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Technical Challenges in Achieving Widespread Implementation of Wave Energy Converter Systems and Future Directions

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Abstract. The abundance of wave energy has resulted in a strong interest towards the development of industrial-scale wave energy converter systems. Despite the significant energy harvesting potential, several technical challenges associated with the manufacturing, survivability, cost of production, maintainability, environmental impact and grid integration of wave energy converters are yet to be addressed. It is not surprising that although a large number of alternative designs have been proposed, only few have been tested under actual conditions and even fewer at industrial scale with mixed results. In this paper we consider the technical challenges that need to be addressed before widespread implementation of wave energy converters can be realised. Furthermore, we analyse the future directions of research and development which can meaningfully contribute towards achieving the aim of large-scale wave energy production with minimal environmental impact and at an acceptable cost for prospective operators of such systems. In our analysis, we discuss the technical specifications of the SUNBIO prototype hybrid wave energy converter which will be installed off the coast of Barcelona. The SUNBIO prototype will operate in conjunction with the expandable seafloor observatory OBSEA managed by Universitat Politecnica de Catalunia.

1 Introduction

Wave energy is an abundant renewable energy source to which coastal countries around the globe have direct access. The wave energy annual production potential has been estimated to be almost 30,000 TWh [1]. Considering that the electricity demand in the European Union (EU) during 2023 was approximately 2,700 TWh [2] then it is easy to comprehend the vast positive implications that the untapping of wave energy could have in increasing energy security. Exploitation of wave energy at greater scale would also contribute meaningfully to mitigate climate change by reducing our dependence on power generation from fossil fuels.

Although large-scale exploitation of wave energy resources has been a long-term objective for several countries around the world, so far very few projects have reached commercial exploitation, e.g. Pelamis and CorPower [3-4]. Several wave energy harvesting technologies have been proposed, designed, researched and patented [5-6]. However, only a small number of energy converter designs have reached the point of being tested at scaled-down level in wave tanks under laboratory conditions. Even less have been tested at sea, with only a handful of prototypes being trialled at full scale or connected to the grid.

Unfortunately, the trials of industrial-scale prototypes at sea so far have not proven the long-term financial viability of wave energy production [7]. The associated investment risk has also been deemed to be higher than other renewable energy sources, particularly offshore wind energy. Furthermore, the impact of large-scale deployment of different wave energy converter systems on the environment and marine lifetime has yet to be satisfactorily evaluated due to lack of sufficient data and inadequate experience in operating such systems.

2 Types of wave energy converters

Different types of wave energy converters have been proposed, including, point absorbers (single-body and two-body), wave attenuators, oscillating surge devices, overtopping devices, submerged pressure differential, and others. Each type of wave energy converter has a different level of technical complexity, associated manufacturing and installation cost, and power output capability. For example, wave attenuators have a higher power output potential than point absorbers as their harvesting capability is a function of the area they cover.

At the same time however, their design and operation are far more challenging as they need to accommodate complex motions at sea (heaving, swaying, rolling, pitching, surging and yawing) without failure. In addition, the dynamic energy oscillations due to wave crests and troughs have to be translated into electrical energy through complex hydraulic systems which drive the electric generator onboard the attenuator.

The fact that the wave attenuator has to be moored in position and connected to the grid through a subsea armoured cable enhance the design and operational issues that have to be resolved. Further complications arise due to the variable sea state during the year,

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influencing the significant wave height and mean wave direction. These parameters not only affect the amount of power generated but also can result in degradation of the hydraulic systems onboard.

Point absorbers are much simpler to design and operate but the power generation capacity is also significantly lower. This is why point absorbers tend to be preferred for powering scientific equipment rather than being used for utility scale production, which is the case of wave attenuators.

Wave energy converters can be installed either as standalone units or as farm. Standalone units are not justifiable for utility-scale production as the cost is prohibitive. Nonetheless, they can be used as decentralised energy sources for various purposes of interest, such as powering scientific measurement buoys installed out at sea. Farms comprising several industrial-scale wave energy converters can be used for utility-scale power generation. The power output of such farms has to be sufficient in order to justify the cost of the subsea cable and associated offshore transformer to ensure the project is financially viable. From there on the availability and capacity factor need to be maximised so the power generated is also optimised.

3 Technical challenges

There are several technical challenges to be addressed in achieving widespread implementation of wave energy harvesting devices for utility-scale power production.

First of all, the design of the wave energy converter needs to be able to withstand the operational offshore environment for a minimum of twenty to twenty-five years. The materials used to build the structural components of these devices have to be strong enough to withstand the variable loads that will occur throughout the operational lifetime, including extreme loads during stormy conditions.

Secondly, corrosion resistance is of paramount importance. The materials exposed to seawater will need to be able to resist corrosion with minimum need for intervention at any given time during nominal operation. Antifouling protection is also important, since it can affect the overall operational efficiency of the device and potentially damage moving parts exposed in the seawater. Leak tightness has to be ensured, particularly for all moving components and hydraulics, as well as the lubrication system, power generator, controller, batteries, etc. housed onboard the device.

Thirdly, the manufacturing materials employed should be relatively cheap and easy to recycle. They should result in minimum environmental impact throughout the lifecycle. This also applies to moorings and anchoring system.

Furthermore, the device should be designed to fail safe. Under no circumstances catastrophic failure which could result in possible navigation and environmental hazards to arise should be allowed to occur.

Maintainability is a key issue for economically viable long-term operation of utility-scale wave energy converter systems. Obviously being installed offshore, when maintenance intervention is required to be carried out, the appropriate trained technical personnel need to be sent out at sea with the necessary equipment and spare parts to perform this task. Maintenance has to be performed during good weather conditions and calm sea state to allow the maintenance personnel to work safely and efficiently.

Ideally, maintenance should be carried out on the spot, without the requirement for recovery of the device. In addition, maintenance should be targeted specifically to the actions that are really required so downtime, resource effort and allocation, and cost can be kept to a minimum. The reliability of the device should be restored to the original or close to the original level once the maintenance intervention has been completed.

The distance from the shore, sea state and water depth can significantly complicate maintenance activities. This is why maintenance should be carried out at specific times of the year, when the weather and sea state conditions are ideal. Corrective maintenance during adverse weather and sea state conditions may not be possible to carry out for prolonged periods of time. This can result in significant production losses, hence reducing the long-term financial viability of the present and future projects.

Remote condition monitoring has a critical role to play in ensuring the accurate evaluation of the actual condition of the device and its critical subcomponents, including power electronics, batteries, hydraulic systems, generator, etc.

The environmental impact of wave energy converters has to be carefully assessed regardless of their type. Since, such devices are designed to remove energy from the waves, this can have a significant effect on the shoreline along which they are installed [8]. The noise generated and the presence of these devices in remote locations out at sea has to be assessed with respect to their effect to the local marine life and habitats [9].

4 Future of wave energy converters

Research on wave energy converters has been strong around the world. Particularly in Europe and the UK several prototypes have been designed and tested either in the laboratory or at sea.

Although research is still ongoing strong, unfortunately commercial exploitation of such systems is yet to take off. The reason behind this is that several technical challenges still remain to be decisively addressed. More importantly the cost of such devices remains higher than competing technologies, which are already proven in the field such as offshore wind energy. The significant competition from offshore wind energy projects, reduces the sites as well as the investment available for wave energy projects. Coupled with the fact that most prototypes are not adequately proven in the field, like wind turbines are, results in increased financial, operational and reputational risk for prospective investors in such projects.

The legal framework is also not sufficiently defined and further refinement on policy and regulatory framework of commissioning, operation and decommissioning of large-scale wave energy projects is required.

The potential to use wave energy converters for decentralised power production for various purposes, such as scientific measurements, habitat restoration, or power for offshore facilities, such as fish farms, is quite appealing. Utility-scale power generation using wave energy converters remains challenging due to the higher risks associated with the technology as well as the strong competition from large-scale offshore wind farms. However, it may be possible to install wave energy converters in conjunction with offshore wind farms to reduce their installation costs by allowing the use of the existing subsea cable and transformer whilst increasing the overall power output of the project.

5 The Horizon Europe SUNBIO project

The SUNBIO project (grant agreement no. 101157493) is a three-year Research and Innovation Actions project funded by the European Commission through the Horizon Europe Research Framework and the UK through UKRI. The consortium consists of six partners from the EU (CSIC, ESI, ROBUST, Atlantis, NTUA and UPC) and the University of Birmingham from the UK. The project is coordinated by CSIC (Project Coordinator Dr. J. Aguzzi) with technical coordination undertaken by the University of Birmingham (Prof. M. Papaelias).

The project started in June 2024 and is expected to be completed by May 2027. The scope of the project is to develop a prototype 5 kW hybrid wave energy harvester which combines power generation from waves and solar rays with the creation of an artificial marine habitat in the location where the converter will be installed.

The prototype system combines a wave attenuator harvesting the dynamic energy from the waves and converting it to electric, photovoltaic panels installed on its top to harvest solar energy, and low-temperature thermoelectric semiconductor devices to harvest heat energy through the Seebeck effect due to the temperature difference between the top of the device, where the photovoltaic panels are installed and the sea water at the bottom.

The moorings and anchoring system of the device will be designed and manufactured in a way so as they act as an underwater sanctuary for fishes and other marine life in order to promote biodiversity. Figure 1 shows the overall concept of SUNBIO prototype.

The trials of the SUNBIO prototype will be undertaken off the coast of Barcelona, Spain, at the location of the expandable seafloor observatory OBSEA (figure 2) managed by UPC [10].

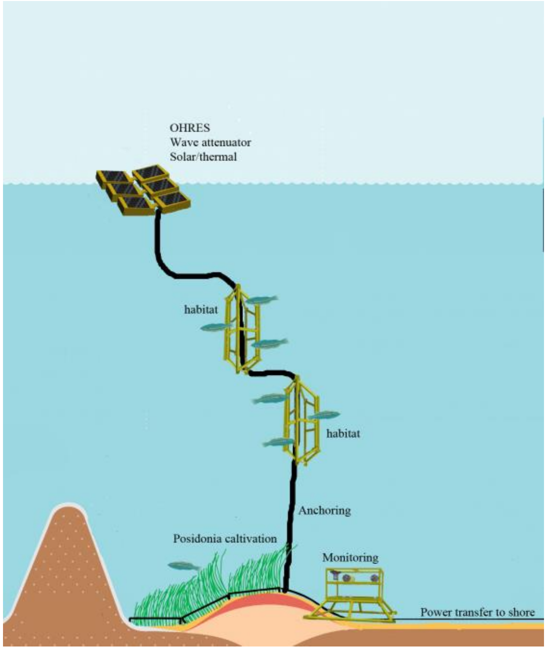

Fig. 1. The SUNBIO protype concept.


Fig. 2. The expandable seafloor OBSEA observatory managed by UPC off the coast of Barcelona.

The depth of the site is 20 m and it is located 4 km from the shore of Vilanova i la Geltrú. The protype sea trials are expected to start in June 2026. The power output from the hybrid wave energy converter will be supplied through an underwater cable to the observatory.

The OBSEA observatory is already connected to the grid onshore so when power demand is lower than the power output from the SUNBIO hybrid wave energy converter, the excess energy will be stored in the lithium iron phosphate (LFP) batteries onboard or transmitted to the shore. The energy output from the SUNBIO hybrid wave energy converter will also be used to power the various instruments onboard, including the ecological monitoring system of the artificial underwater marine habitat. The potential net biodiversity and ecosystem functioning gain will generate significant socioeconomic value in addition to the energy production, possibly helping mitigate the increasing impact of Invasive Alien Species (IAS).

6 Conclusions

The potential contribution of wave energy is significant. However, several technical challenges are yet to be overcome. Although several wave energy converter designs have been proposed, only a handful have been tested at sea at industrial scale. The results of these trials have been mixed, particularly with respect to the financial viability of such projects due to the strong competition from alternative energy sources, particularly offshore wind energy. However, by exploiting the synergies arising between wave energy converters and offshore wind farms it may be possible to increase the investment potential for such projects. Particularly if they contribute to the restoration of marine habitats and encourage biodiversity. Within the framework of the SUNBIO project, a hybrid wave energy converted, consisting of a wave attenuator, photovoltaic panels and thermoelectric devices will be built and installed at the OBSEA site. The prototype underwater will comprise an underwater hub which acts as an artificial habitat for fishes and other marine life to promote biodiversity as well as generate power. The system will incorporate ecological monitoring sensors that assess the condition of the habitat, whilst providing power to the OBSEA observatory. Excess power will be stored onboard in LFP batteries or transmitted back to the shore. The proposition of the SUNBIO project may offer distinct features which may contribute to increase the implementation of wave energy projects more widely in the future for scientific purposes, for powering offshore facilities such as fishing farms, or for utility-scale production in combination with offshore wind farms.

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