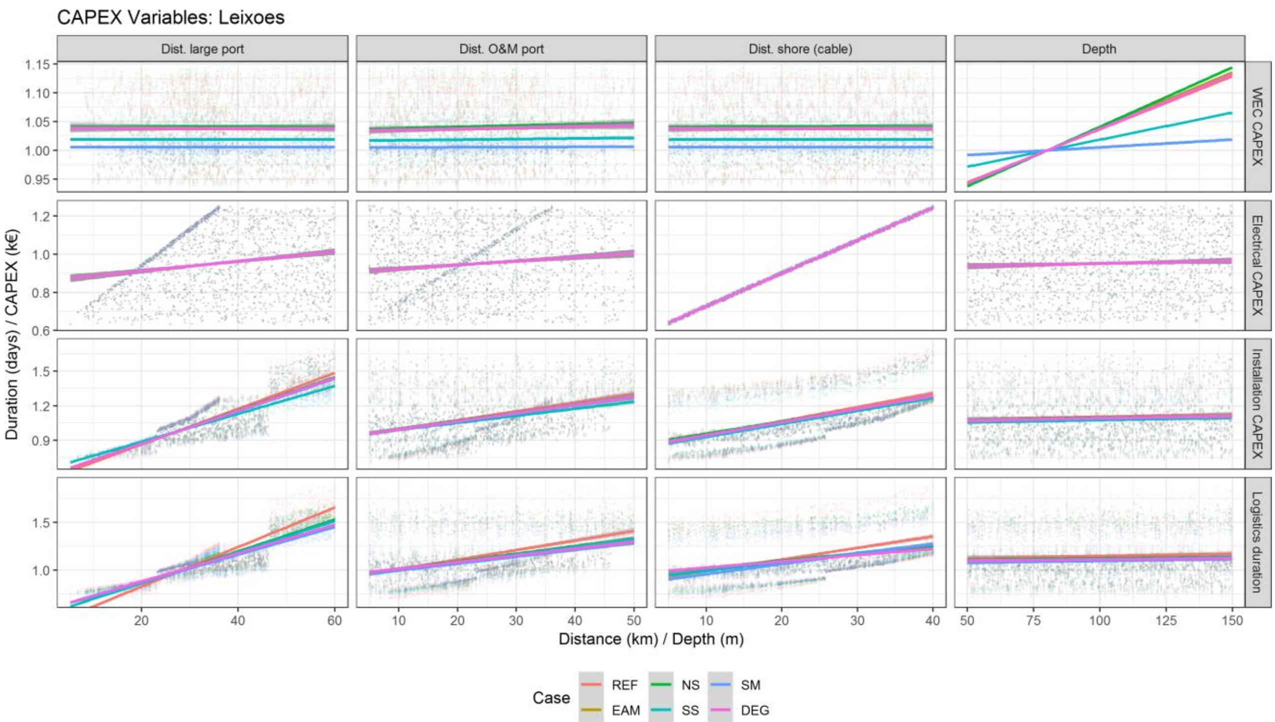


FIGURE 3:3 CAPEX VARIABLES VARIATION FOR THE LEIXÕES SITE

The depth has a strong impact on the cost of the device, through the cost of moorings. However, for the case of the shared moorings and submergence, the effects of larger depths are less strongly felt in the cost of device, emphasising the viability of these breakthroughs in deep waters.

The export cable length is directly related to the distance to shore, and it is equal across breakthroughs. The installation CAPEX is also affected by the distance to shore, as the cable needs to be laid out on this path. This also has a small influence on the logistic duration.

The distance to large port has a strong impact on the installation CAPEX and the logistic duration. A smaller impact can be seen from the distance to small port, however this is due to these two distances being loosely related.

In terms of OPEX variables, shown in Figure 3:4 for EMEC and Figure 3:5 for Leixões, the distance to ports plays a major role on the OPEX, vessel related costs and on the availability.

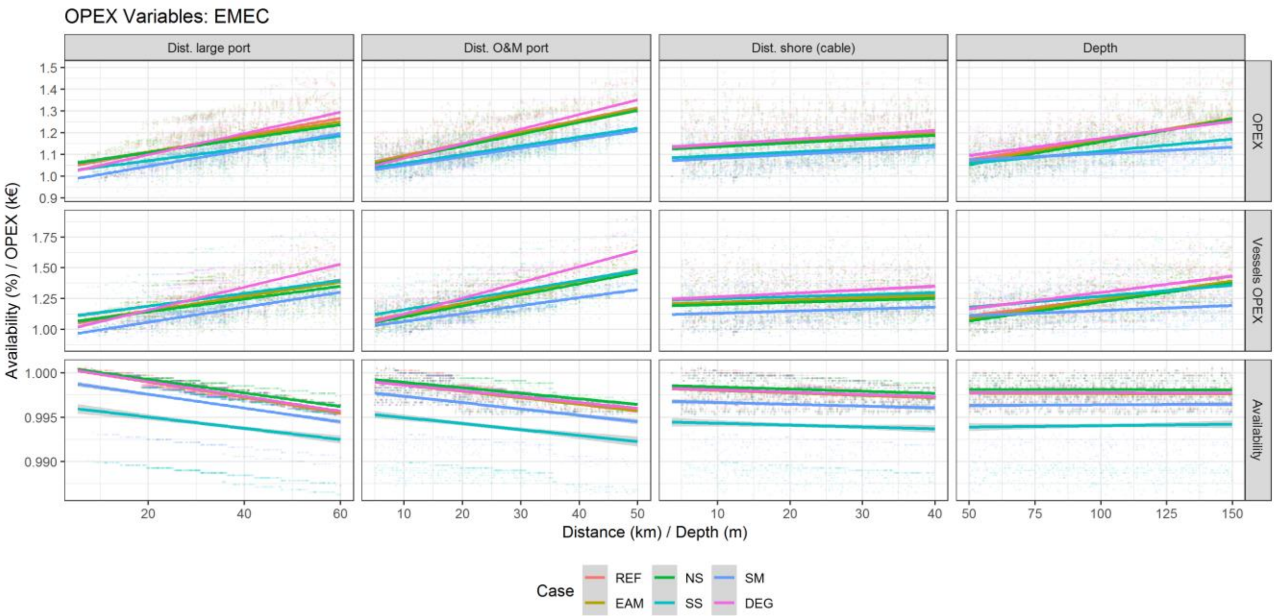


FIGURE 3:4 OPEX VARIABLES VARIATION FOR THE EMEC SITE

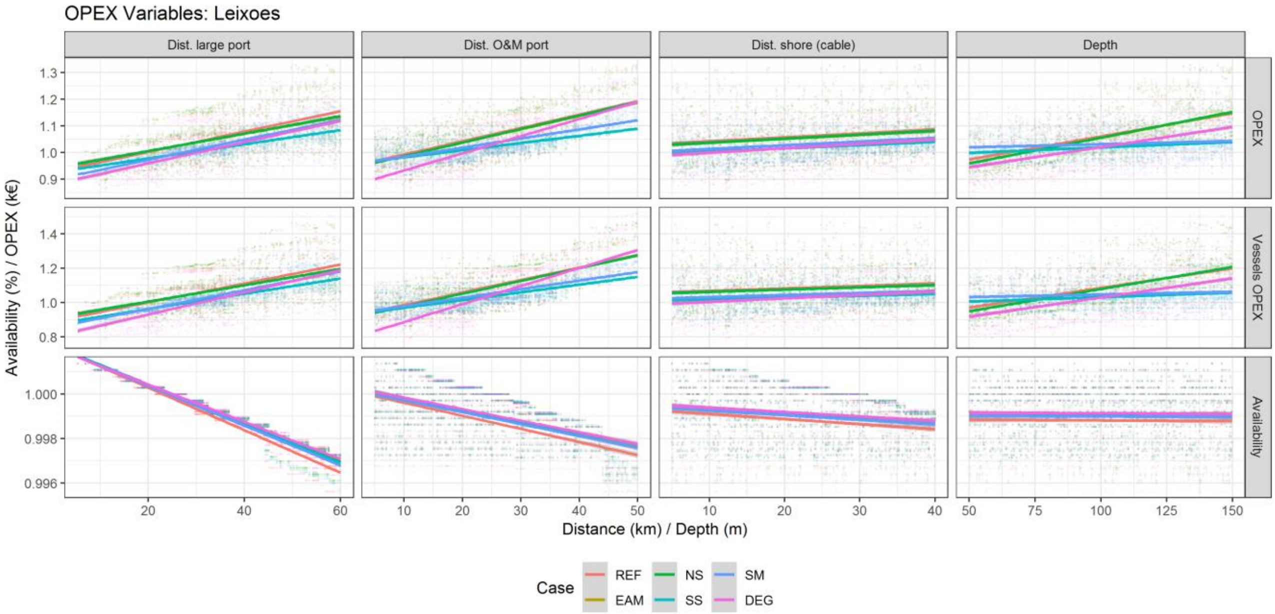


FIGURE 3:5 OPEX VARIABLES VARIATION FOR THE LEIXÕES SITE

3.1.1.1 Survivability submergence

As seen before, the depth is a determinant factor for device CAPEX, and the way the costs scale up differs for the reference case and the survivability submergence breakthrough. Plotting the variation of the LCOE according to depth (Figure 3:6), shows how for deeper locations the relative benefit of the breakthrough increases.

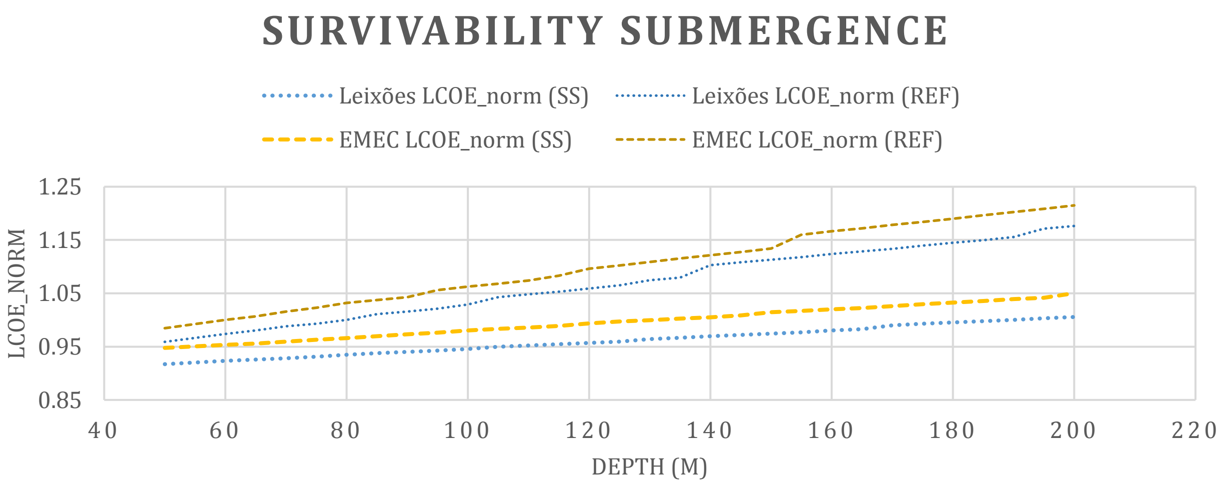


FIGURE 3:6 SURVIVABILITY SUBMERGENCE LCOE VARIATION WITH DEPTH

In this case, distance to shore was kept constant, but there are also benefits in lower OPEX values associated with the distance to O&M port, as demonstrated by the graph bellow.

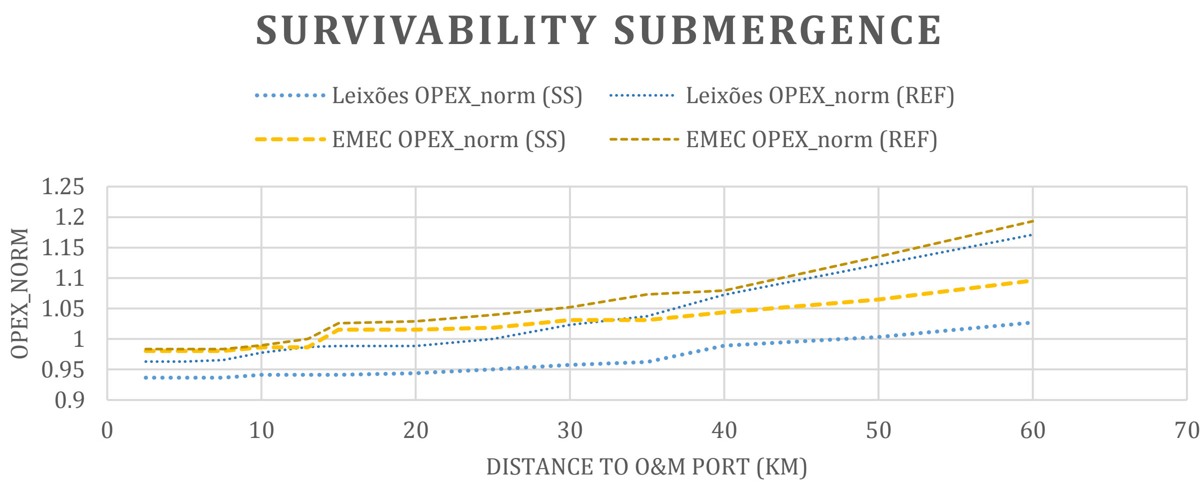


FIGURE 3:7 SURVIVABILITY SUBMERGENCE OPEX VARIATION WITH DISTANCE TO O&M PORT

3.1.1.2 Shared moorings

As with the previous breakthrough, the shared moorings case also shows a significantly different scaling function of costs in relation to depth. In this case, the improvement is very significant, and it would be feasible even

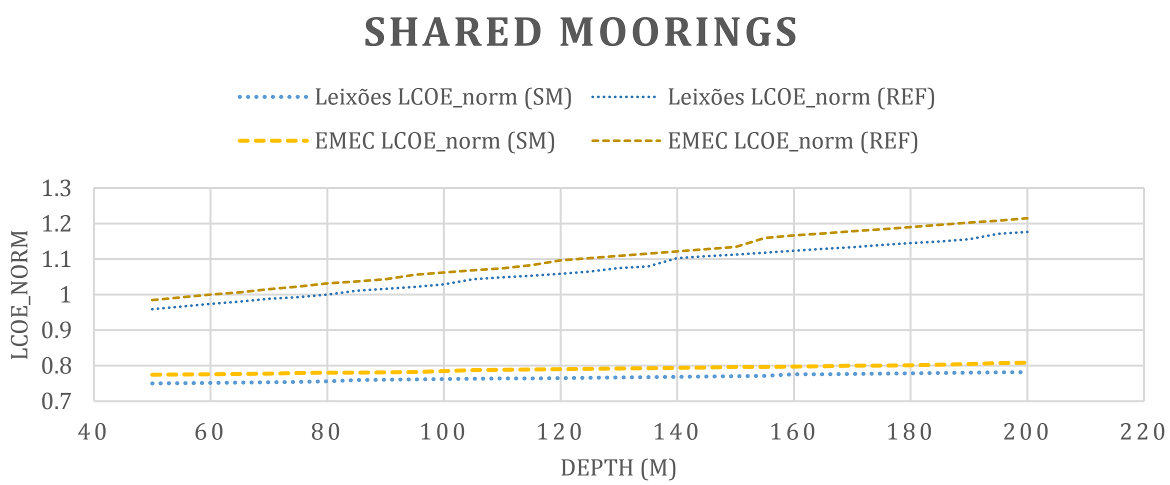


FIGURE 3:8 SHARED MOORING LCOE VARIATION WITH DEPTH

3.1.1.3 Dielectric elastomer generator

The DEG variant is the only one that showed negative results. A few of the reasons identified for the increase in LCOE were:

- Low capacity factor
- High structural costs
- High OPEX values

The low capacity factor is due to an unoptimized system: the OWC Spar-Buoy was designed with an Impulse turbine in mind. By altering the PTO system but maintaining the structure the system may not be optimized.

The high failure rates assumed in the model translate into high OPEX values, as well as low availability.

Looking at the impact of the failure rates, structure CAPEX and capacity factor of the devices, the following graph plots the different LCOE curves, normalized to value of the LCOE of the refence case.

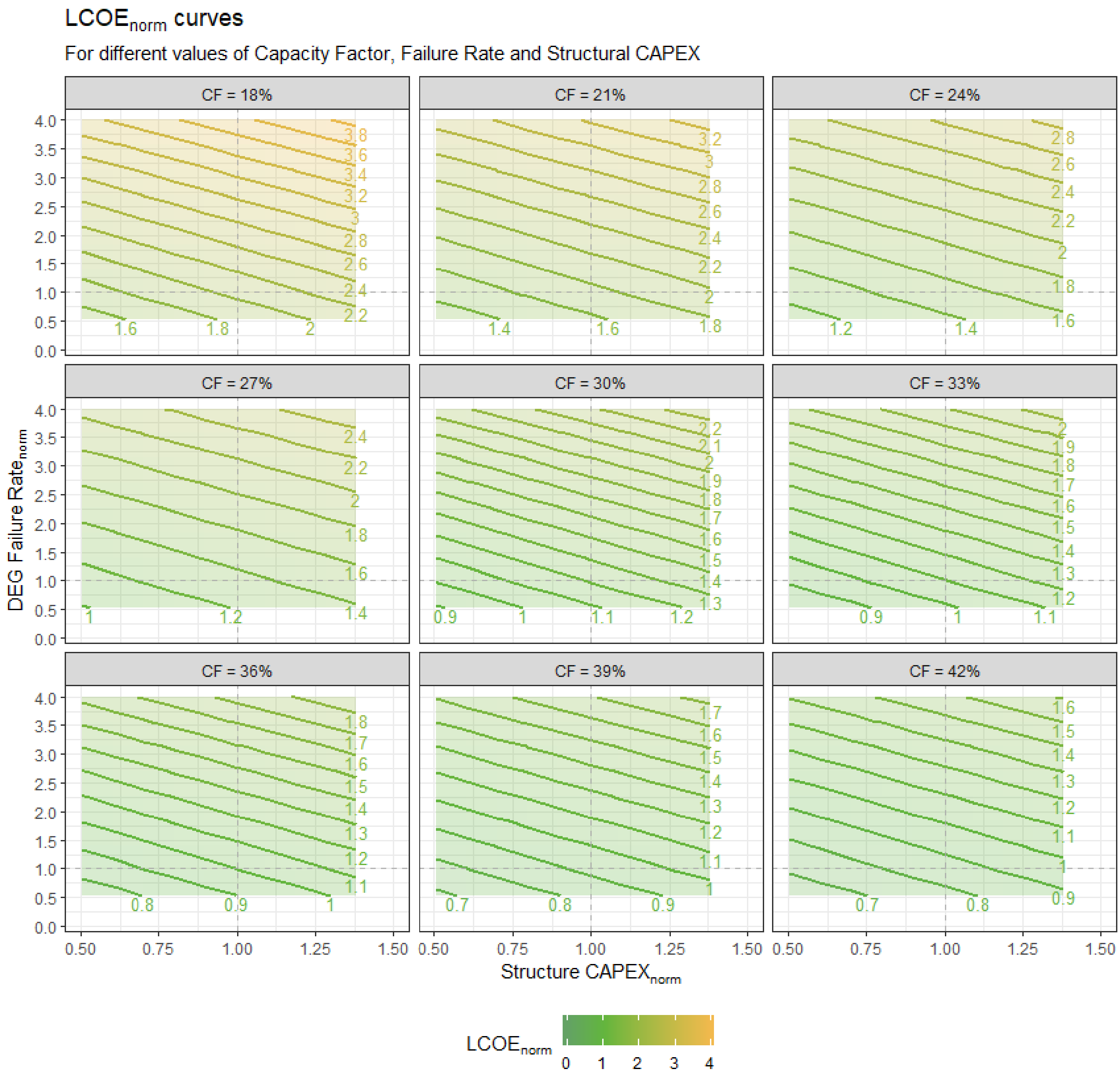


FIGURE 3:9 NORMALIZED LCOE CURVES ACCORDING TO STRUCTURE CAPEX, FAILURE RATE AND CAPACITY FACTOR

For values of capacity factor of the same level of the reference case (33%), the LCOE of the DEG system becomes comparable to that of the reference case. Furthermore, if the same capacity factor can be

achieved with a smaller buoy, or with improved reliability, the DEG variant outperforms the reference case.

3.1.1.4 Tetra-radial turbine

The tetra-radial turbine breakthrough was not analysed due to lack of sufficient data for a full LCOE analysis. However, using the reference case as normalization basis for analysis and the turbine cost, failure rate and efficiency, a sensitivity analysis for LCOE was conducted. In the graphs below, the variation of normalized LCOE was plotted against the variation of turbine cost (Figure 3:10), turbine failure rate (Figure 3:11), and device capacity factor (Figure 3:12). All other parameters remain constant.

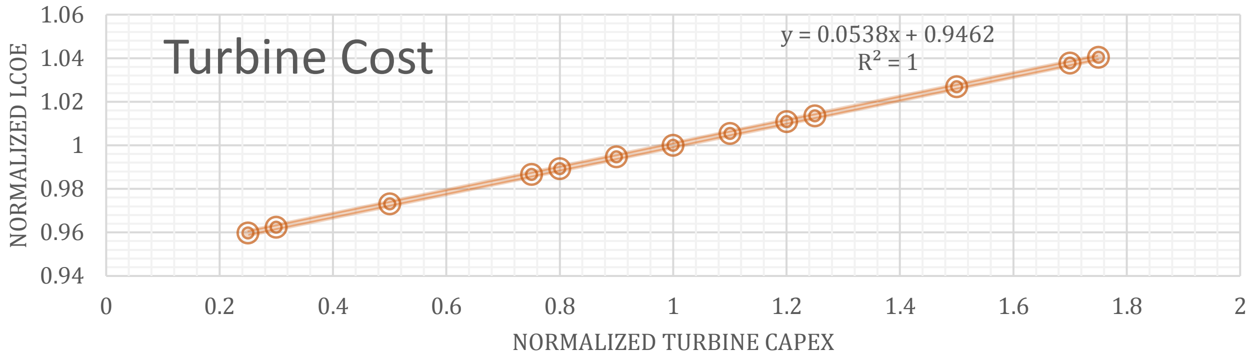


FIGURE 3:10 NORMALIZED LCOE VARIATION WITH NORMALIZED TURBINE COST

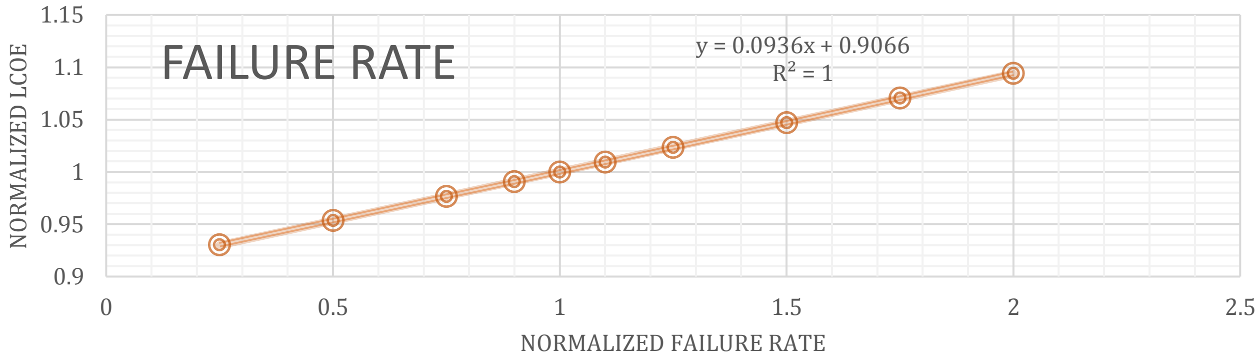


FIGURE 3:11 NORMALIZED LCOE VARIATION WITH NORMALIZED TURBINE FAILURE RATE

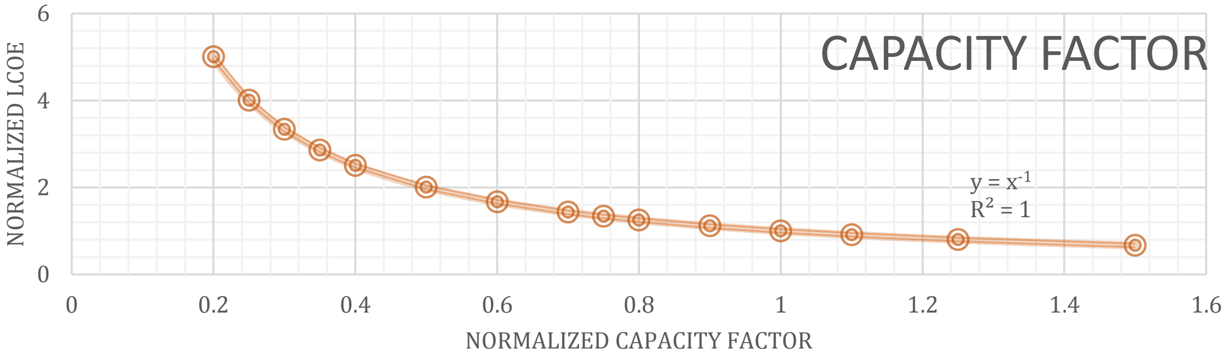


FIGURE 3:12 NORMALIZED LCOE VARIATION WITH NORMALIZED CAPACITY FACTOR

Of the three variables, the capacity factor is the one with the most impact on the LCOE, especially for the case of lower efficiencies. The turbine cost is the one of lower impact, as it represents less than 3% of the CAPEX of an array project.

The graph below combines the three variables into isocurves of normalized LCOE. For different device efficiencies (CF_norm), each line corresponds to a value of normalized LCOE, according to the turbine cost and failure rate. It reinforces the point that the economic viability of the tetra-radial turbine is tied to the efficiency. For instance, a 5% improvement in capacity factor allows a turbine with double the cost, without sacrificing the LCOE.

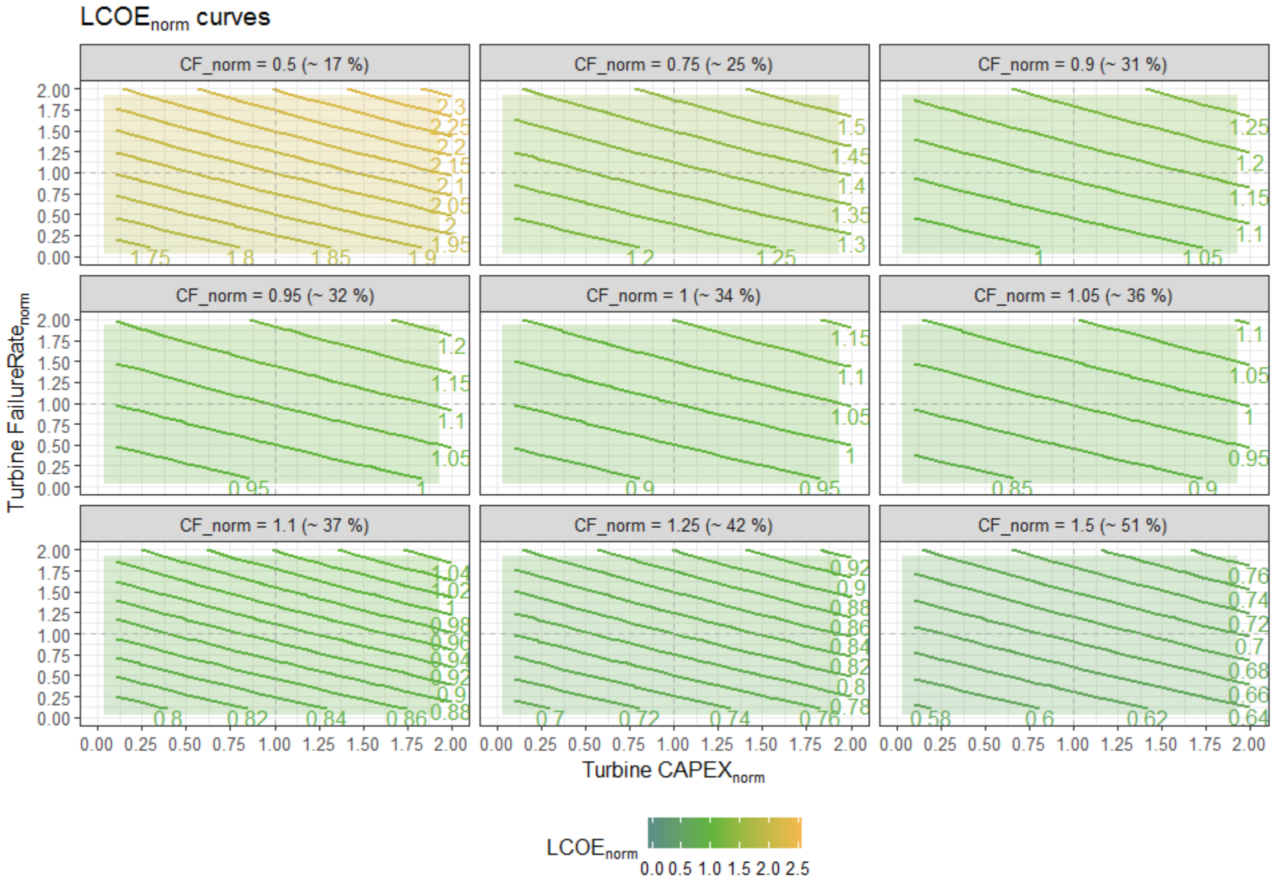


FIGURE 3:13 NORMALIZED LCOE CURVES ACCORDING TO TURBINE CAPEX, FAILURE RATE AND CAPACITY FACTOR

3.2 Symphony device

The LCOE of the first 5 MW SPDD device array farm, assessed through techno-economic analysis, was of 284c€/kWh for the Leixões site and 269 c€/kWh for EMEC. These values are quite large, especially as the reference device is quite large, with low efficiency.

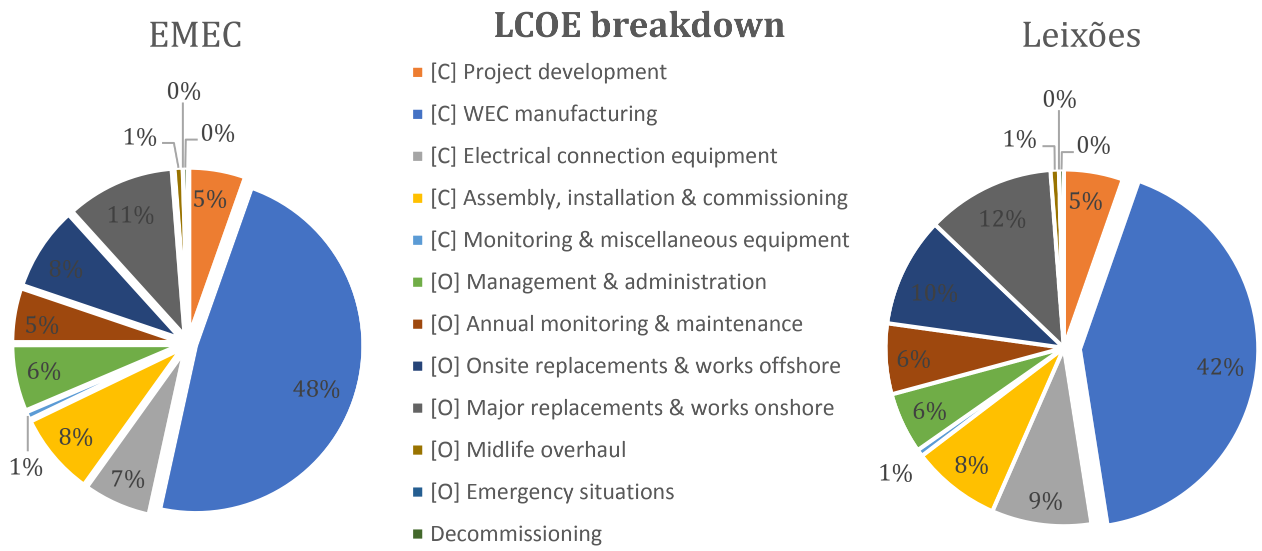


FIGURE 3:14 LCOE BREAKDOWN FOR REFERENCE CASE

The symphony device, with the associated breakthroughs, achieves a LCOE of 109 c€/kWh in Leixões and 90 c€/kWh at EMEC. This reduction happens at all levels of the LCOE, from lower CAPEX, lower OPEX, and improved capacity factor.

The table below presents the ratio of breakthrough and reference case, for CAPEX, OPEX, energy extraction and the LCOE.

TABLE 3:2 AVERAGE RESULTS OF THE SYMPHONY DEVICE IN RELATION TO REFERENCE CASE

		1. REF	2. SYM
CAPEX	**Total**	**1.00**	**0.64**
	Device	*1.00*	*0.58*
OPEX	**Total**	**1.00**	**0.69**
	Inspection/Maintenance	*1.00*	*0.69*
AEP	**Farm Capacity Factor**	**1.00**	**1.83**
	Device Capacity Factor	*1.00*	*1.82*
	Availability	*1.00*	*1.00*
LCOE	**Total**	**1.00**	**0.36**
	CAPEX	*1.00*	*0.35*
	OPEX	*1.00*	*0.38*

4 CONCLUSIONS

Through techno-economic analysis of potential projects, the viability of the breakthroughs for large scale deployment has been demonstrated. While the analysis was performed in related to two specific technologies, these breakthroughs can be applied to other wave energy technologies.

Both the Enhanced Added Mass and the Negative Spring have shown that there are improvements that can be achieved through design optimization, that can result in smaller and/or lighter devices, that are cheaper to build, and to install. These breakthroughs can be an important step in design and cost optimization.

The Survivability Submergence breakthrough has shown that by using this strategy, mooring costs can be reduced, even if it requires additional equipment. The cost benefits are more evident on more deeper waters. With the move of devices further offshore, towards more energetic sites, the survivability of the devices must be assured, and removal of the device also becomes more conditioned by suitable weather windows.

The sharing of mooring lines across devices has long been proposed for wave energy devices. In the specific case studied, this breakthrough showed the most promised, with LCOE reduction potential of up to 25% in the cases studied. As with the previous breakthrough, the deeper the project site, the more economically attractive becomes this solution.

The Dielectric Elastomer Generators, in the case studied, did not provide an improvement on the reference case. However, the study did not optimize the geometry of the buoy to the new PTO. If capacity factors similar to the reference case can be achieved by a tuned device, this DEG becomes comparable to the reference case. Solutions using DEGs designed from the ground up with this type of PTO in mind will likely perform better.

For the Symphony device, the use of innovative concepts has allowed a drastic reduction of costs and increase in performance, when comparing to a hypothetical AWS.

WETFEET

BIBLIOGRAPHY

[1] A. H. Clément *et al.*, 'Wave energy in Europe: current status and perspectives', *Renewable and Sustainable Energy Reviews*, vol. 6, no. 5, pp. 405–431, Oct. 2002.

[2] A. F. O. Falcão and J. C. C. Henriques, 'Oscillating-water-column wave energy converters and air turbines: A review', *Renewable Energy*, vol. 85, pp. 1391–1424, Jan. 2016.

[3] Carbon Trust, 'Future Marine Energy', London, UK, 2006.

[4] DOE and EIA, 'Annual Energy Outlook 2015 : With Projections to 2040', U.S. Energy Information Administration, Apr. 2015.

[5] IEA and NEA, *Projected Costs of Generating Electricity*, vol. 118 Suppl. 2010.

[6] Intergovernmental Panel on Climate Change, *Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change*, vol. 49. 2012.

[7] IRENA, 'Renewable Power Generation Costs: Summary for Policy Makers', International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, Nov. 2012.

[8] European Commission, 'A Roadmap for moving to a competitive low carbon economy in 2050', COM(2011) 112 final, 2011.

[9] US EIA, 'Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2014', Apr. 2014.

[10] IEA, *Experience Curves for Energy Technology Policy*. OECD/IEA, 2000.

[11] IEA-OES, 'International Levelised Cost Of Energy for Ocean Energy Technologies', Ocean Energy Systems - International Energy Agency, 2015.

[12] Carbon Trust, 'Capital, operating and maintenance costs', 2006.

[13] SI-OCEAN, 'Wave and Tidal Energy Market Deployment Strategy for Europe', 2014.

[14] Carbon Trust, 'Accelerating Marine Energy: The Potential for Cost Reduction', Carbon Trust, London, UK, July, 2011.

[15] Carbon Trust and Amec, 'UK Wave Resource Study', Carbon Trust, 2012.

[16] B. Teillant *et al.*, 'Designs and specifications of an OWC able to integrate the negative spring', WETFEET, Project Deliverable 2.1, Jan. 2016.

[17] B. Teillant *et al.*, 'Engineering challenges related to full scale and large deployment implementation of the proposed breakthroughs', WETFEET, Project Deliverable 2.3, Jan. 2016.

[18] R. Schuitema, H. van Noorloos, and F. Neumann, 'Report with designs and specifications of a Symphony able to integrate the control cocoon, electro-mechanic PTO, structural membrane and dielectric generators', WETFEET, Project Deliverable 2.2, Jan. 2016.

[19] M. Silva and A. Maximiano, 'Logistic requirements associated with the proposed breakthroughs for large scale deployment', WETFEET, Project Deliverable 7.1, 2018.

[20] S. Draycott, I. Szadkowska, C. Chaperon, and A. Yerzhanov, 'LCA and socio-economic implications of large scale deployment of the proposed breakthroughs', WETFEET, Project Deliverable 7.5, Apr. 2018.

[21] HMRC, 'State of the Art Analysis : A Cautiously Optimistic Review of the Technical Status of Wave Energy Technology', WAVEPLAM, 2009.

[22] K. Nielsen and T. Pontes, 'Annex II: Task 1.1 Generic and Site-related Wave Energy Data', Sep. 2010.

[23] T. Pontes, J. A. Pinto Simões, H. O. Pires, R. Aguiar, M. Gonçalves, and J. Cândido, *Ondatlas*. INETI, 2005.

[24] Wave Energy Scotland, 'WES O&M model: P2'. Wave Energy Scotland, 2017.

[25] M. Gradowski, M. Alves, R. Gomes, and J. Henriques, 'Integration of a hydrodynamic negative spring concept into the OWC spar buoy', in *Proceedings of the Twelfth European Wave and Tidal Energy Conference*, University College Cork, Ireland, 2017, pp. 938\hyphen 1–938\hyphen 7.

[26] A. F. de O. Falcão, 'Stochastic modelling in wave power-equipment optimization: maximum energy production versus maximum profit', *Ocean Engineering*, vol. 31, no. 11–12, pp. 1407–1421, Aug. 2004.

[27] M. Fontana and G. Moretti, ‘Personal communication: Data on Spar-OWC with DEG PTO’. 2017.
[28] G. Moretti, M. Fontana, and R. Vertechy, ‘Parallelogram-shaped dielectric elastomer generators: Analytical model and experimental validation , Parallelogram-shaped dielectric elastomer generators: Analytical model and experimental validation’, *Journal of Intelligent Material Systems and Structures*, vol. 26, no. 6, pp. 740–751, Apr. 2015.
[29] A. F. O. Falcão, L. M. C. Gato, J. C. C. Henriques, J. E. Borges, B. Pereiras, and F. Castro, ‘A novel twin-rotor radial-inflow air turbine for oscillating-water-column wave energy converters’, *Energy*, vol. 93, Part 2, pp. 2116–2125, Dec. 2015.
[30] S. Lundberg, ‘Performance comparison of wind park configurations’, 2003.
[31] M. Silva, S. Weller, M. Lejart, K. Charbonier, and A. Collin, ‘Prediction of reliability and economics of the offshore electrical infrastructure with recommendations and guidelines for the environmental impacts of the proposed array configurations’, DTOcean, Project Deliverable D3.4, 2015.
[32] P. Vicente *et al.*, ‘Engineering analysis of the submergence as a survivability strategy for floating OWCs’, presented at the Proceedings of the Twelfth European Wave and Tidal Energy Conference, 2017, pp. 914hyphen 1--914hyphen 10.
[33] K. Collins, D. Greaves, G. Iglesias, M. Hann, B. Howey, and V. Harnois, ‘Analysis of different potential configurations of non-rigid inter-moored devices’, WETFEET, Project Deliverable 6.1, Apr. 2016.
[34] M. Woznicki, ‘Methodology for offshore renewable energy site selection using economic decision factors’, Master, Mines Paristech, 2016.
[35] WavEC Offshore Renewable, ‘Logistic functions for ocean energy arrays’, DTOcean, Project Deliverable D5.4, 2015.
[36] B. Teillant *et al.*, ‘Report on Logistical model for ocean energy array and considerations’, DTOcean, Project Deliverable D5.6, 2016.
[37] K. Collins *et al.*, ‘Design guidance on the use of shared moorings in compact arrays’, WETFEET, Project Deliverable 6.5, Apr. 2018.