Techno-economic Analysis of Breakthrough Concepts into the OWC Spar-buoy

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Abstract

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

DEG breakthroughs involve an overall increase of the LCOE but they have a good potential for further implementation. It was not possible to assess the effect of the TRT case because of the lack of data regarding the power outcome. It is important to notice that the breakthroughs were analyzed separately in this study, while the combination of two or more concepts in the same project is expected to have a greater positive impact.

1. Introduction

The increasing trend of global energy consumption witnessed in the past decades and foreseen for the next future has stressed the need for extensive research and development in the energy sector, mainly regarding polluting-free energy sources because of the recent growth in awareness and concern related with the climate change debate. In this context, wave energy is one of the most promising renewable sources. In fact, wave energy shows a great potential compared to the traditional renewable energy sources like wind and solar. Nevertheless, there are several constraints, mainly related with competitiveness from an economic point of view, that have limited its development and prevented it to follow the expected trends. Despite the intensive research witnessed in the past decades, the wave energy sector has not reached the commercial exploitation phase yet and still needs further development in order to be economically feasible.

2. Wave energy state of the art

Sea-waves, created by the winds blowing across the oceans, can carry a great amount of energy for kilometers without significant losses. The most important parameters used to assess the power of waves are the wave height and the energy period. The energy fluxes in deep waters can be very large, justifying the interest towards wave energy harvesting. Nevertheless, the resource is highly fluctuating and often complex to be assessed and forecasted.

A wave energy converter (WEC) is a device that can exploit the power carried by the waves to produce electricity. Because of the irregularity in time of the wave parameters, the WECs have to be efficient in harvesting energy over a wide range of excitation frequencies. Therefore, the hydrodynamic response of the devices has to be optimized for the location where they are installed and a very efficient control system is needed. In fact, in order to achieve the best power outcome, there should be resonance in between the natural frequency of oscillation of a floating device and the dominant frequency of the incoming wave field and the resonance can be achieved through an accurate control strategy acting on the power take-off (PTO) system.

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

The main challenges that the wave energy sector is facing are related with the harsh marine environment, the technological reliability of the WECs and their survivability, which lead to high development costs. Moreover, the lack of experience in logistics, maintenance, operation and decommissioning of offshore farms increases the complexity of economic assessment and the risk perception of potential investors.

In this context, the EU H2020 WETFEET project aims to provide a new boost to overcome the stagnation in the development of the wave energy sector through the introduction of innovative ideas. In fact, the so-called "breakthrough concepts" introduced within the project are supposed to improve the techno-economical performances of the studied devices.

3. OWC spar-buoy

The OWC spar-buoy is one of the selected devices within the WETFEET project. The spar-buoy is a floating WEC of the oscillating water column (OWC) typology. In the OWC concept the mechanical process of energy absorption from the waves is carried out through a moving air-water interface subject to a time-varying pressure. The air-water interface in the OWC spar-buoy is created through the floating hollow structure which has an opening towards the sea, below the water surface. The air is trapped in the air chamber, between the inner free-surface of the water and the hollow structure. The action of the incoming waves results in the motion of the inner surface of the water that alternatively compresses and decompresses the trapped air, forcing it to pass through an air turbine coupled with a generator.

The OWC spar-buoy is composed by an upper floater and a lower hollow column that extends underwater and that is open at its bottom. The column can be further divided in two parts: the higher one is a straight cylinder with fixed diameter, the lower one has a variable diameter that enlarges towards the bottom of the structure. The air-water interface is created at the height of the floater that hosts in his top part the PTO system, composed of a bi-radial self-rectifying air turbine.

The station-keeping of the OWC spar-buoy is ensured through a slack-mooring system composed by three equally-spaced mooring lines connecting the device to the sea bottom. The mooring lines are formed by a spiral-strand steel wire attached to a studded chain that is connected to a weight anchor placed on the sea bottom.

The described OWC spar-buoy corresponds to the reference device, with no breakthrough applied, and it is the comparison basis for the cases with the innovative concepts introduced.

4. Breakthrough concepts

The six breakthrough concepts for the OWC spar-buoy developed within the scope of the WETFEET project as possible solutions for the challenges in wave energy development are:

- Enhanced added mass (EAM): the geometry of the lower part of the structure, the enlarged bottom of the hollow column, is changed in order to improve the power absorption from the incoming wave field.
- Negative spring (NS): the air chamber, inside the floater, is enlarged in order to allow the structure of the device to be

smaller but to keep a similar power output compared to the reference case.

- Survivability submergence (SS): the device can be submerged through the combined effect of water pumps, filling internal cavities of the structure, and winches, pulling the device towards the sea bottom winding the mooring lines. The submergence procedure is applied when rough storm conditions, over the operating limit conditions, are forecasted.
- Shared moorings (SM): the devices in a farm are connected together through interconnection lines in order to reduce the total number of bottom lines. There are three different possible configurations for the shared moorings breakthrough (B, C and D) but just the one offering the best cost-reduction performance is considered (configuration C).
- Dielectric elastomer generator (DEG): the PTO system composed of the self-rectifying air turbine is replaced by three circular membranes of solid-state deformable transducers made of elastic polymers that can produce directly electricity from the mechanical stress induced on them, based on the variable-capacitance electrostatic generation principle.
- Tetra-radial turbine (TRT): the bi-radial turbine of the reference case is replaced by a new generation self-rectifying air turbine, featuring 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 tetra-radial turbine is more complex compared to the reference bi-radial turbine but it has a greater efficiency according to numerical predictions. This last breakthrough concept is just presented but not analyzed in the study because of the lack of data regarding the power output of the new generation self-rectifying air turbine.

5. Methodology

The assessment of the effectiveness of the breakthrough concepts is performed through the analysis of the levelized cost of energy (LCOE), using a model developed by WavEC Offshore Renewables. The main parameters affecting the LCOE of a wave energy farm project are defined in the model: the installation site, the WEC characteristics (structure, PTO and mooring systems), the farm and the electrical system layouts, the installation logistics and the maintenance strategy.

Two possible locations have been chosen to study the installation of a wave energy farm: Wave Hub pilot zone and Leixões deployment site. The wave climates of the two installation sites are defined through scatter diagrams describing the average probability, in hours, of the combinations of wave height and energy period to verify throughout a year. The other important parameters related with the farm location include: water depth, distance to shore and distance to both the nearest large and small ports.

The WEC characteristics might change according to the breakthrough under analysis. In fact, the structure is modified in both the EAM and the NS concepts. Moreover, the PTO system is different compared to the reference case for the DEG breakthrough. The changes in both structure and PTO system have an effect on the energy production of the device. The power output is defined through a power matrix, where the maximum power that the device can extract for each combination of wave height and energy period is assessed. It is important to know that even if the power matrix is different for some cases, the rated power for the reference device and for each breakthrough is 150 kW. Finally, the mooring system is different from the reference case for the SS and the SM breakthroughs, since for the SS an extra set of mooring lines attached to the bottom of the structure is needed for the submergence procedure and for the SM the number of bottom lines is lower.

The farm layout is defined considering the characteristic disposition of the devices for the SM breakthrough. Thus, the devices are installed in clusters of five devices forming an array. The five devices are disposed with four of them at the corners of a square and the last one in the middle. The number of arrays deployed at sea is defined by the target capacity of the farm, set at 5 MW.

The electrical system is composed by subsea cables, connectors and sub-station. The dynamic cables are connected directly to the devices. The electrical configuration of the dynamic cables can be of two typologies: string or star. Accordingly, the lengths of the cables are different as well as their power ratings and consequently their losses. Moreover, the connectors have different locations as well depending on the electrical configuration and thus the lengths of the static array cables, connecting the dynamic cables to the export cable, change accordingly. The sub-station is useful to step-up the voltage (to 33 kV) during transmission and reduce the costs for the export cable that would be significantly more expensive if the cable voltage remains the same as in the other cables (11 kV). It is important to know that the maximum losses allowed for the electrical system correspond to the 5% of the energy produced.

The installation of the farm is assumed to be performed through rented vessels. For each of the installation tasks, corresponding to mooring, devices, electrical system and sub-station installations, specific vessels with adequate features are rented. The cost of the operations is assessed computing the total time needed. The mobilization time of the vessels and the waiting time for adequate weather windows for each operation are taken into account.

The assessment of the operation and maintenance of the farm is performed computing the average number of failure per year for each component of structure, PTO, mooring and electrical systems. Every failure is supposed to be repaired individually, using rented vessels. Minor and major failures are considered in the model and their probability of occurrence is defined through fixed failure rates. For the minor failures the repairs can be performed directly at sea while for the major failures the devices have to be brought back at port for maintenance. Annual inspections and a midlife overhaul are considered as part of the maintenance strategy. Moreover, an emergency situation protocol for rough storm conditions provides that the devices have to be brought to port whenever the operating limit conditions are forecasted.

6. Results

The main results of the model concern the capital expenditures (CAPEX), the operational expenditures (OPEX), the annual energy production (AEP) and the LCOE of the wave energy farm project.

Concerning the CAPEX, it includes all the expenditures necessary in order to reach the operational phase of the farm, such as project development, WEC manufacturing, electrical connection equipment, assembly, installation, commissioning and monitoring costs.

Four of the five analyzed breakthrough concepts show a good potential for capital cost reduction: EAM, NS, SM and DEG. In fact, for both the EAM and the NS concept there is a reduction of the WEC manufacturing cost due to the changes in the structure of the device. The SM case allows a reduction of the total number of mooring lines installed and thus the WEC manufacturing cost is reduced, as well as the installation cost since the operation time for the mooring system is shorter. The PTO system in the DEG breakthrough is cheaper compared to the reference air-turbine and it lowers the WEC manufacturing cost.

On the other hand, the SS concept induces an increase in the CAPEX. In fact, for applying the SS breakthrough an extra set of mooring lines, with the same configuration as the reference one but connected to the bottom of the device structure, is needed and therefore the costs for procurement and installation are higher.

Concerning the OPEX, it includes all the expenditures necessary to keep the farm operating properly, such as management administration, annual monitoring and maintenance, minor and major replacements, midlife overhaul and emergency situations costs.

All the five analyzed breakthrough concepts show a good potential for operational cost reduction. In fact, for both the EAM and the NS cases the costs related with minor and major replacements concerning the device structure are lower because the cost for spare components is computed as a percentage of the structural cost that is lower compared to the reference case. For the SS breakthrough there are contrasting effects: both the annual monitoring and maintenance and the minor replacements costs are higher because of the higher number of mooring lines while the major replacements costs are lower because the device structure is supposed to have an increased reliability due to the survivability procedure. Moreover, the emergency situations costs are negligible because the devices can be submerged instead of be brought back to port, as it happens for all the other cases when rough storm conditions, over the operating limit conditions, are forecasted. Altogether, the final OPEX of the project results to be lower when the SS breakthrough is applied. For the SM concept both the annual monitoring and maintenance and the minor replacements costs are lower because of the lower number of mooring lines installed. For the DEG system the maintenance strategy concerning the PTO system is different compared to all the other cases because of the characteristic of the PTO design that is formed by 12 independent modules with 12.5 kW rated power each. Since the power outcome of a single module is not enough to justify a trip at sea every time a failure occurs and since the failure rate of the modules is relatively high, the maintenance strategy is based on two annual trips at sea during which all the damaged modules are replaced. The PTO repairs are then all accounted in the minor repairs. Therefore, the cost for minor repairs is considerably higher compared to the reference case while the cost for major repairs is substantially lower. The overall effect is a reduction in the operational expenditures.

Concerning the AEP, the two parameters that have the greatest influence on the energy production are the power matrix of the devices and their availability. The availability represents the amount of time throughout the year during which the devices can effectively produce energy. The availability is influenced by failures and by the time needed to perform the repair when the failure occurs.

Four of the five analyzed breakthrough concepts show a good potential for increasing the energy production: EAM, NS, SS and SM. In fact, for the EAM concept the changes in the structure of the spar-buoy induce a variation in the power matrix of the devices that makes the power outcome match better with the scatter diagram of the chosen locations. For the NS, the SS and the SM cases the energy production is computed using the same power matrix as for the reference case. For the NS case there is a slight improvement due to a better inter-array interaction caused by the larger ratio between the distance between devices and the diameter of the devices. For both the SS and the SM cases the energy production increases slightly because the farm availability increases, respectively due to the absence of downtime for emergency situations for the SS case and to the reduction of the failures related with the mooring system for the SM case.

On the other hand, the DEG breakthrough induces a drop in the AEP. In fact, for the DEG case there are two different effects that contribute to lower the energy production. The availability is lower because of the different maintenance strategy that is based on two annual replacements of all the damaged modules of all the PTO systems in the wave energy farm. Between two consecutive maintenance procedures the damaged modules do not produce energy. The average downtime is assumed to be equal to the half of the time between the two consecutive maintenance procedures (3 months). Therefore, the availability results to be lower compared to the reference case, affecting the AEP. Moreover, the geometry of the device was not optimized for none of the chosen locations. Therefore, the energy production results to be low because there are a low amount of hours per year during which the device is able to work at its maximum capacity.

The final result of the combination of the effects that the breakthroughs have on CAPEX, OPEX and AEP is the LCOE of the project. Concerning the LCOE, three of the five analyzed breakthroughs show an improvement in the economics of the project: EAM, NS and SM. In fact, the three concepts induce a consistent reduction in the capital costs related with the WEC manufacturing, which is the cost component with the greatest contribution to the final LCOE value (around 40%). Thus, the LCOE is reduced mainly because of the reduction in the investment costs of the project.

On the other hand, the SS and the DEG concepts induce an increase in the final LCOE of the project. For the SS case the main reason is the increase in both capital and operational expenditures related with the extra set of mooring lines attached to the bottom of the devices, needed for the submergence procedure. In fact, the gain in availability and the benefits due to the absence of need for emergency situations procedures do not compensate for the increased expenses related with the double mooring system. For the DEG case the dramatic decrease in energy production is the main cause of the increase in the LCOE of the project. In fact, the breakthrough shows good potential for both capital and operational costs reduction but without optimization for the chosen location the energy production results to be extremely low compared to all the other cases.

Table 1 presents the values of CAPEX, OPEX, AEP and LCOE for a farm composed of reference case devices.

Table 1: CAPEX, OPEX, AEP and LCOE values for a farm composed of reference case devices.

Data	Unit	Reference case
CAPEX	€/kW	23130
OPEX	€/kW	1710
AEP	MWh/y	14105
LCOE	c€/kWh	176.0

The values presented in Table 1 refer to the installation of the wave energy farm in Leixões deployment site and to an electrical configuration of the string typology, because the lowest value of LCOE for the reference case is obtained in this scenario.

Table 2 presents the percentage variations in CAPEX, OPEX, AEP and LCOE of the five analyzed breakthrough cases compared to the reference case.

Table 2: Percentage variations in CAPEX, OPEX, AEP and LCOE values for the five analyzed breakthrough cases compared to the reference case.

Data	EAM	NS	SS	SM	DEG
CAPEX	-1%	-6%	31%	-9%	-1%
OPEX	-2%	-4%	-1%	-3%	-14%
AEP	2.6%	0.4%	0.2%	0.1%	-45.1%
LCOE	-4.9%	-5.6%	19.2%	-6.8%	71.0%

7. Conclusions

The best results concerning the reduction of the LCOE, thus the improvement of the economic feasibility of a wave energy farm project, have been obtained through the application of breakthroughs that were implying a considerable reduction of the capital investment. In fact, as it can be noticed from Table 2, the most effective concepts are the EAM, the NS and the SM.

Apart from cost reduction, mainly regarding the capital expenditures, another possibility for improving the economics of a wave energy farm project is the increase of the annual energy production. Therefore, the TRT needs specific assessment in order to verify its expected improvement in efficiency compared to the reference PTO system. Moreover, the SS concept needs to be developed further because its benefits can be relevant when locations with frequent highly-energetic sea-states are considered for the installation of a wave energy farm. Concerning the DEG case, the geometry of the structure needs to be optimized in order to have more reliable results. Otherwise, locations with more energetic wave climates have to be chosen for the assessment in order to have a more reliable comparison.

The integration of breakthroughs in the same wave energy farm project is considered as a potential way to overcome the issues related with the single concepts or to improve further the results obtained considering them individually. Three combinations of pairs of breakthroughs have been assessed: SM and EAM, SS and NS, DEG and SM.

Table 3 presents the percentage variations in CAPEX, OPEX, AEP and LCOE of the three aforementioned combinations of breakthroughs cases compared to the reference case.

Table 3: Percentage variations in CAPEX, OPEX, AEP and LCOE values for three combinations of breakthroughs compared to the reference case.

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

The lowest LCOE value in the whole set of results of the study is obtained for the combination of SM and EAM breakthroughs. Moreover, for both the SS and the DEG concepts the combination with the NS and the SM concepts respectively causes a considerable improvement in the economics of the project, as it can be noticed comparing the percentages of variation of the LCOE in Table 2 and Table 3.

Finally, the integration of several breakthrough concepts appears to be the most effective way to overcome the challenges and the barriers that the wave energy sector is facing nowadays.