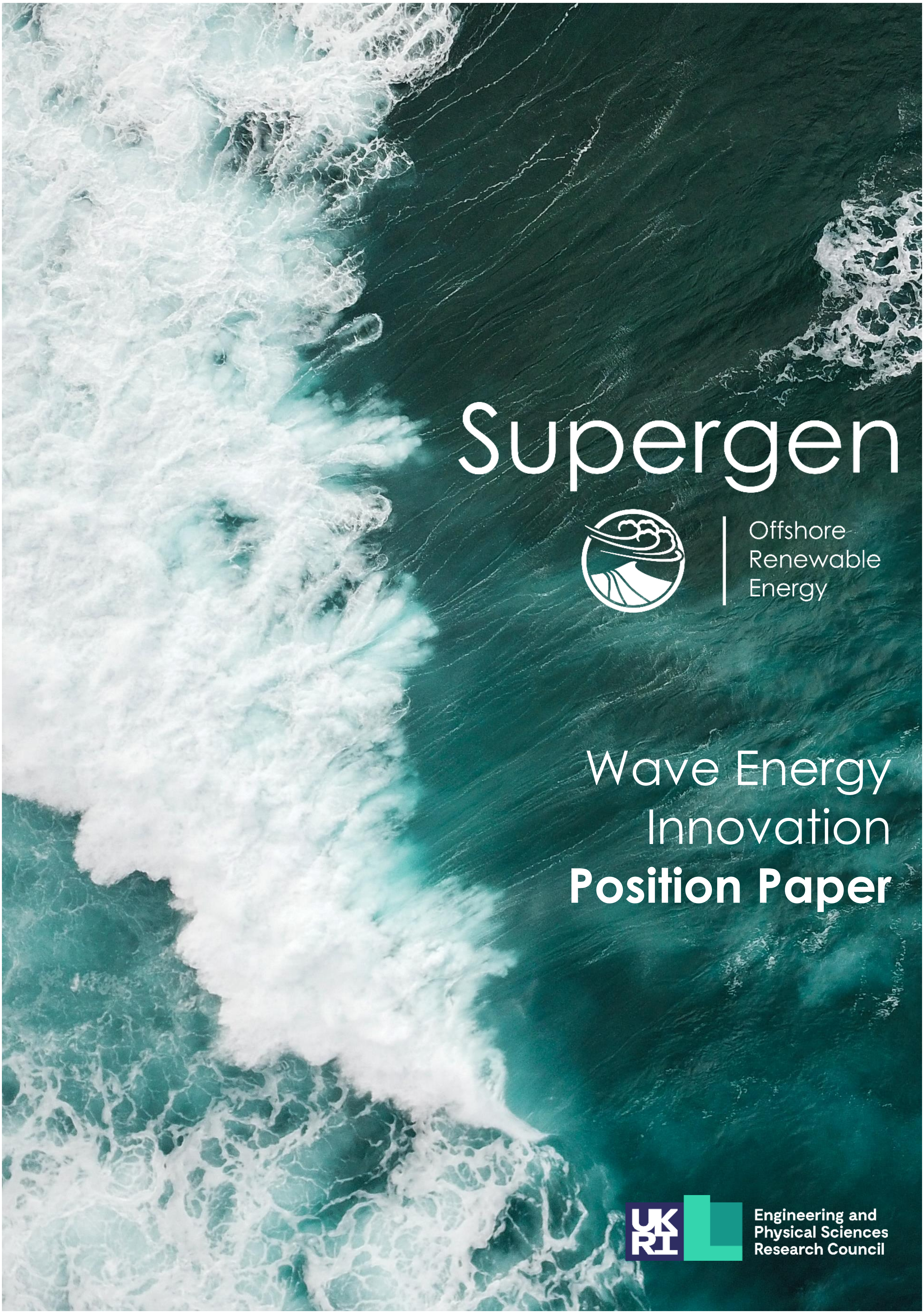

Supergen

Offshore Renewable Energy

Wave Energy Innovation **Position Paper**

Engineering and Physical Sciences Research Council

Supergen Offshore Renewable Energy Hub
Wave Energy Innovation Position Paper

Contents

Acknowledgements

This Innovation Position Paper has been written in collaboration with members of the Supergen Offshore Renewable Energy (ORE) Hub and the wider offshore renewable energy community. The Supergen ORE Hub is a £9 Million Engineering and Physical Sciences Research Council (EPSRC) funded programme which brings together academia, industry, policy makers and the general public to support and accelerate the development of offshore wind, wave and tidal technology for the benefit of society.

The Hub is led by University of Plymouth, and includes Co-Directors from the University of Aberdeen, the University of Edinburgh, the University of Exeter, the University of Hull, the University of Manchester, the University of Oxford, the University of Southampton, the University of Strathclyde, and the University of Warwick.

The Supergen ORE Hub is one of three Supergen Hubs and two Supergen Network+ created by the EPSRC to deliver sustained and coordinated research on sustainable power generation and supply. The Supergen ORE Hub brings together and builds on the work of the former Supergen Wind and Supergen Marine Hubs following consultation with the research community and looks for synergies between offshore wind, wave and tidal technologies as well as connecting stakeholders and inspiring research in each area.

The Supergen ORE Hub would like to thank everyone who attended the Wave Energy workshop held in Plymouth in January 2020, and stakeholders who provided their time to be interviewed.

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List of abbreviations

Abbreviation	Explanation/Meaning
CfD	Contracts for Difference
CO2	Carbon dioxide
EMEC	European Marine Energy Centre
ESME	Energy System Modelling Environment
ETP	Energy Technology Perspectives
FOW	Fixed Offshore Wind
GHG	Green House Gas
GVA	Gross Value Added
GWh	Gigawatt hour
IEA	International Energy Agency
kW/m	Kilowatt meters
LCoE	Levelised Cost of Energy
Mt	Metric Tonnes
MWh	Megawatt hour
O&M	Operations and Maintenance
ORE	Offshore Renewable Energy
OWC	Oscillating Water Column
PCP	Pre-commercial Agreement
PTO	Power take-off
PV	Photovoltaics
RO	Reverse Osmosis
TWh	Terawatt hour
UKERC	United Kingdom Energy Research Centre
WE	Wave Energy
WEC	Wave Energy Converter

List of tables and figures

Executive Summary

This report is intended to show the potential benefit of Wave Energy as a UK industry and a contributor to sustainable development goals and achieving the UK net zero GHG emissions target for 2050. To assess the viability of new forms of renewable energy, the UK Government's clean growth strategy has set out three tests:

- Can we see a clear cost reduction pathway for this technology, so we can deliver low cost solutions?
- Can the UK develop world-leading technology in a sizeable global market?
- Does this deliver maximum carbon emission reduction?

In this report, we show that with targeted action, Wave Energy can meet these tests and provide a significant source of energy and growth for the UK economy. The role of Wave Energy in our future energy system is framed within the UK Government's overall strategy to cut emissions, increase efficiency, and help lower the amount consumers and businesses spend on energy whilst supporting economic growth. Wave Energy delivers five key aims:

Delivering net zero

Wave Energy will be required to meet net zero emissions; exploitable wave resource in the UK has the potential to deliver in-grid electricity of around 40-50 TWh/year, which would contribute approximately 15% of the UK's current electricity demand and valuable grid balancing energy system benefits.

Achieving value for money

Wave Energy is one of the few domestically led technology sectors in the net zero mix that advances our low carbon economy with significant UK content.

Supporting communities

Wave Energy resource maps directly to fragile communities, generating significant impact on community identity, reflecting their local environmental and economic context.

Maintaining energy security

Wave Energy delivers security of supply chain infrastructure with an abundant local energy resource that is well matched to demand.

Advancing the low carbon economy

Wave Energy delivers economic benefit, creating high value jobs and supporting growth in coastal communities.

In this report, we show that the UK has the necessary infrastructure, markets, technology, legislation and regulation in place, and that with key strategic interventions a successful Wave Energy sector can deliver the following major opportunities:

Major opportunities: **Delivering net zero**

- 235 GW of Wave Energy in global energy mix by 2050.
- 22 GW by 2050 in the UK.
- Wave Energy brings benefits through diversification of the UK energy mix.
- Provides system balancing services in combination with other renewable sources.
- Wave Energy and Tidal Energy together have potential to displace at least 4MtCO2 per year of fossil fuel emissions after 2040.

Major opportunities: **Achieving value for money**

- Net cumulative benefit to the UK of £64.4bn by 2050.
- £39.1bn GVA from domestic market.
- £39.9bn GVA from export market.
- 6:1 ratio of GVA benefit to industry support.

Major opportunities: **Supporting communities**

- Jobs and economic growth for fragile coastal communities: 50-60% of the economic benefit in terms of both GVA and jobs is expected to be generated in coastal areas.
- 8,100 new jobs in Wave Energy by 2040.
- A sustainable domestic market and supply chain in the UK.

Major opportunities: **Maintaining energy security**

- Abundant and local renewable energy resource.
- Potential to deliver 15% of the UK's current electricity demand.

Major opportunities: **Advancing the low carbon economy**

- A sustainable domestic market and supply chain in the UK.
- Wave Energy industry with 80% UK content.
- Excellent infrastructure for research and demonstration already established.

To deliver on the potential contribution that Wave Energy can make to the UK net zero targets, economy, jobs and a secure and resilient clean energy future, the following **key recommendations** are made:

Key recommendations: **Delivering net zero**

- ✓ Deliver **evidence-based case** for Wave Energy, its integration in the energy system contribution to net zero 2050.
- ✓ Establish a **policy framework** and revenue support mechanism that recognises Wave Energy and Tidal Energy separately and separate from more established offshore renewable energy technologies, and declines over time.
- ✓ Link time limited revenue support mechanisms to **Commercial Readiness Levels**, as opposed to Technology Readiness Levels, in order to create future domestic and international markets.

Key recommendations: **Achieving value for money**

- ✓ Target research effort to demonstrate **survivability and step change** in Wave Energy technology cost.
- ✓ Adopt **structured innovation** to ensure advances are shared and solutions for common components and design aspects may be appropriately utilised by the Wave Energy sector as a whole.
- ✓ Target research effort to exploit **technology transfer** from other sectors and exploit **synergies** across ORE.
- ✓ Target research effort to support Wave Energy **niche markets**.

Key recommendations: **Supporting communities**

- ✓ **Local solutions** – framed in national policy perspective to create localised opportunity in Wave Energy and grow supply chain.
- ✓ **Incentivise local content** in the development of Wave Energy deployment, particularly in fragile coastal communities
- ✓ Build **supply chain** in synergy with Floating Offshore Wind.
- ✓ Encourage **transition**: introduce Carbon Tax.

Key recommendations: **Maintaining energy security**

- ✓ Establish **value metric** including climate, ecology, social, economic, diversity, resilience benefits.
- ✓ Target **Inter-disciplinary research** to ensure ecological and social factors are integrated into technology design and do not become barriers to development.

Key recommendations: **Advancing the low carbon economy**

- ✓ Establish **UK Centre for Wave Energy**.
- ✓ Enable easy access to Wave Energy **test facilities**.
- ✓ Development of at-sea technology/component **test bed** for WEC stakeholder community use and collaboration on all stages of project life cycle.
- ✓ Promote and facilitate **international collaboration**.

Introduction

Studies indicate that generation from low-carbon sources will need to grow to more than 80% over the next 30 years to limit temperature change to 2°C and even more than this for 1.5°C [15].

The ORE Catapult report [3] estimates that marine energy technologies have the potential to displace coal and natural gas generation on the grid and to reduce at least 4MtCO2 per year after 2040. Therefore, electricity generation using renewable Wave Energy can contribute to reducing greenhouse gas (GHG) emissions and achieving our net zero target by 2050.

Wave Energy also brings benefits through diversification of the UK's energy mix, providing a balanced supply, in combination with other renewables, and transforming economically disadvantaged areas with high value jobs. Exploitable wave resource has the potential to deliver in-grid electricity of 40-50 TWh/year, which would contribute approximately 15% of the UK's current electricity demand [13].

It also provides an attractive option for niche market applications, such as a power supply to offshore installations and remote and island communities.

This Paper is intended to show the potential benefit of Wave Energy as an industry for the UK, as a contributor to sustainable energy generation and to achieving our net zero GHG emissions target for 2050. It summarises the views of the Wave Energy Sector following consultation through scoping workshops and a series of structured interviews, and should be read alongside the Wave Energy Road Map included at *Annex E*.

The role of Wave Energy in our future energy system is framed within the Government's overall strategy to cut emissions, increase efficiency and help lower the amount consumers and businesses spend on energy, while supporting economic growth.

Delivering net zero	Achieving value for money	Supporting communities	Maintaining energy security	Advancing the low carbon economy
• Deliver in-grid electricity of 40-50 TWh/year • Contribute approximately 15% of the UK's current electricity demand and valuable grid balancing energy system benefits • 22 GW by 2050 in the UK [18]	• One of the few domestically-led technologies in the net zero mix which advances our low carbon economy with significant UK content. • Benefit to industry support creates GVA ratio of 6:1 [18]	• Wave Energy resource maps directly to fragile communities • Impact on community identity, reflecting local environmental and economic context. • 8,100 new jobs in Wave Energy by 2040 [3]	• Security of supply chain infrastructure • Abundant local energy resource that is well matched to demand.	• Economic benefit, high value jobs and growth to support coastal communities. • Wave Energy industry with 80% UK content [18]

1. Delivering net zero

What should be the position of Wave Energy in the 2050 energy system?

OPPORTUNITY

- 235 GW Wave Energy in global energy mix by 2050 [18].
- 22 GW by 2050 in the UK [18].
- Wave Energy brings benefits through diversification of the UK's energy mix.
- Provides system balancing services in combination with other renewables.
- Wave Energy and Tidal Energy together have potential to displace at least 4MtCO2 per year of fossil fuel emissions after 2040 [3].

POSITION

The UK has an excellent wave resource, estimated at 35% of Europe's, and 2–3% of the global wave resource [1, 16]. The total resource is estimated to be around 230 TWh/year with the majority found in the deeper offshore parts of the UK's exclusive economic zone [2]. This can translate to a practical wave resource of up to 70 TWh/year for offshore and 5.7 TWh/year for nearshore regions and an exploitable wave resource of between 40 and 50 TWh/year [2], contributing approximately 15% of 2018 electricity generation in the UK (333 TWh). The University of Edinburgh's Policy and Innovation Group and Energy Systems Catapult in 2020 [18] estimate Wave Energy capacity of 22 GW in the UK and 236 GW globally by 2050. Furthermore, the ORE Catapult in 2018 [3] estimated that Marine Energy has the potential to displace at least 4 MtCO2 per year of fossil fuel emissions after 2040.

"We should see the UK's offshore renewable energy resources as sovereign wealth. The UK has some of the best wave resource in Europe, so not exploiting this wealth by developing and deploying marine renewables to move us towards net zero carbon is a wasted opportunity"

- Quote from Wave Energy Workshop participant

Wave Energy also has a valuable role in providing diversity and resilience to the UK's energy mix, complementing offshore wind and solar PV. Advancing all offshore renewables should be seen as an essential transition risk mitigation strategy. There is intrinsic value in diversity when relying on renewable energy sources for a significant proportion of energy supply and this will provide resilience and energy security for the UK as we approach much larger renewable energy penetration towards 2050. Wave Energy provides energy balancing services in combination with other renewables and increases their value and utilisation by reducing the intermittent need for alternative sources of energy [4, 5]. The electricity grid would benefit from energy profiles rising at different times of the day and seasonal variability of different renewable sources to help reduce the need for both diesel-based and energy storage backup power. For example, under the same environmental conditions, the peaks of wave climate trail the wind peaks by several hours [6]. In consequence, the combined exploitation of wave and wind technologies will smoothen power output and thus result in a reduction of sudden disconnections from the grid. Wave and solar PV technologies are sensitive to varying seasons [7]. The variation in wave power density can change from 10 kW/m in summer to 100 kW/m in winter, whereas solar PV resource is higher in summer and lower in winter, thus, wave and solar PV power generation are complementary. The contribution of diversity and resilience to energy systems is missed in most models and there is a need for these additional value elements to be included into energy system modelling. The current status of Wave Energy in the UK is summarised in the briefing paper prepared for the Wave Energy Road Mapping Workshop in January 2020, included in *Annex A*. The Road Map for delivering the potential contribution of Wave Energy is included at *Annex E*.

The high cost of Wave Energy is still a key issue for the sector. Compared with the levelised cost of energy (LCoE) of approximately £100/MWh for offshore wind estimated by International Energy Agency (IEA) in 2019 [8], the LCoE from Wave Energy remains considerably higher, and is estimated at around £350/MWh by ORE Catapult in 2018 [3]. The commercial development pathway for Wave Energy may be expected to follow that of offshore wind, which is now cheaper than new gas and nuclear electricity generation. However, it should be remembered that offshore wind commercialisation and recent cost reduction builds on 30 years of research and demonstration, a successful onshore wind industry, and was supported by policy and financial support structures, feed-in tariffs and contracts for difference (CfD). Although potential synergy between offshore wind, wave and tidal technologies may exist, the different technologies should not compete directly or be supported with the same financial mechanisms as they are at very different stages of commercial development and, to be effective, such support needs to differentiate between innovation stages. Innovative financial mechanism have been proposed to address these different stages, such as by Scottish Renewables (2019) [19], who set out a proposed route to market for marine energy (including Wave Energy), to address the policy and financial barriers, see Figure 1. Further details can be found in *Annex D*.

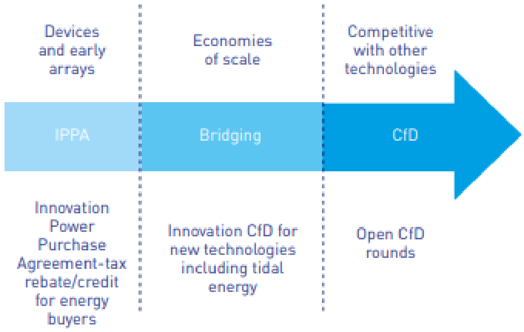


Figure 1. Summary diagram of cost competitive solutions

The key goal of developing Wave Energy technology is to realise its value at grid scale, contributing to carbon reduction targets and providing diversity to the energy mix. However, a critical barrier is its complexity and the large number of different concepts being investigated, although this can also be seen as an advantage in that there are many different applications, locations and metocean conditions that Wave Energy solutions can be designed for. It was felt by Workshop participants that the multiplicity of technology concepts can be confusing and a barrier to investors. More than a thousand Wave Energy Converter (WEC) ideas have been patented, but at the present time only a few technologies have reached deployment. The sector tends to be fragmented, is dominated by start-up companies and is highly dependent on government policy and support.

WEC technologies can be classified by: operating principle; orientation to the wave front; distance to shore. The commonly used definitions can be found in Falcão's paper [20], EMEC [21] and Aquaret websites [22]. Based on operating principle, WECs are classified, as shown in Figure 2:

- **Oscillating Body**: converts wave motion into device oscillations to generate electricity. Based on the dominant oscillating mode, three main sub-categories can be further given: (1) heaving body, which is driven by waves into vertical motion; (2) pitching body, which rotates around a hinged axis parallel to the wave crests; (3) articulated body, which is oriented parallel to the wave direction and produces relative rotation between adjacent segments.

- **Oscillating Water Column (OWC)**: uses trapped air above a water column to drive turbines for electricity generation. Fixed OWCs can be sited onshore or embedded into breakwaters, floating OWCs can be installed offshore in deeper water.
- **Overtopping**: uses reservoirs to generate a head flow and subsequently drive turbines for electricity generation. Fixed devices can be sited onshore or integrated into breakwaters, floating overtopping devices can be installed offshore.

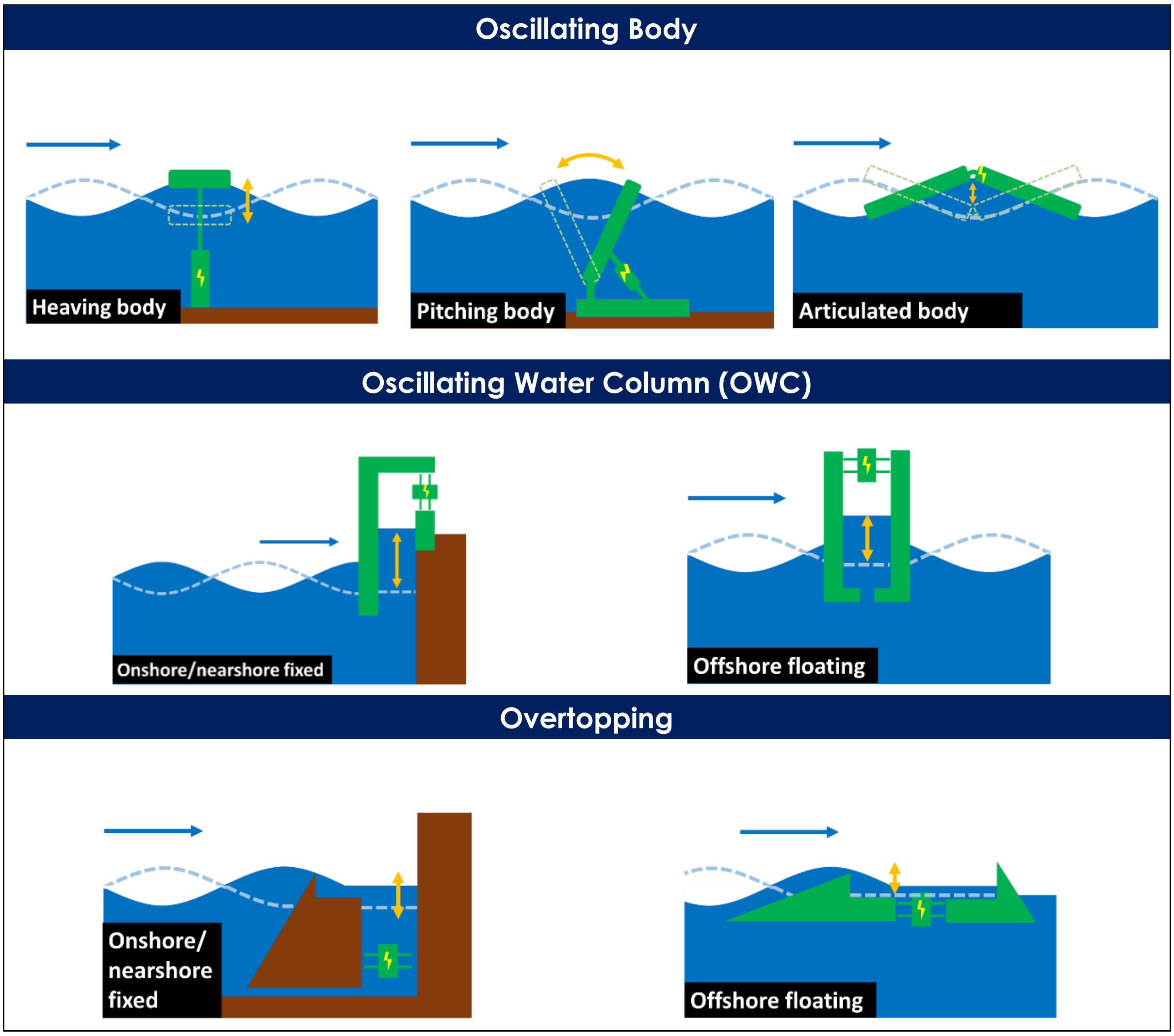


Figure 2. Categories of WEC technologies by operating principles

Based on proximity to coast, we can classify WECs as:

- **Onshore**
- **Nearshore**
- **Offshore**

Based on size and orientation to the wave front, we can classify WECs as:

- **Point absorber**: its dimension is much smaller than the incoming wave length.
- **Attenuator**: is oriented parallel to the wave direction, with its length is comparable to or even larger than one wave length.
- **Terminator**: is aligned perpendicular to the wave direction.

Figure 3 illustrates the WEC categorization based on size and orientation, with sub-categories indicated according to the working principle. This diagram illustrates the complexity of WEC classification and terminology. It is also apparent from Figure 3 that the performance of a point absorber is generally independent of wave direction, whereas that of an attenuator or a terminator is highly dependent on the wave direction.

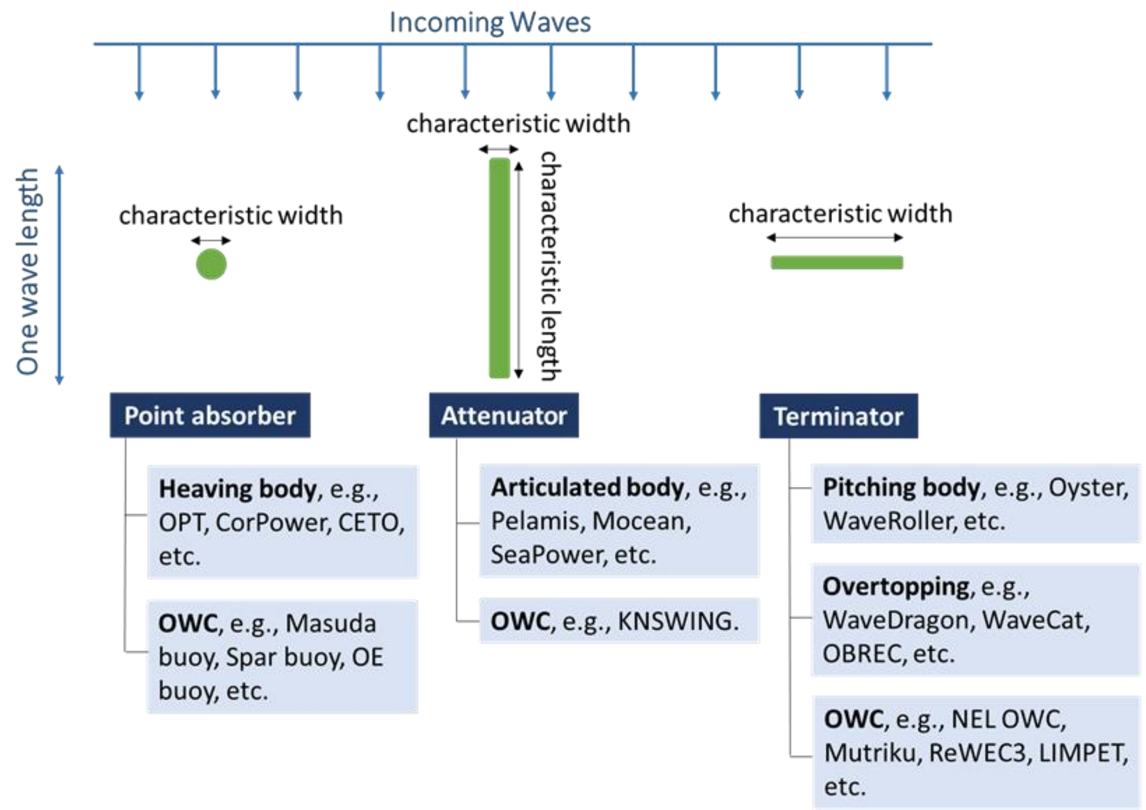


Figure 3. Categories of WEC technologies based on their orientation and the sub-categories with respect to working principle.

Wave power for utility or grid scale applications has been the main driver for its development, yet the grid scale Wave Energy market still faces a number of challenges, and long-term at-sea field experience is needed now to secure confidence for the sector. In order to learn valuable lessons, help de-risk the technology and attract further investment, Niche applications of Wave Energy are attracting increasing attention. It is believed by some Workshop participants that the rapid growth of niche markets will enable the value of Wave Energy and its integration within the Energy System to be demonstrated. Whereas the cost of energy production is the over-riding consideration for the grid-scale market, by contrast, niche applications will have local evaluation criteria, and the diversity of WEC systems can be an advantage for optimisation to different applications.

"Part of the trajectory for Wave Energy is through the small-scale deployment of niche applications, but we have to be technology agnostic and look for the markets."

- Quote from Wave Energy stakeholder interview

A comprehensive review of Wave Energy niche applications is given in *Annex B*, and summarised in Table 1.

Table 1. Summary of Wave Energy Niche applications

WEC-Integrated Breakwaters

Embed WEC devices into breakwaters to save cost and supply green power to the facilities in the vicinity

WEC for Coastal Protection

Reduce nearshore wave height to protect shorelines from coastal erosion and flooding

WEC-Powered Desalination

Convert sea water to drinking water

WEC-Integrated Microgird on Island

Build wave microgrid on islands for power supply

WEC-Integrated Aquaculture

Offer power and shelter for offshore aquaculture farms

WEC for Offshore Oil & Gas Applications

Provide power to oil & gas platforms or their subsea facilities

WEC for Military and Surveillance

Provide electricity to navy bases or provide offshore communication and stand-alone power stations for unmanned subsea facilities for military use

Combined Wind-Wave/Solar-Wave Platforms

Use wave technology to complement wind and solar energy for higher power density and smoother power output

RECOMMENDED ACTIONS:
Delivering net zero

- Deliver evidence-based case for Wave Energy, its integration into the energy system and contribution to net zero 2050.
- Establish a policy framework and revenue support mechanism that declines over time, that both recognises Wave Energy and Tidal Energy separately and separates them from more established offshore renewable energy technologies.
- Link time limited revenue support mechanisms to Commercial Readiness Levels, as opposed to Technology Readiness Levels, in order to create future domestic and international markets.

2. Achieving value for money

What are the remaining technical challenges?

OPPORTUNITY

- Net cumulative benefit in GVA to the UK of £64.6bn by 2050.
- £39.1bn GVA from domestic market.
- £39.9bn GVA from export market.
- Representing a 6:1 ratio of GVA benefit to industry support.

POSITION

The Policy and Innovation Group at the University of Edinburgh in collaboration with Energy Systems Catapult [18] present the potential long-term economic benefits in terms of GVA of the wave and tidal sectors 2030 – 2050. A highly ambitious scenario is explored in which a step change in innovation and technology development of the wave and tidal industries enables these technologies to reach cost parity with other forms of generation by 2030. Achieving this would result in significant benefits to the UK in the subsequent 20-year period between 2030 and 2050. The deployment modelling assumes that the UK 'gets everything right' by enacting policy support mechanisms now, to enable wave (and tidal) generation to reach cost parity with other sources of generation by 2030 (LCoE of £90/MWh).

The deployment figures used in this study are wholly informed by modelling. This study employs the ESME (Energy System Modelling Environment) model to establish UK capacity by 2050. ESME is a whole-systems model that deploys technologies for all parts of the energy system to produce a least-cost system capable of fulfilling demand subject to carbon targets and techno-economic assumptions. Outputs demonstrate how significant technology breakthroughs and the proper support to the wave industry through to 2030 can realise a large potential prize to 2050. ESME was formerly run by the Energy Technologies Institute (ETI) but is now hosted by the Energy Systems Catapult (ESC). As with the ORE Catapult study, global deployment capacity is informed by the IEA's ETP-TIMES model.

The outputs of this ESME (UK) and ETP-TIMES (global) modelling under this scenario is a 2050 capacity of 22 GW in the UK and 236 GW globally. Assuming a global lead, UK content in domestic projects is assumed at 80% and global projects at 15%, falling to 5% by 2050. The net benefit in GVA for this scenario is £64.6bn overall, of which £39.1bn comes from domestic markets and £39.9bn GVA from export, offset by £14.4bn in industry support representing a 6:1 ratio of GVA benefit to industry support. When discounted at the Treasury Green Book rate of 3.5%, this net benefit is equivalent to £39.7bn. Almost half of this GVA comes from the UK supply chain exporting to projects overseas within the timeframe. These results are shown in Figure 4 and summarised in Table 2 [18].

"If you are going to create a market you need to have revenue support to enable a technology to move through Commercial Readiness Levels. Relying on capital grants just does not work."

- Quote from Wave Energy stakeholder interview

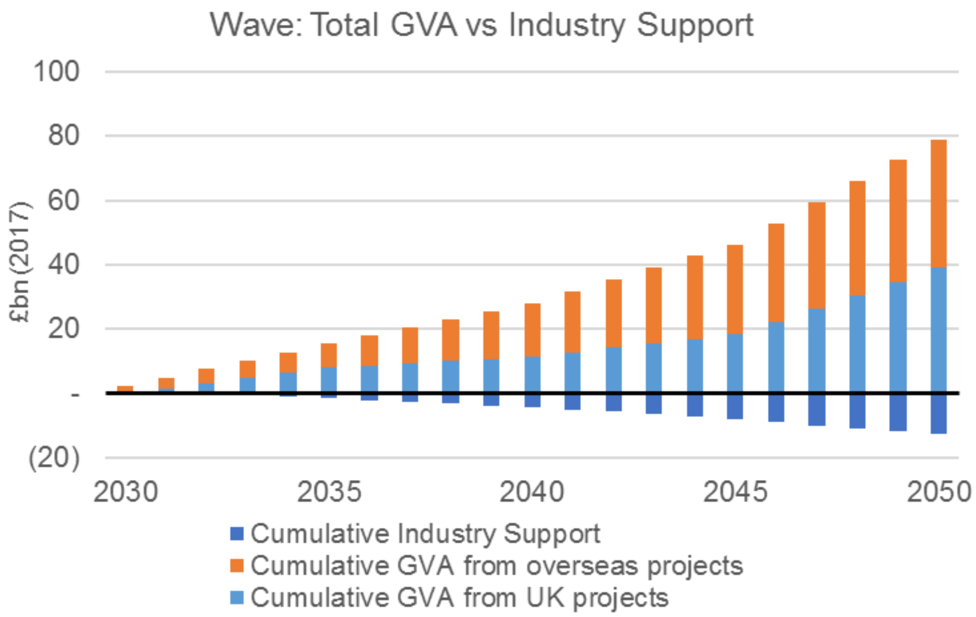


Figure 4. Cumulative GVA from wave energy and corresponding Industry Support 2030–2050 [18]

Table 2. Potential Economic Value of Wave Energy 2030–2050 [18]

Key results from Study 2	2030–2050
UK Wave Energy Installed Capacity by 2050	22 GW
Global Wave Energy Installed Capacity by 2050	236 GW
GVA from domestic market for wave energy	£39.1bn
GVA from export market for wave energy	£39.9bn
Gross GVA to UK from global wave energy deployments	£79bn
Total revenue support (subsidy) to wave energy to 2050	£14.4bn
Net GVA (less subsidy) from wave energy	**£64.6bn**
Ratio of economic benefit to revenue support	**6:1**

Modern research and development of Wave Energy in the UK was pioneered from the mid-1970s in response to the oil crisis, and has been supported intermittently since then, with a lack of support in the 1980s and more recently. The world's first commercial shoreline fixed OWC, LIMPET (500 kW), was constructed in 1999 and connected to the UK's national grid in 2001, continuously operating for a decade before it was decommissioned in 2012. The world's first offshore floating WEC prototype, Pelamis (750 kW), was deployed and connected to the UK grid in 2004. In 2009, the first wave array (2.25 MW) was tested in Portugal based on three Pelamis prototypes. Two second-generation Pelamis devices were tested at EMEC from 2010, accumulating over 15,000 hours of operation before going into administration in 2014. The world's first near shore hinged flap device, Oyster (315 kW) developed by Aquamarine Power was installed at EMEC in 2009. The second-generation Oyster 800 kW was tested at EMEC in 2012 and accumulated 20,000 hours of operation by 2015 when the test programme ended and the company went into administration. Nevertheless, these major WEC programmes generated significant experience and knowledge that has been assimilated into the community and informs ongoing research and development in Wave

Energy. For Pelamis and Oyster, there was a mismatch between financial and technical drivers that forced developers to embark on costly large-scale demonstrations too early in their development. Clearly, the development of Wave Energy is highly dependent on targeted government policy and support [17].

To attract investors and realise the potential utility scale contribution to the 2050 energy mix, Wave Energy technologies need to be able to demonstrate their scalability. This is achieved by scaling up the power capacity either by: (1) increasing the scale of a single WEC device; or (2) integrating a number of WECs in a wave power plant. Lessons learnt from review and analysis of numerical, laboratory and field test data of WECs with different working principles [9, 11, 12] to assess scalability and identify remaining challenges are detailed in *Annex C*.

The power take-off (PTO) of a WEC is an important component affecting its performance. Referring to the database in *Annex C*, there are six types of PTO utilised within the WEC data listed, including from numerical, laboratory field studies: hydraulic, hydro, pneumatic, linear generator, mechanical damping and numerical damping. Whereas in numerical models it is relatively easy to tune the numerical PTO damping to achieve optimal performance, the physical operation of a typical PTO in realistic conditions can significantly affect the performance of a WEC. This means a WEC with high hydrodynamic performance may achieve reduced power capture by having low PTO performance. Therefore, it is important to understand carefully the actual power capture of a WEC, which may depend on a large number of parameters such as: device dimension, wave regime and PTO performance.

Table C6 in *Annex C* summarises ten leading Wave Energy technologies that have achieved or are on the verge of grid-connection in chronological order to demonstrate the significant steps in their development and current status. Clearly, some operations have been closed, whilst some have been successfully commercialised in recent years or are developing into larger scale units and arrays. In the past, mismatches between financial and technical drivers have hampered progress in the sector, and costs remain high. Programmes that are still active are developing into grid applications at a steady pace, allowing for changes of direction and incremental improvements. Key technological challenges remaining are summarised in Table 3.

It was proposed by Workshop participants that a route to consolidating learning from Wave Energy experience and to coordinating development of the sector is to broaden the structured innovation process as trialed by Wave Energy Scotland (WES) [10]. This process aims to secure advances and share them between developers, ensuring that solutions for common components and design aspects may be appropriately utilised by the Wave Energy sector as a whole. This model encourages consortia design teams that subcontract to experts where necessary and implement a systems engineering approach, to avoid the technology developer doing it all and reinventing or duplicating existing technology.

Although some niche applications are emerging in specific markets, for example replacing diesel generation offshore, the economic model has not been proven yet in utility scale applications. Some utility investors would like to see Wave Energy developers considering scale deployments at an early stage in their designs, whereas, others call for devices to be proven at sea and to generate investor confidence by demonstrating survivability first in an important milestone for the industry. The industry then needs to have confidence in Wave Energy reliability at reasonable cost, and this means being able to survive the large waves while being able to generate power in the small waves. Survivability is an essential hurdle for Wave Energy and may need radical or alternative solutions, either in the operating principle of a WEC or in specific materials or components. Unlike Offshore oil and gas and OW, where progress could be made incrementally from on shore to offshore, proof of Wave Energy survivability needs a different, targeted approach.

Addressing the storm wave survivability challenge and proving technology at sea for lengthy periods at reasonable cost would unlock investor confidence in the sector. It would enable greater utilization of the seabed by making possible Wave Energy developments to access wave resource in areas of high wind that are unsuitable for FOW.

A managed programme of research could be coupled with deployment competition to award a Wave Energy prize to promising technology achieving field deployment over a set period. Innovation to achieve survivability and reasonable cost may involve modular devices, modular construction, new materials, novel fabrication and installation processes.

Niche applications may be an effective route to building experience in Wave Energy and have the advantage of an economic model that works [14]. These niche applications may help the development of Wave Energy technology as a stepping-stone and essential developmental step to utility scale. Synergy between offshore wind, wave and tidal technologies exist and advances can be shared between sectors. Another advantage of partnering with other aligned technologies, such as offshore wind, offshore oil and gas during transition, and coastal engineering, might be that companies investing in these aligned industries will start to invest in developing larger scale Wave Energy.

"Niche applications will play a role, but the Wave Energy sector needs to consider at an early design stage how they are going to get to large scale arrays for utility scale. The technical aspects of how to get to utility scale are currently underestimated."

- Quote from Wave Energy stakeholder interview

Table 3. Technological challenges in Wave Energy

Multiplicity of the technology concepts
The large number of different technology concepts being explored in Wave Energy adds to the complexity of the sector and it was felt by Workshop participants that greater design consensus is needed to encourage investment. However, it should be noted that the diversity of Wave Energy concepts is related to the variety of wave characteristics and site conditions they can be deployed in. For example, under nearshore waves, a terminator type WEC can be more suitable; fixed OWC and overtopping devices integrated with breakwaters are recommended for shoreline locations; whereas offshore, floating WECs are needed. Focusing efforts into a small number of generic technologies would help to gain consensus and simplify the sector for potential investors. A possible approach to this is structured innovation promoted by Wave Energy Scotland (WES), which is designed to generate technological convergence on sub-components (design, generator, control strategies and material) and other generic elements.
Reliability and survivability
It is important for WECs to survive extreme waves during hurricanes and storms. Most of the reliability and survivability studies undertaken to date have been based on computer modelling or laboratory scale tests, and long-term at-sea field experience is needed now to secure confidence the sector. Excellent progress has been made in numerical modelling for WEC concepts and it is important to build on this to provide high precision analyses especially under extreme wave conditions. Furthermore, tailored control and monitoring strategies can be alternatives to increasing reliability and survivability.
Installation, operation and maintenance
The installation, operation and maintenance of any facility in the open seas is always more challenging than for land-based structures. Unlike 'static' oil & gas platforms and fixed offshore wind turbines, offshore WECs are designed to respond actively to ocean waves in operating conditions, while surviving extreme sea states. Significant progress has been made, and collaboration with the offshore energy industry, including offshore wind, and oil & gas, will enable the Wave Energy sector to learn from their experience associated with operating and maintaining facilities offshore.

RECOMMENDED ACTIONS:
Achieving value for money

- Target research effort to demonstrate survivability and step change in Wave Energy technology cost.
- Adopt structured innovation to ensure advances are shared and solutions for common components and design aspects may be appropriately utilised by the Wave Energy sector as a whole.
- Target research effort to exploit technology transfer from other sectors and exploit synergies across ORE.
- Target research effort to support Wave Energy niche markets.

3. Supporting communities

How do we attract investors into Wave Energy?

OPPORTUNITY

- Jobs and economic growth for fragile coastal communities: 50-60% of the economic benefit in terms of both GVA and jobs is expected to be generated in coastal areas.
- 8,100 new jobs in Wave Energy by 2040.
- A sustainable domestic market and supply chain in the UK.

POSITION

Wave Energy resource maps directly to fragile coastal communities, and much of the economic benefit is expected to be generated in coastal areas needing economic regeneration, thus bringing further value for the UK. This is especially the case where there is heavy co-dependency on tourism, such as areas of Scotland, Indonesia and China, where often offshore wind cannot be deployed, there may be the need to replace diesel imports and there is resistance to industrialisation in pristine environments. Development of wave farms and of the supply chain supporting them has the potential to generate significant impact on community identity, reflecting the local environmental and economic context. Energy system modelling predictions show that if the right policy conditions are met and technological advances are made, a GVA ratio of 6:1 benefit to industry support is achievable.

Since the early 2000's, the Wave Energy innovation policy landscape within the UK has been particularly complex, with various policies being managed by numerous different funding agencies across three levels of government, i.e. Scottish Government, the UK Government and the EU. There have also been rapid changes within policy, with a variety of new schemes being developed, each with their own eligibility criteria and objectives. The main changes within the policy landscape however has been the shift from commercially focused, full-scale device RD&D programmes in the mid-2000s and early 2010s, to innovation programmes supporting early-stage development through to largescale prototype demonstration, i.e. Wave Energy Scotland. A review of finance policy is given in *Annex D*.

> *"This resource is also mainly located in the west of the UK, away from the North Sea, where there is a genuine need for economic regeneration within communities which the wave and tidal sectors could support"*
>
> *- Quote from Wave Energy stakeholder interview*

Recovering investor confidence in Wave Energy and encouraging investors back to the sector is a critical need for Wave Energy, however different actors have different priorities. Utility investors want to see Wave Energy developers thinking at commercial scale and tackling electrical connection challenges at scale from the outset, whereas developers want to prove individual technology first.

The LCoE cost of offshore wind has reduced dramatically during the last two years. Whereas prices were expected at approximately £100 per MWh in the Round 3 CfD auction, they emerged at £57/MWh in 2018 and less than £40/MWh since then. These low prices make it impossible for Wave Energy to compete in a CfD auction process, and even with the proposed 2020 changes to the structure, in which fixed offshore wind would be placed in a separate pot allowing other marine renewables to complete with floating offshore wind, this is unlikely to improve as floating offshore wind is likely to attract investment far more quickly than Wave Energy.

This is because although the new floating technology is high cost and faces many of the same technical challenges as Wave Energy, the upper part of the technology is familiar and understood, and the investment considered far less risky than unfamiliar Wave Energy technology and the need to develop new floating structures for offshore wind turbines is not seen as a major barrier to investment.

Other innovation funding avenues are needed for developers of Wave Energy technology, such as innovation power purchase agreements (IPPAs) for devices and early stage arrays linked to local economic strategies.

Rather than a focus on cost through LCoE measures, the value metric of renewables to society and the climate should be encouraged. This can be derived from study of supply chain and natural capital benefits to the region, consumer and to society. There is also a close synergy with offshore oil and gas expertise, knowledge and infrastructures. Wave Energy can provide an excellent opportunity for redeployment of workforce and infrastructure from offshore oil and gas and can provide an attractive route to transition away from fossil fuel business.

RECOMMENDED ACTIONS:
Supporting communities

- Generate local solutions, framed in national policy perspective, to create localised opportunities in Wave Energy and incentivise growth in the supply chain.
- Incentivise local content in the development of Wave Energy deployment, particularly in fragile coastal communities
- Build supply chain in synergy with Floating Offshore Wind.
- Encourage transition: introduction of a Carbon Tax.

4. Maintaining energy security

What are the non-technical barriers and enablers for Wave Energy?

OPPORTUNITY

- Abundant and local renewable energy resource.
- Potential to deliver 15% of the UK's current electricity demand.

POSITION

In the 2012 Technology Innovation Needs Assessment commissioned by BEIS [13], the UK's large natural resource of energy from waves and tidal streams and the potential to deliver over 75 TWh/y, making up 10% of the UK's forecast electricity needs in 2050, was noted. The ORE Catapult 2018 review reported that the UK has 137 MW of Wave Energy in operation or under various stages of development including grid connected demonstration zones at the European Marine Energy Centre (EMEC), Wavehub, Pembrokeshire and West Anglesey [3]. It is estimated that Wave Energy has the potential to deliver 15% of the UK's current electricity demand.

Transformation of the energy system and integration of new renewable energy sources is complex. A new value metric should be established for renewable energy in terms of social, economic and ecological benefits and not just in LCoE. The value of diversity and resilience should be measured and the contribution to grid balancing of a combination of renewable resources with complementary phasing. The diverse mix of technologies in Wave Energy are difficult for consenting authorities to deal with. Interaction with navigation and shipping needs to be considered in project planning, but in the experience of Wave Energy and offshore wind early engagement with stakeholders is vital and liaison and mitigation processes are well established. Non-technological challenges to Wave Energy sector development include: barriers related to policy and finance; ecological and social environment; wave resources measurement and supply chain. Non-technological challenges to Wave Energy sector development are given in Table 4.

"We should be the world leader in wave and tidal sector as we have the natural resources to exploit. This resource is also mainly located in the west of the UK, away from the North Sea, where there is a genuine need for economic regeneration within communities which the wave and tidal sectors could support."

- Quote from Wave Energy Workshop participant

Table 4. Non-technological challenges in Wave Energy

Policy and financial support
Policy and financial support was highlighted in the workshops as a key enabler for the development of Wave Energy, and has been intermittent since the Wave Energy programme was launched in the 1970s. This has led to Wave Energy projects moving to large scale too quickly, locking in designs before they were ready and leading to failure. There is a lack of consolidation of wave technologies in contrast to the mature wind and solar renewables and although the different concepts mean that Wave Energy solutions can be found for a wide range of applications, locations and environmental conditions, targeted policy and financial support is difficult. It is therefore critical to create policy to enable the long-term ambitions for Wave Energy's contribution to the 2050 energy mix to be realised. A suggested mechanism is to apply performance measures and stage evaluations, remembering that in order to develop successful technologies there will be failures and failures are simply part of the learning process. This would substantially facilitate the innovation in technology development, reduce the risks of losing investments and as a result boost confidence and further investment in the Wave Energy sector.
Ecological and social environment
Experience from large-scale Wave Energy deployments is needed to advance the understanding of WEC effects on marine ecology and coastal socioeconomics. In addition to interaction with the marine ecosystem, public acceptance of Wave Energy developments nearshore needs consideration as they can affect the visual seascape and compete for space with other sea-based activities, such as fishing, tourism and leisure. Research carried out at EMEC and Wavehub has demonstrated successful outcomes for lobster stocking [23], little effect on the displacement of animals apart from that associated with increased boat traffic [24], very little effect on ambient noise levels [25, 26], and very little effect on physical processes and on biomass [27] in areas where WECs are deployed.
Characterisation of metocean conditions
Accurate information on metocean conditions has a significant impact on selecting project sites, predicting power production and designing appropriate WECs to withstand wave loads during the project lifetime. However, uncertainties remain in the estimation and understanding of actual Wave Energy resource. Innovations needed in wave resource characterisation include: (1) the development of new sensors that can offer more accurate real data and survive extreme waves; (2) deployment of more data buoys or sensors to generate increased volume of measurement data; (3) improved wave modelling and forecasting capabilities and (4) promotion of the development and collaboration of metocean characterisation at global scale, e.g. using satellite data.
Supply chain
A strong supply chain for WEC devices and their subsystems will enable the UK's wave Energy sector to grow, prevent duplication of effort and encourage knowledge sharing. The UK has good capacity and capability in marine operations, ship building, Health and Safety, control systems, electrical infrastructure, foundations and mooring systems, thanks to the mature oil and gas and fixed offshore wind sectors. However, the requirements are different in these sectors; for example, new solutions will be needed in floating and moored technologies for Wave Energy, and it is therefore important to develop cost effective, tailored supply chains for the sector.

RECOMMENDED ACTIONS:
Maintaining energy security

- Establish value metrics including climate, ecology, social, economic, diversity, resilience benefits.
- Inter-disciplinary research to ensure ecological and social factors are integrated into technology design and do not become barriers to development.

5. Advancing the low carbon economy

Do we have the necessary skills, capability, facilities and supply chain?

OPPORTUNITY

- A sustainable domestic market and supply chain in the UK.
- Wave Energy industry with 80% UK content.
- Excellent infrastructure for research and demonstration already established.

POSITION

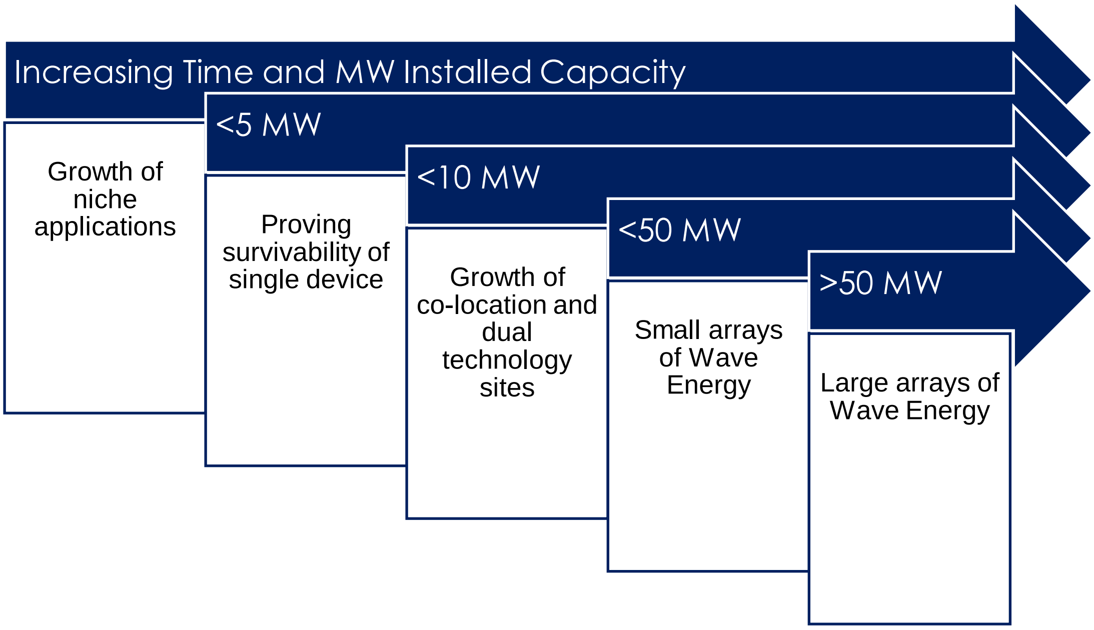
Despite not being sufficient to mobilise investment and accelerate development of Wave Energy, partly as a result of the stop start nature of support, the Wave Energy community in the UK is strong and has achieved a considerable amount. However, with continued lack of funding and market incentive, the research landscape is beginning to change, and researchers are moving attention towards offshore wind. There is a danger that we will lose our leading position in Wave Energy R&D. We have an opportunity to lead in Wave Energy technology development and potentially to secure substantially greater UK content in Wave Energy than is achievable for offshore wind. Although leading the world in offshore wind installed capacity, the UK misses out on much of the economic benefit because most fixed wind turbines manufacturing is imported. Currently, UK content in offshore wind projects is approximately 50% and the Sector Deal aims to increase this to 60% by 2030. In contrast, it is projected that the wave industry could secure approximately 80% UK content in the domestic market and Wave Energy Scotland projects have secured 71% on average to date. However, to achieve the potential for the industry, we need to invest properly. Wave Energy is different from offshore wind and cannot progress incrementally from small scale domestic solutions, rather it needs to be led as a high-level initiative with Government support. As of yet, the Wave Energy sector has not secured the sustained and high level of investment needed to succeed.

The UK has established excellent facilities for all scales of development testing, and UK facilities are in demand from national and international research groups and developers. Large scale laboratory facilities designed for marine energy include the COAST Laboratory (University of Plymouth) and FloWave (University of Edinburgh) and are used for proof of concept and medium scale testing of Wave Energy concepts and arrays under controlled conditions. At-sea nursery test sites, such as Fabtest (University of Exeter), are used to test installation and deployment at approximately half-scale prototype, and grid connected at sea demonstration sites, such as the Pembroke Demonstration Zone, EMEC, Wavehub, provide demonstration at full scale and with electricity generated to the grid.

“We are great project developers in the UK, but no one has recognised that we need to be technology developers within the UK to ensure we don’t miss the benefits to the UK economy generated by manufacturing, IP and export. We don’t want to miss the opportunity as we did with the offshore wind sector"

- Quote from Wave Energy stakeholder interview

These facilities have enabled excellent learning experience and substantial progress in understanding of Wave Energy conversion, Wave Energy concepts developed and understanding of WEC hydrodynamics. In addition to these physical facilities, significant advances have been made over the last 20 years in the development of numerical modelling tools for Wave Energy analysis and a good level of confidence has been achieved in numerical tools and their ability to predict performance. Investment in research has generated a strong base of skilled expertise in Wave Energy workforce, researchers and academics, and a leading position in Wave Energy with good interaction and collaboration between academia and industry facilitated by networks supported by EPSRC Supergen ORE and ORE Catapult.



The global potential for Wave Energy is clearly recognised, and many countries have active and ambitious programmes for Wave Energy development. The UK, as an early sector leader, has accumulated most experience from the deployment of various WEC prototypes, and with strategic investment could retain this advantage in what is set to become an important global sector for our energy future

RECOMMENDED ACTIONS: Advancing the low carbon economy

- Establish a UK Centre for Wave Energy.
- Enable easy access to Wave Energy test facilities.
- Development of at-sea technology/component test bed for WEC stakeholder community use and collaboration on all stages of project life cycle.
- Promote and facilitate international collaboration.

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Annex A - Wave Energy in the UK: Status Review

This report is intended to give a picture of the current landscape for Wave Energy. It follows a scoping workshop hosted by EPSRC on 20th August 2019 and forms the background briefing to inform attendees of a Wave Energy Road Mapping Workshop held by the Supergen ORE Hub in January 2020.

Electricity generation using renewable wave energy can make a significant contribution to reducing greenhouse gas emissions and achieving our net zero carbon target. Wave energy also brings benefits through diversification of the UK's energy mix, providing a balanced supply, in combination with other renewables, and transforming economically disadvantaged areas with high value jobs. Exploitable wave resource has the potential to deliver in-grid electricity of 40-50 TWh/year, which would contribute approximately 15% of the UK's current electricity demand. It also provides an attractive option for niche market applications, such as a power supply to offshore installations and remote and island communities.

The key issue is to reduce the cost of wave energy from the current price of £350/MWh (estimated by ORE Catapult in 2018 [6]) to a competitive price level as offshore wind of £100/MWh (estimated by International Energy Agency (IEA) in 2019 [12]). This pathway to cost reduction is expected to be achieved through sustained technology innovation, revenue support and multi-disciplinary research. Technological innovation is needed to prove survivability and scalability of wave energy for grid scale deployment and revenue support is needed to provide the market pathway for investors. Small-scale wave energy devices already compete with diesel generators, and are used to provide power to island communities, offshore desalinisation plant and fish-farm sites, and these applications may act as stepping stones to grid scale development. The Supergen ORE Hub research landscape is multi-disciplinary, including environmental and socio-economic aspects, and will require engagement from right across the ORE stakeholder community of research, business, government, and across the remit of multiple UKRI research councils to respond to the research and development challenges identified. A thorough understanding of where we are now is of fundamental importance for the sector going forward. This brief report is intended to provide a useful resource summarising the opportunities and challenges of developing wave energy in the UK and more importantly inspiring the future strategies.

1. Wave Energy Description

Wave energy is distinct from tidal energy. Waves are formed by winds blowing over water and their size depends on the wind speed, duration and the distance over which the wind blows. Wave Energy Converters (WECs) capture the energy contained in waves and convert it into electricity. On the other hand, tides are created by the gravitational pull of the moon and sun on the sea. Tidal energy is converted into electricity using the rise and fall of the sea level for tidal range and tidal currents for tidal stream. The UK's exploitable wave resource (40-50 TWh/year) is larger than the tidal resource (20-30 TWh/year) [1].

WEC technologies typically fall within three categories as shown in Table A1: (1) oscillating water columns (OWC) that use trapped air pockets in a water column to drive turbines for electricity generation; (2) oscillating body converters that convert wave motions into device oscillations to generate electricity; (3) overtopping converters that use reservoirs to generate a head flow and subsequently drive turbines for electricity generation [2]. Novel concepts that fall outside of these categories include the Bombora device, which features air-inflated rubber membranes mounted on the sea floor, and the PolyWEC, which uses deformable lightweight and low-cost electroactive polymers for wave energy conversion (see Figure A1). Although wave energy has fascinated scientists and engineers since the first patents in 1799, there is a lack of consensus in design and the large number of different concepts and their categorisation can be confusing.

Table A1. Categories of the various wave energy technologies based on working principles

Categories	Sub-categories	Technologies
Oscillating water column	Fixed	NEL OWC, Pico, LIMPET, Sakata, Mutriku, ReWEC3, Wave Swell Energy
	Floating	Masuda buoy, Mighty whale, Oceanlinx, OE buoy, Spar buoy, KNSWING
Oscillating body	Heaving body	CETO, Seabased, OPT, LifeSaver, OPT, Corpower, Aquabuoy, WaveBob, AWS
	Pitching body	Edinburgh Duck, Oyster, WaveRoller, BioPower
	Articulated body	Cocerell's raft, Pelamis, McCabe Wave Pump, DEXA, M4 WEC, Seapower, Mocean Energy,
Overtopping	Fixed	Tapchan, SSG, OBREC
	Floating	WaveDragon, WaveCat
Other	Flexible membrane	Bombara, PolyWEC
	…	…

(a)

(b)

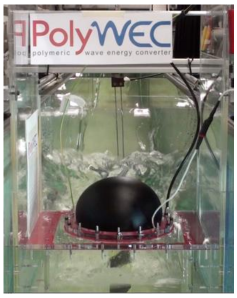

Figure A1. Bombora device [18] (left) and PolyWEC [27] (right)

2. Wave energy resources in UK

The UK has an excellent wave resource, estimated at 35% of Europe's, and 2–3% of the global wave resource [3]. Most of the UK's wave energy arrives from the Atlantic to the west. Shelter from Ireland reduces the wave energy resource in the Irish Sea and the energy levels in the North Sea are significantly lower than in the west, as shown in Figure A2.The total resource is estimated around 230 TWh/year with the majority found in the deeper offshore parts of the UK's exclusive economic zone [4]. Using the 2012 Carbon Trust analysis [4], this translates to a practical wave resource of up to 70 TWh/year for offshore and 5.7 TWh/year for nearshore regions and an exploitable wave resource of between 40 and 50 TWh/year.

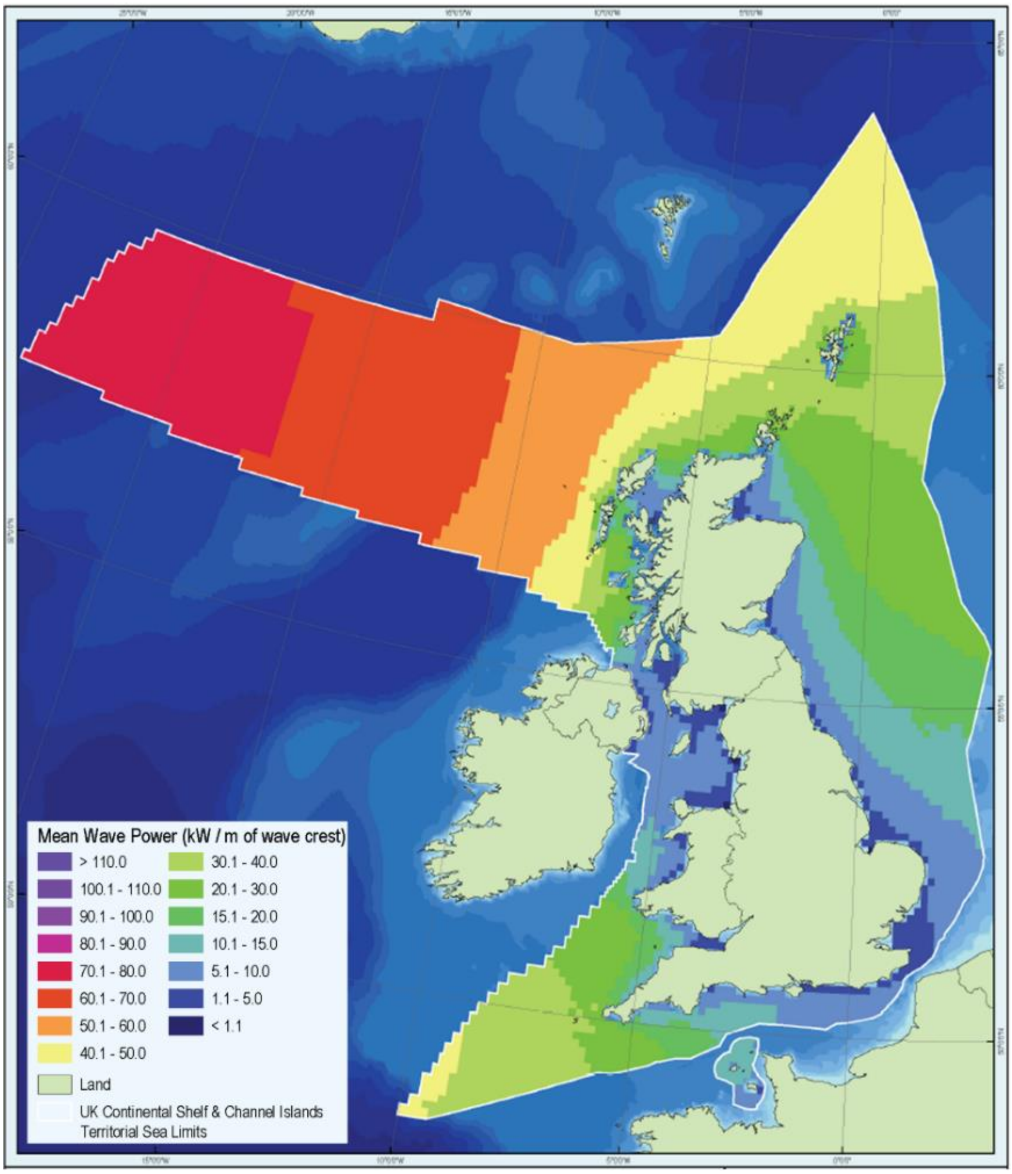

Figure A2. Average mean wave power in the UK (From the Atlas of Marine Renewable Energy Resources, published by BERR, 2008)

3. Potential role of wave energy in UK's energy mix

Using the 2012 Carbon Trust analysis [4], this translates to an exploitable wave resource of between 40 and 50 TWh/year. This would contribute approximately 15% of 2018 electricity generation in the UK (333 TWh) and up 10% of the UK's forecast electricity needs in 2050. Considering the early stages of technology development and demonstration at that time, the deployment scenarios for 2050 ranged from zero to over 20 GW and it was expected that most would occur post 2020. Nevertheless, wave energy was not considered in the BEIS 2019 Energy Innovation Needs Assessment (EINA) exercise, where EINAs were selected based on the estimate of energy system benefits of innovation per technology using the Energy Systems Modelling Environment (ESME) [5]. Meanwhile, the ORE Catapult's 2018 review reported that the UK has 137MW of wave energy in operation or under various stages of development, including grid connected demonstration zones at the European Marine Energy Centre (EMEC), Wavehub, Pembrokeshire and West Anglesey [6]. It is estimated that wave energy will contribute a net cumulative benefit to the UK economy of £4,000m GVA from domestic and export markets and support 8,100 jobs by 2040. Much of the economic benefit is expected to be generated in coastal areas needing economic regeneration, thus bringing further value for the UK.

In addition to these economic and electricity generation benefits, wave energy potentially has a valuable role in providing diversity and resilience to the UK's energy mix, complementing offshore wind and solar PV. The electricity grid would benefit from energy profiles rising at different times of the day and seasonal variability of different renewable sources to help reduce the need for both diesel-based and energy storage backup power. For example, under the same environmental conditions, the peaks of wave climate trail the wind peaks by several hours [7]. In consequence, the combined exploitation of wave and wind technologies will smoothen power output and thus result in a reduction of sudden disconnections from the grid. Wave and solar PV technologies are sensitive to varying seasons [8]. The variation in wave power density can change from 10 kW/m in summer to 100 kW/m in winter, whereas solar PV resource is higher in summer and lower in winter, thus, wave and solar PV technology power generation is complementary [9]. Benefiting from the energy complementarity between wind, wave and solar technologies, more and more combined platforms are under development. Floating Power Plant (FPP) was the pioneer for hybrid wave-wind technology [25]. In 2008, a 37 m scale model was tested at sea offshore of Denmark (see Figure A4), a structure hosting 3 wind turbines of 11 kW each and 10 WECs with 3 kW capacity each. In 2015, FPP received €1.14m from the European Commission's Horizon 2020 research and innovation programme to further develop a commercial P80 wind-wave hybrid platform with capacity of up to 8MW. By 2017, FPP had raised over €15 million for the full scale P80. In addition, two Australia-based projects: King Island co-located wind-wave-solar and Garden Island co-located wave-solar. A 200 kW OWC by Wave Swell Energy (see Figure A3) is under construction off the coast of King Island, Australia and expected to be installed and operational by the middle of 2020 [26]. The project will be integrated with the existing high penetration wind and solar microgrids on King Island operated by Hydro Tasmania to demonstrate the role of wave energy within mixed renewables.

(a)

(b)

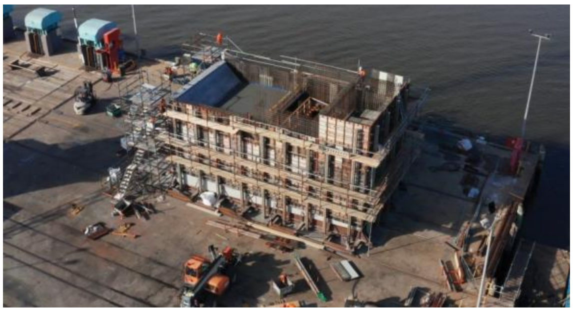

Figure A3. Combined renewables platforms. (a) P37 hybrid wave-wind [25]. (b) Under construction of the Wave Swell Energy's King Island wave energy project [26].

4. Progress and current status of wave energy in the UK

4.1. Early Initiatives and programmes

Modern research and development of wave energy in the UK was pioneered from the mid-1970s in response to the oil crisis [10]. In 1974, Stephen Salter of the University of Edinburgh published the Edinburgh Duck WEC [28]. In the same year, the UK Government launched an ambitious government wave energy programme aiming at a 2 GW wave energy plant. At least ten wave energy projects were supported within this programme including Salter's Duck, the National Engineering Lab (NEL) OWC, the Cockerell Raft and the Bristol Cylinder (see Figure A4). However, the British wave energy programme was abruptly terminated in 1983 when the oil crisis ended and the UK Government moved away from alternative energy sources, ending without any full-sized prototype having been constructed. Following the closure of the Programme, development of wave energy concepts continued to be developed in the UK, such as the PS Frog, the Solo Duck, the Circular SEA Clam, and the Shoreline OWC [30] (see Figure A5). In 1995, Wavegen designed a shoreline OWC, reducing the cost of electricity generation from OWCs by over 60% [31], and as a consequence, in 1999, LIMPET (developed by Wavegen), the world's first commercial shoreline fixed OWC, was constructed and connected to the UK's national grid in 2001, continuously operating for a decade before it was decommissioned in 2012 (see Figure A6). In the early 2000s, with the concerns of climate change, renewable technologies like wave power were revisited. The UK Government declared renewed support for research and development in wave energy with a budget of around £3m during 2000–2003. In 2004, the world's first offshore floating WEC prototype, Pelamis (750 kW), was deployed and connected to the UK grid (see Figure A6). In 2009, the first wave energy array (2.25 MW) was tested in Portugal based on three Pelamis prototypes, and two second-generation Pelamis devices were tested at the EMEC between 2010 and 2014, accumulating over 15,000 hours of operation. However, the company developing Pelamis went into administration in 2014. The 315 kW Oyster WEC (see Figure A6) was installed at the EMEC in 2009 followed by the 800 kW Oyster in 2011, and had completed 20,000 hours of operation by 2015 when the programme was halted and the company Aquamarine Power developing Oyster went into administration. Through their development and operation, these past WEC programmes generated significant experience and knowledge that has been assimilated into the community and informs ongoing research and development in wave energy. In the cases of Pelamis and Oyster, there was a mismatch between financial and technical drivers that forced developers to embark on costly large scale demonstrations too early in their development. Clearly, the development of wave energy is highly dependent on government policy and support [36].

(a) (b) (c)

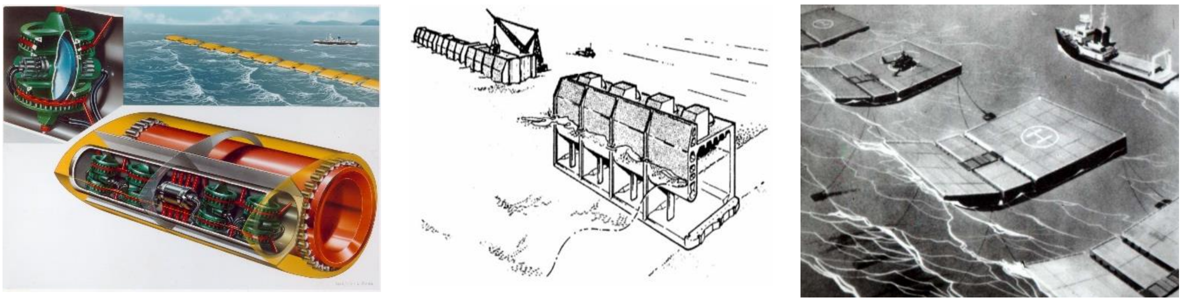

Figure A4. Representative WEC technologies supported by the British wave energy programme 1974–1983. (a) Edinburgh's Duck [28] (b) NEL OWC [24] (c) Cockerell Raft [30].

(a) (b) (c)

Figure A5. Early WEC technologies developed in the UK. (a) PS Frog [31] (b) Circular SEA Clam [29] (c) Shoreline OWC on the island of Islay, Scotland [24].

(a) (b) (c)

Figure A6. In-grid WEC technologies developed in the UK. (a) LIMPET OWC installed on the island of Islay, Scotland, rated 500 kW [24] (b) Pelamis [32] (c) Oyster 800 [33].

4.2. Wave Energy Scotland (WES)

In 2014, the Scottish government set up Wave Energy Scotland (WES) [11] to support and facilitate the development of wave energy in Scotland. WES purchased the IP of Pelamis (2014) and Oyster (2015) and secured the learning and considerable experience gained in the development and deployment of Pelamis and Oyster. A structured innovation approach was developed within the WES. Rather than focus on designing the complete technical solution in isolation, the approach aims to develop more efficient sub-systems that could be implemented across different WECs. WES tailored a new funding scheme using pre-commercial procurement (PCP) in conjunction with a stage-gate development process. Four funding calls have been released with each one targeting a specific topic, i.e. power take-off systems, novel wave energy converters, structures and materials, control systems and quick connection systems. In each call, winning projects are selected to move on to the next funding phase, with technologies converging towards the final stages. To date, the Scottish Government has invested nearly £40m in more than 90 projects through the WES programme. Two WEC developers from Scotland, Mocean Energy and AWS Ocean Energy (see Figure A7) have secured £7.7m to deploy demonstration prototypes at EMEC in 2020. Both WEC companies have built collaborations with other sub-system technologies such as power take-off, structural materials and control systems that have been developed and proven independently through parallel WES Programme investments or the other programmes.

.

(a)

(b)

Figure A7. Two firms secured £7.7m funding from WES for field test in 2020. (a) 'Blue Horizon' from Mocean Energy [16] (b) Archimedes Waveswing from AWS Ocean Energy [17].

4.3. Current status

The high cost of wave energy is still a key issue for the sector. The commercial development of offshore wind lagged onshore wind by approximately 15 years and was built on 30 years of onshore wind development from demonstration to the first commercial wind farms of the 1990s. This pathway to a commercially viable sector, which today is cheaper than new gas and nuclear electricity generation, was supported by policy and financial support structures, feed-in tariffs and contracts for difference (CfD). Further efforts are needed to achieve the necessary cost reduction for wave energy, and it is not clear whether existing technologies will be able to meet LCoE targets. However, some developers believe that progress is constrained through socio-economic as opposed to technical challenges. To address this, evidence is needed on the environmental and social impact of wave energy development [13]. Supergen ORE hub is active in designing communication and outreach activities to increase public engagement in the understanding of wave, tidal and offshore wind technologies [14]. ETIP Ocean delivered a 'Report on presentation of stakeholder engagement results workshops' in 2018 which clearly clarified the prioritised challenges within wave energy from the aspects of technology, financial, environmental and socio-economics. Furthermore, ETIP Ocean suggested actions to be taken to overcome the challenges and their responsible stakeholder(s) [15]. Strategic Environmental Assessment of Wave (SEAWave) project, co-ordinated by EMEC, is aiming to address long-term environmental concerns around the deployment of wave and tidal energy converters in the marine environment. The project is co-funded by the European Maritime and Fisheries Fund (EMFF) of the EU and is supported by a diverse range of project partners across UK, Portugal, Finland, Belgium, Sweden and Ireland [34].

To address the technical challenge, the Scottish Government continues to champion the wave energy sector. This includes providing ongoing support for WES. The WES funding scheme is regarded as a powerful tool that could be used more widely by governments and funding authorities. WES 'Novel Wave Energy Converter Projects' competition winners, 'Blue Horizon' from Mocean Energy [16], and Archimedes 'Waveswing' from AWS Ocean Energy [17], will both be tested at EMEC in 2020.

The Welsh Government has a 70% renewable electricity mix contribution target by 2030, a proportion of which is expected to come from wave resources. For this, the Welsh Government has allocated €100.4m 2014–2020 for marine energy development. Marine Energy Test Area (META), is a newly established test site developed by the Marine Energy Wales in the Milford Haven Waterway in Pembrokeshire. META Phase 1 was officially opened in September 2019. In addition, a new wave energy test site located off the South Pembrokeshire coastline: the Pembrokeshire Demonstration Zone (PDZ) is going to be submitted in 2021. The zone comprises a 90 km^2 area of seabed with water depths of approximately 50 metres and a wave resource of 19 kW/m. It is located between 13-21kms offshore and has the potential to support the demonstration of wave arrays with a generating capacity of up to 30MW for each project. The Australian company Bombora (see Figure A1) secured £10.3m of Welsh Government European Funding in 2018 to deploy their WEC in Pembrokeshire, Wales [18]. WaveSub (see Figure A8), from Welsh company Marine Power Systems, is supported by a £12.8m grant from the Welsh Government to test a full scale WaveSub at sea in 2022 [19].

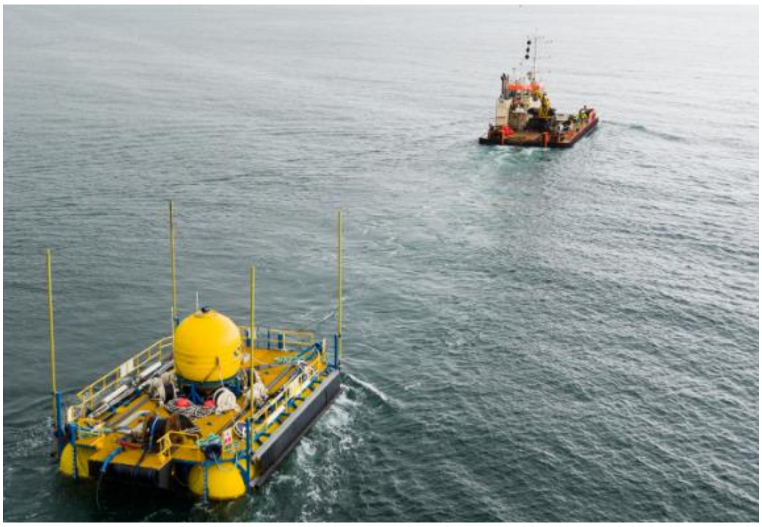

Figure A8. WaveSub from Marine Power Systems [19]

Most of the devices mentioned above are designed for large scale in-grid generation, but alternative smaller scale off-grid applications are also being investigated. Albatern are working with aquaculture companies to supply power to working fish farms using their 7.5 kW 'WaveNet' WEC to replace diesel generation [20]. Mocean Energy developed a relatively small size WEC, 'Blue Star' to power a range of sub-sea applications, from subsea control systems to fully autonomous underwater vehicles [16] and has attracted funds of

£200,000 from Scottish Enterprise and the Oil and Gas Technology Centre in Aberdeen for the development. The M4 WavePower (see Figure A9) from University of Manchester has been validated with impressive performance under 1/10 and 1/50 scale lab tests. Researchers from the Queen Mary University of London provided the control strategy for the M4 device and showed that, under optimal control, the device power can be improved by 40-100%. The team are now working towards field trials at Shenzhen, China, where the prototype will be built by China Construction Steel Structure Corp. Ltd. in collaboration with Tsinghua University.

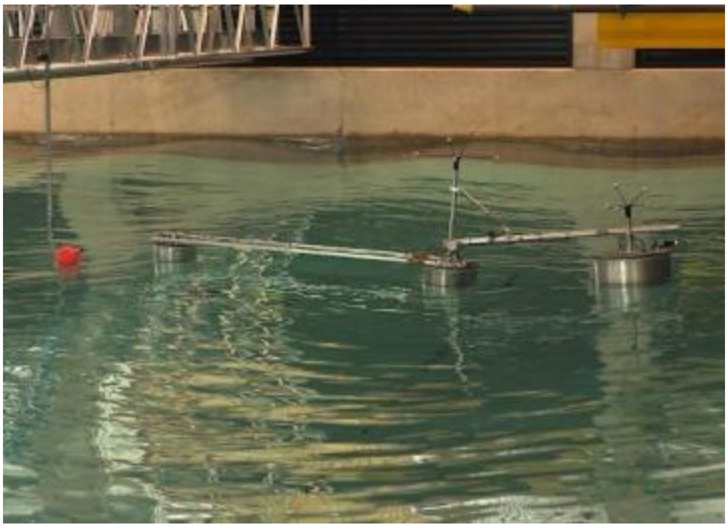

Figure A9. M4 WavePower from University of Manchester [35]

Although still dominated by start-up wave energy companies, other engineering firms and utilities are entering the market. Saipem and Wello Oy have signed a memorandum of understanding to enhance the Penguin WEC2 technology. Utilising their long experience in offshore engineering, Saipem will support Wello Oy to optimize the installation procedure and operability of their WEC [21]. CorPower have signed a Strategic Collaboration Agreement with Simply Blue Energy to develop a number of significant wave energy projects off the coasts of the UK and Ireland. With the experience of offshore wind, Simply Blue Energy will also investigate the development and deployment of combined floating wind and wave energy farms. This is to explore opportunities to reduce costs and increase output by dovetailing the variations in resource availability between wind and wave energy [22]

5. International Position of UK

Other European countries with an Atlantic coastline also have accessible wave resources and are developing wave energy, including France, Ireland, Spain, Portugal, Denmark and Norway. Further afield, high levels of resource can be found in North America, Chile, Australia, China, Japan and Korea. EMEC has summarised a list of 244 wave energy developers globally, with 23 active in the UK and the largest number based in the US [23]. Globally, most developers are still at the early research stage. The US and China are particularly active in developing wave energy technology. In the US, Northwest Energy Innovations tested a half-scale device at the US Wave Energy Test Site (WETS) in 2015 and a full-scale system was deployed in 2018. US Ocean Power Technologies (OPT) has a contract to supply Oil & Gas Company, Premier Oil, with one of its PowerBuoy systems for deployment in an oil and gas field in the Central North Sea. US Columbia Power Technology has plans for open-water demonstration of their WEC at WETS in 2019. In China, many WECs are being developed and tested, including the Guangzhou Institute of Energy Conversion 100 kW ‘Sharp Eagle’ WEC, which was deployed in the Wanshan Islands in 2015, with its next generation 260 kW version combining wave, solar and desalination deployed in 2018.

The global potential for wave energy is clearly recognised and many countries have active and ambitious programmes for wave energy development. The UK, as an early sector leader, has accumulated most experience from the deployment of various WEC prototypes, and with strategic investment could retain this advantage in what is set to become an important global sector for our energy future.

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Annex B - Wave Energy Niche Applications

1. WEC-Integrated Breakwaters

Integrating WEC devices into breakwater structures has attracted increasing attention due to the cost reduction and reliability improvement benefits [1]. Table B1 includes a summary of the most important worldwide prototypes.

Table B1. Prototypes of WEC-integrated breakwaters and key characteristics

OWC SLOPING CAISSON IN JAPAN	
The first successfully deployed system was an OWC plant integrated into a breakwater at Sakata harbour, Japan, in 1990 [2] [3]. This OWC device had a rated power of 60 kW with a length of 20 m. *WEC Type: Onshore OWC*	
MUTRIKU PLANT IN SPAIN	
The first integrated system installed in Europe was a multi-chamber OWC plant embedded into a breakwater at Mutriku harbour, Basque Country, Spain, in 2008 [1]. This OWC system consists of 16 chambers with a total length of 100 m. Each chamber was designed with a capacity of 18.5 kW, giving a total power of 296 kW. In February 2020, it was announced that the Mutriku plant had accumulated 2 GWhr production. *WEC Type: Onshore OWC*	
REWEC3 CAISSON IN ITALY	
An innovative cross-shape OWC integrated with a breakwater was proposed and known as the U-shaped ReWEC3 [3]. With this design, the water column can have a relatively long length (578 m) without requiring the opening to be far below the sea surface. The prototype was installed at Civitavecchia harbour, Italy in 2014, it has 136 chambers with capacity of approximately 2720 kW in total. *WEC Type: Onshore OWC*	
OBREC IN ITALY	
The first prototype of an overtopping WEC embedded into a rubble mound breakwater was successfully constructed at the port of Naples, Italy in 2016 [4]. Furthermore, OBREC was the first prototype to be retro-fitted into an existing breakwater. The system is located above the sea surface, consisting of a frontal ramp, a basin and an in-situ machine room. *WEC Type: Onshore overtopping*	

KEY CHARACTERISTICS

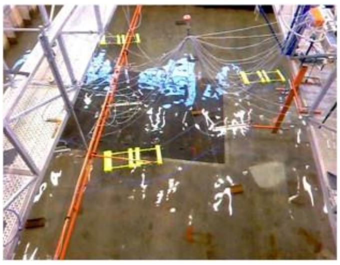
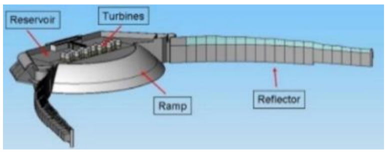
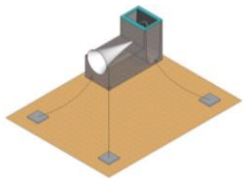
- **Aims** – Embed WEC devices into breakwaters to save cost while also supplying green power to the facilities in the vicinity.
- **WEC types** – Fixed OWC and overtopping WECs in use.
- **Site selection** – The plants are integrated into the host breakwaters located mostly onshore/nearshore. As is well known, the wave resource towards nearshore/onshore is relatively low and therefore, it is important to select suitable sites with sufficient wave resource.
- **Suitability** – use of shared infrastructure by developing WEC-integrated breakwaters, mature technologies of onshore OWC and overtopping WECs, accessible O&Ms and mild wave conditions nearshore.
- **Scalability** – The plants can be constructed from several to hundreds of metres, power production can be scaled by increasing the number of chambers to meet the balance of capacity demand and cost.
- **Main evaluation criteria** – Trade-off between cost reduction and power production, ease of O&Ms and reliability

2. WEC for Coastal Protection

Breakwaters, groins and artificial reefs, are the conventional coastal defense schemes. However, the efficiency of these interventions would decrease with increasing sea level [5]. To address this issue, the innovative idea of utilizing offshore WEC farms for coastal protection has been proposed as floating WECs are not affected by sea level rise. At the time of writing, there are no WECs currently being used for this application and the study is still under academic research. Representative studies are described here.

Table B2. Academic studies on applying WECs for coastal protection and key characteristics

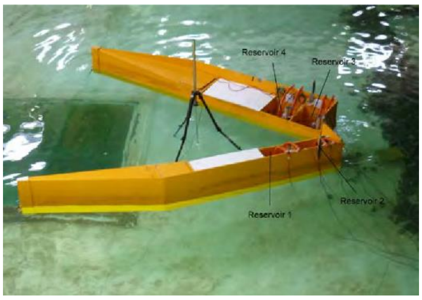
<table>
<tr><th colspan="2">LABORATORY TEST OF DEXA</th></tr>
<tr><td>Laboratory tests on the study of 1:30 and 1:60 scale DEXA hinged-type WEC for coastal protection was performed in the wave tank at Aalborg University, Denmark in 2012. The results showed that a park of DEXAs could be used to reduce the wave energy reaching the coast and could significantly affect the sediment transport and the direction of the net transport [6].

WEC Type: Oscillating body, Attenuator</td><td></td></tr>
<tr><th colspan="2">NUMERICAL TEST OF 4 TYPES OF WECS</th></tr>
<tr><td rowspan="4">Numerical tests were carried out to study the effectiveness of applying WECs for coastal protection and sediment transport. Four different WEC types, named Wave Dragon, Blow-Jet, DEXA and Seabreath, were numerically built in front of two different beaches, i.e., the semi-closed Bay of Santander in Spain and the open Las Glorias beach in Mexico. Recommendations of the WEC farm layouts for shore protection with respect to different beach sites were given [7].</td><td>
Wave dragon
WEC Type: Offshore floating overtopping</td></tr>
<tr><td>
Blow-Jet
WEC Type: Innovative WEC with the use of blowhole</td></tr>
<tr><td>
Dexa
WEC Type: oscillating body, Attenuator</td></tr>
<tr><td>
Seabreath
WEC Type: Offshore floating OWC</td></tr>
</table>

NUMERICAL TEST OF WAVECAT

An array of 11 WaveCat WECs were numerically arranged in front of Perranporth Beach near the Wave Energy demonstration test site, WaveHub in the UK. By using the wave farm, erosion of the beach face was significantly reduced. The authors concluded that wave farms can be 'green alternatives' to conventional coastal defenses, not only for their effectiveness in coastal protection but also for their ability to produce green power [8].

WEC Type: Offshore floating overtopping



KEY CHARACTERISTICS

- **Aims** – Reduce nearshore wave heights to protect shorelines from coastal erosion and flooding.
- **WEC types** – All types of floating WECs can be applied.
- **Site selection** – The plants are deployed in front of the fragile shorelines requiring protection.
- **Suitability** – Laboratory and numerical investigations of WECs used for coastal protection show promising effectiveness. Further investigations are needed to understand the performance in the field and the cost. Also, integration of electricity generation within the plants provides co-benefits, ultimately reducing the effective LCoE.
- **Scalability** – WEC arrays would be required for coastal protection [8]. The layout and scale of the farm should be tailored to meet the specified coastal conditions [7,8].
- **Main evaluation criteria** – Performance of coastal protection, cost, environment sensitivity and reliability

3. WEC-Powered Desalination:

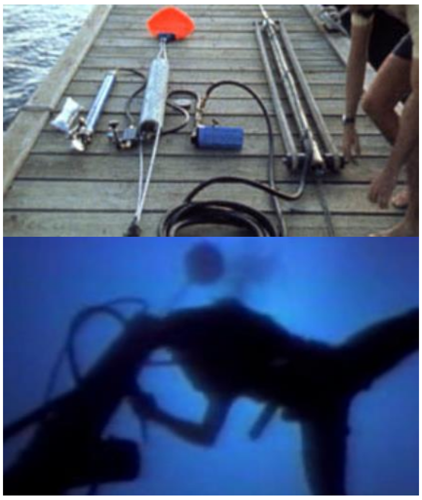
Increasing attention has been paid to providing sustainable access to freshwater under the United Nations (UN) sustainable development goal. One solution is to apply Wave Energy to power a desalination plant for potable water [9]. Wave power has been used to drive a desalination process in three approaches:

A. The movement of a WEC can drive the attached pump to produce pressure difference to run the reverse osmosis (RO) process for freshwater.
B. A WEC can generate electricity from waves to power the desalination plant.
C. The generated wave power is converted into mechanical power to drive vapour compression equipment inside the WEC to produce fresh water

Representative prototypes are listed below.

Table B3. WEC-powered desalination plants deployed in full-scale and key characteristics

<table>
<tr><th colspan="2">DELBUOY IN PUERTO RICO</th></tr>
<tr><td>The first well known system was Delbuoy, deployed in Puerto Rico in 1982. The Delbuoy had its benefit of creating fresh water at low cost, with simple technology and small size. It can be deployed with a small fishing boat and be maintained with a simple set of household tools which made it quite suitable for coastal communities. Approach A was used in this plant, which generated approximately 1100 litres of freshwater each day to meet the daily demand of 7 people [10].

WEC Type: Point absorber</td><td></td></tr>
<tr><th colspan="2">OWC-RO IN INDIA</th></tr>
<tr><td>Following a study of different WEC types (double point absorbers, single heaving point absorber and onshore OWC), the OWC was selected as showing the maximum promise for India. The plant was deployed in Vizhinjam, India in 1990 to produce freshwater for the harbour community. Approach B was used in this system, generating about 10,000 litres of clean water each day [11].

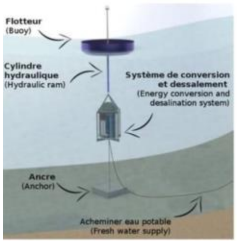
WEC Type: Onshore OWC</td><td></td></tr>
<tr><th colspan="2">CETO FRESHWATER IN AUSTRALIA</th></tr>
<tr><td>Carnegie was the first company achieving commercialisation of WEC-powered desalination by using their CETO device. This system was deployed in Garden Island, Western Australian in 2014. The plant applied approach A with the use of three submerged CETO devices and the pressurized water was pumped ashore to run the RO membrane for clean water [12].

WEC Type: Point absorber</td><td>
</td></tr>
</table>

ODYSSÉE IN CANADA

The Odyssée system was designed and built by a group of researchers from the University of Quebec, Canada. The plant was tested at Magdalen Island, Canada in 2014. The device was designed to generate 10,000 litres of freshwater per day. The device used similar technology as CETO, but Odyssée was designed as an all-in-one system combining power and desalination plant in house [9].

WEC Type: Point absorber



SAROS IN USA

The first prototype of SAROS consisted of a pendulum connected to a high-pressure pump, built atop a floater. As the pendulum is activated by the waves, the sea water is pumped at high pressure through the RO membrane, converting to drinkable water. EcoH20 Innovations secured the second prototype of SAROS in 2016, which had a smaller size and more compact body. SAROS was found to generate over 11,000 litres of drinking water per day [13].

WEC Type: Point absorber

ATMOCEAN IN USA

Atmocean applied a Wave Energy array for desalination in 2017. Each buoy is connected to a pump. As wave passes, each buoy ingests sea water, and as the buoy selltes, it pumps seawater through hydraulic lines back to shore to drive the reverse osmosis membrane for fresh water. Atmocean recently announced that their current plant reaches economy of scale, arrays could also be used for power production in the future by transporting the pressurized water through a water wheel to generate electricity [14].

WEC Type: Point absorber

KEY CHARACTERISTICS

- **Aims** – Convert sea water to drinking water.
- **WEC types** – All types of WECs can be used [9].
- **Site selection** – The plants can be located onshore/nearshore/offshore, in the general vicinity where people are facing scarcity of freshwater and insufficient sanitation.
- **Suitability** – The successful demonstrations of the single and small scale WEC-powered desalination units have built up confidence in this niche application. A number of companies are already looking at the potential of co-benefits by expanding WECs into arrays for larger freshwater yield and also power supply to coastal communities.
- **Scalability** – Scalability varies by using a range of WEC units from tens to thousands of kilowatts. A single small scale WEC can be suitable to meet the freshwater demand for one family per day; for greater freshwater yield WEC-powered desalination arrays would be required.
- **Main evaluation criterion** – Fresh water yield each day, eco-friendly to marine environment, ease of implementation, user friendliness, power production, cost and reliability

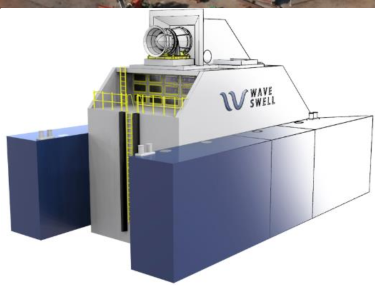
4. WEC-Integrated Microgrid on Islands:

Presently, fossil fuel is still the main resource imported to islands for electricity generation. Importing fossil fuel may lead to marine environmental pollution from high emissions and spill-risk, which are unwanted especially for islands dependent on tourism. Additionally, many small islands experience heavy fiscal burdens associated with imported fuels. Therefore, governments and political supports from UN, Asian Development Bank (ADB), European Union (EU) and Department of Foreign Affairs and Trade for Australia (DFAT) have shown increasing interest in the transition to renewable energies. Wave Energy together with wind and solar energy are promising for use in mixed renewables microgrids on islands.

Table B4. Wave integrated microgrid projects and characteristics summary

<table>
<tr><th colspan="2">GARDEN ISLAND MICROGRID IN AUSTRALIA</th></tr>
<tr><td>Carnegie Clean Energy has completed the commission of the microgrid plant in Garden Island, Western Australia. The microgrid consists of three 1 MW wave buoys, a 2 MW solar PV array, a 2 MW battery and a desalination facility. The plant produces green electricity for Australia’s largest naval base, HMAS Stirling on Garden Island [12].

WEC Type: Point absorber</td><td>
</td></tr>
<tr><th colspan="2">KING ISLAND MICROGRID IN AUSTRALIA</th></tr>
<tr><td>Wave Swell Energy secured 4 million AUD from the Australian Renewable Energy Agency to install a pilot-scale UniWave 200, a 200 kW OWC off the coast of King Island, Australia. The WEC is expected to be installed and operational by the middle of 2020. The project will be integrated with the existing high penetration wind and solar microgrids on King Island operated by Hydro Tasmania to demonstrate the role of Wave Energy within mixed renewables [15].

WEC Type: Onshore OWC</td><td>

</td></tr>
<tr><th colspan="2">KEY CHARACTERISTICS</th></tr>
<tr><td colspan="2">
Aims – Build wave microgrid on islands for power supply
WEC types – All types of WEC can be used.
Site selection – The plants can be located onshore/nearshore/offshore close to islands and remote communities.
Suitability – Several islands worldwide, especially in Australia are already developing mixed renewables microgrids. Successful demonstration of the island microgrids will facilitate the wave technology development and identify its value within the energy mix. Recent studies of power generation for Pacific Islands has clarified that wave energy complements solar and wind very well, and in combination provides a more predictable and consistent resource [16].
Scalability – WEC arrays are required to meet the total electricity demand on islands.
Main evaluation criterion – Cost of energy production, efficiency for energy mix and reliability
</td></tr>
</table>

5. WEC-Integrated Aquaculture:

Most aquaculture farms are presently inshore and powered by using diesel generators. To address the growing demands in seafood and limited inshore space, aquaculture needs an offshore power supply to locate offshore in deeper water where diesel might be prohibitively expensive. Cost-effective wave power is drawing attention as a viable alternative and displacing diesel in offshore aquaculture farms.

Table B5. Examples of WEC-integrated aquaculture and the key characteristics

<table>
<tr><th colspan="2">WAVENET-FISH FARM IN UK</th></tr>
<tr><td>Albatern is working with two leading aquaculture companies, Mowi Scotland and Scottish Salmon Company to demonstrate the ability of WaveNET arrays for powering fish farms.

WEC Type: Point absorber</td><td>
</td></tr>
<tr><th colspan="2">CCELL-CORALS IN UK</th></tr>
<tr><td>Climate change is increasing the stress on corals. CCell is investigating use of Wave Energy technology to provide electrical current for repairing existing corals and growing new coral reefs [18].

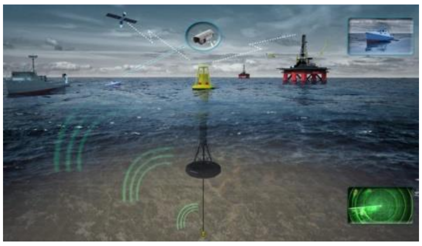
WEC Type: Terminator</td><td></td></tr>
<tr><th colspan="2">EFORCIS-FISH FARM IN EU</th></tr>
<tr><td>eForcis is developed by Smalle Technologies and financed by the European Commission through the Horizon 2020 program. The device is to provide electricity for running fish farms and has been tested in several Spanish locations, such as Barcelona and Castellon. Smalle Technologies has also developed DataForcis, a data buoy to monitor the water temperature, oxygen and current levels to adaptively control the performance of an aquaculture farm [19].

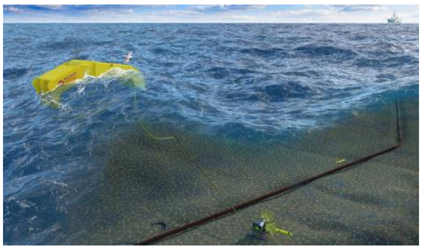
WEC Type: Point absorber</td><td></td></tr>
<tr><th colspan="2">KEY CHARACTERISTICS</th></tr>
<tr><td colspan="2">
Aims – Provide power and shelter for offshore aquaculture farms
WEC types – All types of floating WECs can be applied.
Site selection – Wave climate at a site is a significant factor in choosing a site for an aquaculture farm. At present, most of the fish farms are located in sheltered waters with significant wave heights less than 2 m, but new aquaculture sites in more exposed offshore conditions are being developed to meet the increasing seafood demand [20].
Suitability – A WEC unit or an array can be designed as a suitable offshore station to provide cost-effective green power and shelter in aquaculture sites. Companies, such as Albatern in the UK has shown that wave power is cost-effective to displace diesel.
Scalability – A single WEC unit or an arrays can be used to meet the power demand of an aquaculture farm, typically between 100 KW to 2 MW [21].
Main evaluation criterion – Cost of energy production, eco-friendly, sheltering and reliability
</td></tr>
</table>

6. WEC for Offshore Oil & Gas Applications:

The oil & gas industry has recently ramped up efforts to integrate Wave Energy technologies to provide power to offshore platforms. To support offshore exploration activities, the conventional method of using diesel is expensive and unsustainable, and using umbilical power cables from the shore is very expensive. In contrast, Wave Energy technology will offer the oil & gas platform powering market potential new solutions to drive down the cost and realise a renewable and sustainable pathway.

Table B6. Examples of wave technology for oil & gas applications and key characteristics

OPT-ENI IN ITALY	
Ocean Power Technology (OPT) signed a two year contract with ENI Group, one of the largest oil & gas companies in the world, to supply their PowerBuoy in the Adriatic Sea, Italy in 2018. The aim of the project was to demonstrate the suitability of Wave Energy as a charging station and communication platform, enabling the use of AUVs as long-term remote operations for offshore oil & gas platforms [22]. *WEC Type: Point absorber*	
OPT-PREMIER IN UK	
Premier Oil deployed the OPT PowerBuoy at its Huntington field in the North Sea in 2019. The system generates electricity to power on-board sensors, allowing real-time data transfer and communication with remote facilities. This was regarded as a great opportunity to minimize the environmental impact during decommissioning of oil & gas platforms [22]. *WEC Type: Point absorber*	
ISWEC-ENI IN ITALY	
Following the collaboration with OPT in 2018, ENI activated its first pilot plant ISWEC (inertial Sea Wave Energy Converter) with capacity of 50 KW in Ravenna, Italy in 2019. The system was connected to ENI's PC80 oil & gas platform for powering. ENI are working on an industrial scale ISWEC with 100 KW capacity to meet the electricity demand of medium-scale plants, realising their target of renewable and sustainable hubs [23]. *WEC Type: Point absorber*	
WELLO OY-SAIPEM	
Wello Oy signed a memorandum of understanding with Saipem, a multinational oilfield service company in 2019. The aim is to communicate experience with Saipem to enhance Penguin WEC2 technology and investigate its applications to oil & gas industry [24]. *WEC Type: Point absorber*	

BLUE STAR-SCOTTISH ENTERPRISE & OGTC IN UK	
Mocean Energy, a Scotland-based company has attracted funds of £200,000 from Scottish Enterprise and the OGTC (Oil & Gas Technology Centre) in Aberdeen for the development of its 'Blue Star'. The device can convert Wave Energy to electricity to power a range of subsea facilities from control systems to autonomous underwater vehicles for oil & gas platform applications [25]. *WEC Type: Attenuator*	

KEY CHARACTERISTICS

- **Aims** – Provide power to oil & gas platforms or their subsea facilities.
- **WEC types** – All types of floating WECs can be utilised.
- **Site selection** – The plants need to be located offshore near the oil & gas platforms.
- **Suitability** – Technical challenges, like O&M, survivability in harsh seas can be unlocked with the collaboration and support of the oil & gas industry. In turn, closer cross-sector partnerships with wave technology would release the hydrocarbon-dependence of oil & gas industry to be more sustainable and renewable.
- **Scalability** – Small scale WECs can be more suitable for powering subsea facilities. Larger WEC units and even WEC arrays need to be used to power medium-large oil & gas platforms.
- **Main evaluation criterion** – Cost of energy production, reliability and cost of transport and installation

7. WEC for Military and Surveillance:

Military organisations are looking to switch energy sources from hydrocarbon dependence to renewables. For example, the US military expects to produce 25% of its energy needs from renewable sources by 2025 and, together with Australia, are at the forefront of pushing wave renewable into use for military applications.

Table B7. Examples of wave technology for military and surveillance applications and key characteristics

<table>
<tr><th colspan="2">BOLT LIFESAVER-NAVY BASE IN US</th></tr>
<tr><td>Naval Facilities Engineering Command (NAVFAC) and Expeditionary Warfare Centre (EXWC) has announced a new round of WEC testing at the US Navy's Wave Energy Test Site (WETS) off Marine Corps Base Hawaii, on the island of Oahu. The BOLT Lifesaver received funding in 2018 for the field test. The WEC was tested for its ability to power the on board monitoring package to communicate with and recharge the unmanned undersea vehicle (UUV).

WEC Type: Point absorber</td><td></td></tr>
<tr><th colspan="2">CARNEGIE-NAVY BASE IN AUSTRALIA</th></tr>
<tr><td>The Australian Navy is the first to use Wave Energy, collaborating with Carnegie Clean Energy, to supply electricity to Australia's largest naval base, HMAS Stirling on Garden Island [12].

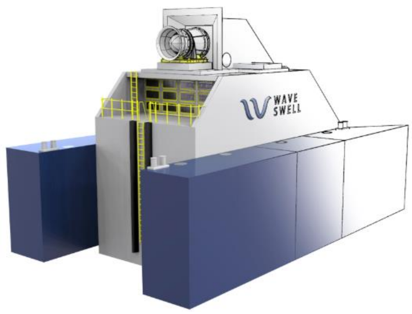
WEC Type: Point absorber</td><td>
</td></tr>
<tr><th colspan="2">OPT-NAVY BASE IN US</th></tr>
<tr><td>In 2019, OPT was awarded a contract from the US Navy to develop reliable and low-lost fibre optic mooring cables for the transmission of subsea sensor data to airplanes, ships and satellites. The fibre optic mooring cables would be incorporated into OPT's PowerBuoy [22].

WEC Type: Point absorber</td><td></td></tr>
<tr><th colspan="2">KEY CHARACTERISTICS</th></tr>
<tr><td colspan="2">
Aims – Provide electricity to navy bases on islands or perform as offshore communication and stand-alone power stations for unmanned subsea facilities for military use.
WEC types – All types of WECs can be applied.
Site selection – The plants can be built onshore/nearshore/offshore, close to a navy base.
Suitability – Applying small scale WECs to serve as offshore communication and power stations is a promising market, incorporating technologies such as, wireless charging, fibre optical mooring cables would reduce the LCoE to some degree. Larger WEC arrays could be used to meet the electricity demand of a navy base.
Scalability – Small scale WECs can be used to serve as offshore communication and power station. Larger scale WECs and even WEC arrays need to be applied to meet the electricity demand of a navy base.
Main evaluation criterion – Performance as offshore communication and power stations, cost of power production and reliability
</td></tr>
</table>

8. Combined wind-wave/solar-wave platforms:

The success of solar and wind onshore have driven their development in offshore locations. In the offshore environment, solar, wind and wave action are closely linked with one another. Wave Energy complements both wind and solar energy with its natural feature of hours' delay from wind peaks and almost opposite seasonal dependence compared with solar power. Wind-wave/solar-wave combined systems are therefore drawing increasing attention with their benefits of producing higher power density and smoother power output for offshore developments. The combined wind-wave/solar-wave platforms can be typically divided into two categories: co-located systems (combining renewables with individual foundation systems but with shared grid connection, O&M equipment, etc.) and hybrid systems (combining renewables within the same foundation structure) [26].

Table B8. Examples of combined wind-wave/solar-wave platforms and key characteristics

P37 HYBRID WIND-WAVE IN DENMARK	
The P37 system was designed by Floating Power Plant (FPP) and a 37 m scale model was tested at sea offshore of Denmark in 2008. The hybrid system combined wave and wind technology on the same structure, hosting 3 installed wave turbines with 11 kW for each and 10 installed WECs with 3 kW for each [27]. *WEC Type: Point absorber*	
P80 HYBRID WIND-WAVE IN DENMARK & UK	
FPP received €1.14 mln from the European Commission's Horizon 2020 research and innovation programme in 2015 to further develop a commercial P80 wind-wave hybrid platform hosting a single wind turbine with capacity around 2.3–5 MW and four WEC units rated at approximately 400–650 kW each. In 2015, FPP teamed up DP Energy to develop two UK projects: Dyfed Floating Energy Park Energy in Wales and Katanes Floating Energy Park in Scotland. The aim is to accelerate the first full scale P80. By 2017, FPP has raised over €15 million for the full scale P80 [27]. The in-house WEC type will be designed with respect to the selected sites. *WEC Type: Tailored WEC types for specified installation sites*	
KING ISLAND CO-LOCATED WIND-WAVE-SOLAR IN AUSTRALIA	
A 200 kW OWC by Wave Swell Energy is under construction off the coast of King Island, Australia and expected to be installed and operational by the middle of 2020. The project will be integrated with the existing high penetration wind and solar microgrids on King Island operated by Hydro Tasmania to demonstrate the role of Wave Energy within mixed renewables [15]. *WEC Type: Nearshore OWC*	

GARDEN ISLAND CO-LOCATED WAVE-SOLAR IN AUSTRALIA	
Carnegie Clean Energy has completed the commission of the wave-solar microgrid plant in Garden Island, Western Australia. The plant included three offshore 1 MW wave buoys, an onshore 2 MW solar PV array. The plant is producing green electricity from both solar and wave [12]. *WEC Type: Point absorber*	

KEY CHARACTERISTICS

- **Aims** – Use wave technology to complement wind and solar energy for higher power density and smoother power output.
- **WEC types** – All types of WEC can be utilised.
- **Site selection** – The plants can be built onshore/nearshore/offshore where wind, wave and solar resources are rich but highly out of sync with one another.
- **Suitability** – The potential of combining wind and wave has been demonstrated at laboratory scale. Larger commercial models are under development to understand better the value and suitability of developing combined renewables platforms.
- **Scalability** – The scalability of the combined platform can vary with respect to the capacity demand.
- **Main evaluation criterion** – Flat-and-smooth performance of electricity output, cost of energy production and reliability

9. WEC as navigation buoys:

Yoshio Masuda from Japan pioneered the use of Wave Energy to power a navigation buoy known as a floating OWC [28]. Since 1965, the technology has been widely used acting as a navigational aid.

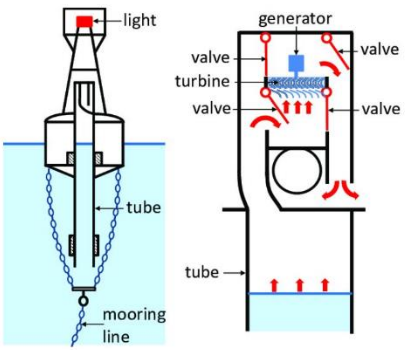


Figure B1. Layout of Masuda's navigation buoy

10. WEC for oceanography services:

The use in this area dates back to the 1940s US Navy's offshore data collection program [29]. Since the 1970s, WEC buoys have superseded the role of ships to collect ocean data such as current, waves, wind speed, salinity, etc., as they are cheaper to operate and maintain, and have smaller data errors than that from ships.

11. WEC for Luxury Resorts:

Green electricity can be generated from Wave Energy to power facilities in the tourism resorts. Some research has highlighted that luxury resorts can be promising markets for WEC commercialization due to the fact that most resorts are privately owned and therefore WEC implementations will not be highly dependent on the support and acceptance from government [30].

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Annex C – Wave Energy Scalability and Technical Challenges

1. Scalability for WECs

To attract investors and realise the potential utility scale contribution to the 2050 energy mix, Wave Energy technologies need to be able to demonstrate their scalability. This is achieved by scaling up the power capacity by:

- Increasing the scale of a single WEC device;
- Integrating a number of WECs in a wave power plant.

Three parameters are in common use to characterise the performance of a WEC device:

- **Power matrix** (unit of kilowatts): shows the electric power outputs of a WEC according to different sea states.
- **Capture width** (unit of metre): represents the ratio of the electric power extracted by a WEC to the theoretical wave power available per metre of wave crest width (assuming unidirectional waves).
- **Capture width ratio** (unit of %): is the capture width normalised by the characteristic dimension of a WEC.

In unidirectional waves, the characteristic dimension is generally equivalent to the characteristic width, which is the physical width of a WEC device orthogonal to the wave propagation direction as shown in Figure 3 in the main document. For a cylindrical heaving point absorber, the device diameter is its characteristic width. For an attenuator, the characteristic dimension is usually taken as the length of the device or the typical wave length [4]. Nevertheless, it is not straightforward to define the characteristic dimension in a realistic sea-state, which instead of being linear, unidirectional and monochromatic, is non-linear, multi-directional and polychromatic. It is also not clear how performance may be compared between device types.

1.1. *Scalability of a single WEC*

Generally, there are two ways to describe the scalability of a WEC device:

- **The theoretical maximum capture width** is generally used as a baseline to predict the possible maximum power in theory.

- **The actual capture width ratio** is commonly used to evaluate the actual performance of a WEC device, measured by experiment or predicted by numerical model.

The theoretical maximum capture width for different WEC concepts have been studied by Evans [1], Newman [2] since 1976. Evans [1] derived the formula for a axisymmetric oscillating body and Newman [2] studied articulated-bodies. In 2013, Falnes and Kurniawan established a general formula of the theoretical maximum capture width without any assumptions of the body shape or size [5]:

$$CW_{max} = N(i) * \lambda/2\pi,$$

where N(i) is the number of degrees of freedom. Table C1 shows the theoretical maximum capture width for different WECs. It can be found that:

- The theoretical maximum capture width is related only to the number of degrees of freedom and the wave climate but not to the device dimension.
- A WEC with most degrees of freedom can achieve the highest maximum capture width.
- Under optimal control, the ‘antenna effect’ means that it is possible to achieve a capture width ratio larger than 100% [9].
- An articulated- body (dominated by heaving and pitching motions) presents the maximum capture width, three times that for a heaving body and 1.5 times that for a pitching or surging body.

Table C1. Theoretical maximum capture widths for different WEC concepts

Oscillating mode	Maximum capture width (λ is the wave length)
Heaving	λ/2π
Pitching or surging	λ/π
Heaving and pitching or surging	3λ/2π
All WECs	N*λ/2π (N as a function of oscillating modes of a WEC)

Nevertheless, WECs need to operate in realistic sea states and technical challenges such as the performance of actuators and wave forecasting remain to be overcome before optimal control can be practically implemented and most WECs rely on passive control. In real sea conditions, the theoretical maximum capacity can never be achieved, and the actual capture width ratio is a more realistic approach to presenting the performance of a WEC device.

The actual **capture width ratio** is used to represent the efficiency of a WEC and is selected as a measure to compare the performance of WECs with different working principles. A database of the performance of a large number of WECs is summarised in Table C2. It is adapted from the comprehensive review work from Barbarit [3]. More than a hundred WEC studies based on numerical, lab and field tests are considered. In the database, we classify the technologies by working principle as: OWC, overtopping and oscillating body (heaving body, pitching body and articulated body). The classification of WECs follows that given in Figure 2 in the main document. According to the database in Table C2, the actual capture width ratios as a function of characteristic dimension and wave resource with respect to different WEC concepts are presented in Figure C1 to Figure C2. In addition, statistical analysis is performed based on the database to further quantify the results, as given in Table C3. Some general conclusions can be drawn:

- Unlike the theoretical prediction, the articulated body moving in heave and pitch combined does not perform better than the WECs moving in pitch or heave alone, although this result is not necessarily reliable due to the small sample size.
- The capture width ratio appears to reach a peak and then reduce with increasing characteristic dimension for oscillating body WECs. This means that the performance is limited by the available resource and is not related to its characteristic dimension.
- The capture width ratio of the overtopping device seems to be constant irrespective of its characteristic dimension, which means that for these terminator WECs increasing the size of the device leads to increased power.
- For pitching body WECs, the capture width ratio increases with characteristic dimension. The improvement with increasing width of these terminator WECs is likely to be because a wider pitching flap has a greater proportion of its surface area unaffected by the fluid flowing round the edges than a narrower pitching flap. These edge effects reduce as the dimension is increased.
- OWC, heaving body and pitching body WECs appear generally to increase to a peak performance and then reduce with increasing wave resource, overtopping WEC performance is relatively constant, and the data for the articulated body are too few to be conclusive.
- Pitching body WECs appear to achieve the highest capture width ratios reaching 80% under numerical simulation and 72% in laboratory tests.
- The pitching body in the data summarised here performs best with an indicative mean capture width ratio of 35%; OWC, floating overtopping, heaving body and articulated body achieve capture width ratios of approximately 20%; fixed-overtopping WECs achieve capture width ratios of 13%.
- Of the WECs considered in the dataset, the overtopping device is largest, with a characteristic dimension around 200 m, the articulated body is approximately 100 m long and by contrast, the OWC, heaving body and pitching body, are much smaller, approximately less than 30 m.
- The WEC technologies considered here are designed to perform under typical wave resources between 10 kW/m to 50 kW/m which fit well with the exploitable wave resources in the UK (see Figure A3 in *Annex A*).

Table C2. Database of WEC Performance adapted from the work in [3]

Category	Sub-category	Device	Characteristic dimension (m)	Capture width ratio (%)	Resource (kW/m)	Method	Power take-off	Ref.
OWC	Fixed	National Engineering Lab (NEL) OWC	22/width	55	30	Lab test	N/A	[3]
		Swan DK3	16/width	20	16	Lab test	N/A	[3]
		Mutriku	6 /width	7	26	Lab test	Pneumatic power	[11]
		NEL OWC	30/width	22 27 29 23	16 23 27 37	Field test	Wells turbine	[3]
		Pico pilot plant	12/width	20	38	Field test	Wells turbine	[12]
	Floating	NEL floating terminator	22/width	24	54	Lab test	N/A	[3]
		NEL floating	20/width	41	54	Lab test	N/A	[3]
		KNSWING attenuator	150/length 240/length	25 15	20 20	Lab test	Air compression	[13]
		V-shaped floating OWC	12.5/width	12 14 15 12	15 23 27 36	Lab test	Pneumatic power	[14]
		Mighty Whale	30/width	15	16	Field test	Wells turbine	[15]
		Spar buoy	8/diameter 12/diameter	17 23	31	Numerical modeling	Pneumatic power	[16]
		OE buoy	24/width	23 32 35 24	15 22 27 37	Numerical modeling	Pneumatic power	[17]
Overtopping	Fixed	SSG	10/width	23	19.5	Lab test	Discharges	[18]
		PowerPyramid	125/width	12	16	Lab test	Discharges	[3]
		Sucking Sea Shaft	125/width	3	16	Lab test	Discharges	[3]
	Floating	WaveDragon	259/width 65/width 97/width 300/width 300/width 300/width 300/width	23 27 18 26 23 21 22	16 6 6 12 21 26 15	Lab test Field test	N/A Propeller turbines	[7] [19]
Wave-activated body	Heaving body	DWP	10/diameter	20	16	Lab test	Mechanical damping	[3]
		AquaBuoy	6/diameter	20 17 14 21	12 21 26 15	Lab test	Mechanical damping	[3]
		SEADOG	5.7/diameter	24 16 16 21	12 21 26 15	Lab test	Mechanical damping	[3]
		Wavebob	15/diameter	40 51 46 45	12 21 26 15	Lab test	Mechanical damping	[3]
		Bolgepumpen	5/diameter	6	16	Lab test	N/A	[3]
		Tyngdeflyderen	30/diameter	12	16	Lab test	N/A	[3]
		LifeSaver	12.5 /diameter	12.5 12	27 26	Field test	permanent magnet synchronous generator	[3]
		Bottom-referenced buoy	3/diameter	4 4 4 3	15 22 27 37	Numerical modeling	Numerical Damping	[17]

	Floating two-body	20/diameter	27 29 36 27	15 22 27 37	Numerical modeling	Numerical Damping	[17]
	Two-body heaving device	15/diameter	25	31	Numerical modeling	Numerical Damping	[3]
	SEACAP	10/diameter 11 15 16.5 20	4 3 6 6 9	25	Numerical modeling	Numerical Damping	[3]
	LifeSaver	10/diameter	19	40	Numerical modeling	Numerical Damping	[3]
	RM3	20/diameter	16	34	Numerical modeling	Numerical damping	[20]
	Bottom-referenced submerged heave-buoy	7/diameter	9 13 13 8	13 19 22 34	Numerical modeling	Numerical damping	[17]
Pitching body	Biopower	6.6/width	45	38.5	Lab test	Viscous dashpot	[21]
	Lancaster flexible bag	20/width	9	51	Lab test	N/A	[3]
	Lancaster Clam	27/width	23	51	Lab test	N/A	[3]
	Wave plunger	15/width	16	16	Lab test	N/A	[3]
	Top-hinged flaps	12/width	25	25	Lab test	N/A	[22]
	WEPTOS	2.9/width 3.6/width 4.8/width 5.4/width 6/width 8.3/width 9.6/width	10 12 15 15 19 32 25	16 16 16 9 16 16 26	Lab test	Mechanical damping	[3]
	Wavepiston	15/width	15 8	12 3.5	Lab test	Mechanical damping	[23]
	Edinburgh Duck	30/width	65 75 79 68	16 23 27 38	Numerical modeling	Numerical damping	[24]
	Vertical flaps on fixed frame	30/width	31 37 30	25 50 25	Numerical modeling	Numerical damping	[3]
Articulated body	Pelamis	120/length	7	12	Filed test	Hydraulic	[3]
	DEXA	57/length	8	26	Lab test	Mechanical damping	[25]
	M4 WEC	85/length	21	25	Lab test	Mechanical damping	[4]
	McCabe Wave Pump	40/length	40	N/A	Lab Test	Mechanical damping	[26]

The power take-off (PTO) of a WEC is an important component affecting its performance. Referring to the database, it can be found there are mainly 6 types of PTO are considered under field, lab and numerical tests: hydraulic, hydro, pneumatic, linear generator, mechanical damping and numerical damping. For numerical modeling, it can be relatively easy to tune the numerical PTO damping to achieve best performance. However, in realistic conditions, the physical performance of a typical PTO can significantly affect the performance of a WEC. This means a WEC with high hydrodynamic performance may present at a low capture width ratio by having low PTO performance. Therefore, it is important to understand carefully the actual capture width ratio of a WEC which may depend on a large number of parameters such as: device dimension, wave regime and PTO performance, etc.

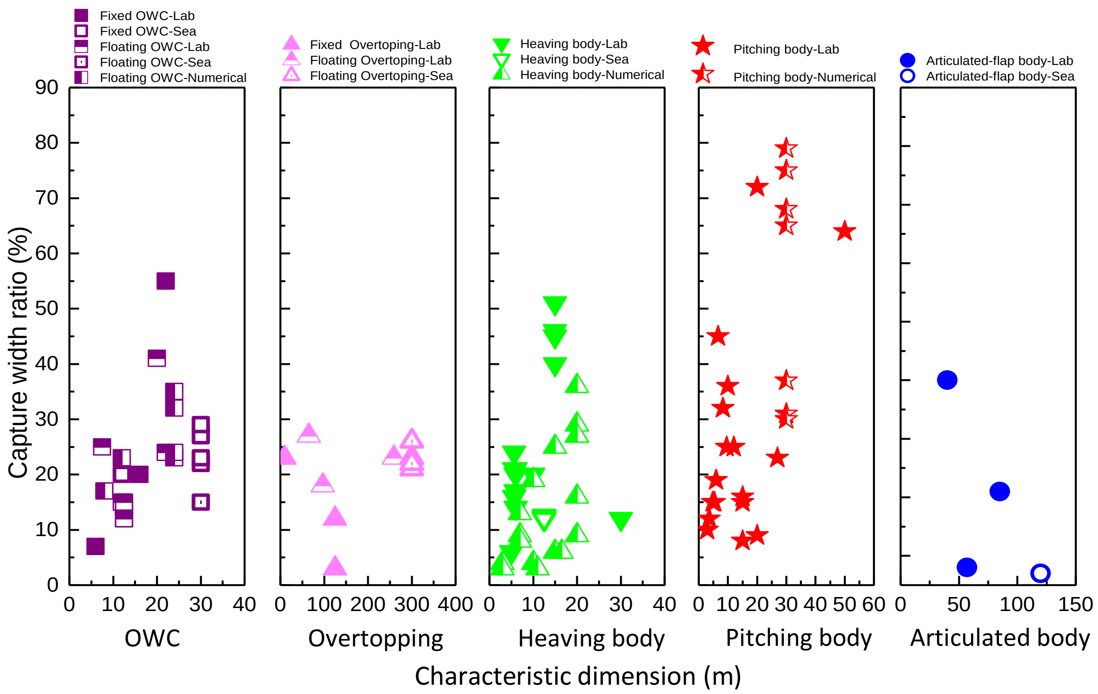

Figure C1. Capture width ratios of WECs as a function of characteristic dimension with respect to different working principles.

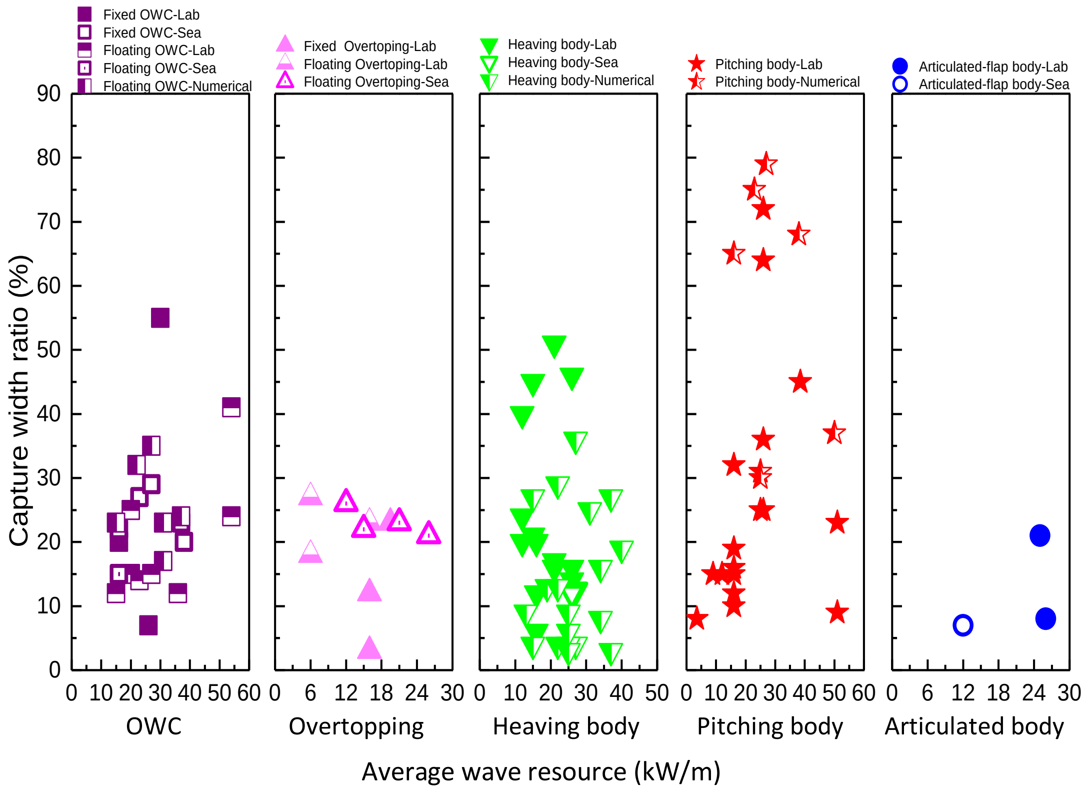

Figure C2. Capture width ratios of WECs as a function of wave resource with respect to different working principles.

Table C3. Indicative actual characteristic dimension and capture width ratio as a function of WEC working principles based on the statistical analysis of the database shown in Table C2.

	OWC		Overtopping		Oscillating body		
	Fixed	Floating	Fixed	Floating	Heaving	Pitching	Articulated
Mean characteristic dimension (m)	22	19	87	232	11	18	75
Mean capture width ratio (%)	25	23	13	23	18	35	19

In addition, we summarise the results by classifying the WECs based on their orientation to the wave front as given in Figure C3 and Table C4. As observed:

- Each of the main categories can be further divided into different sub-categories based on the working principles, as shown in Figure 3 of the main report.
- It appears that the performance of a WEC is more strongly related to its working principles than its size and orientation.
- The terminator WEC has the best performance with capture width ratio about 30%, followed by point absorber and attenuator with capture width ratios around 20%.
- As expected, the point absorber has the smallest dimension around 20 m. This fit wells with the definition of a point absorber that its size is relatively smaller than one wave length. By contrast, the attenuator exhibits the largest dimension around 110 meters and the terminator exhibits the intermediate level.

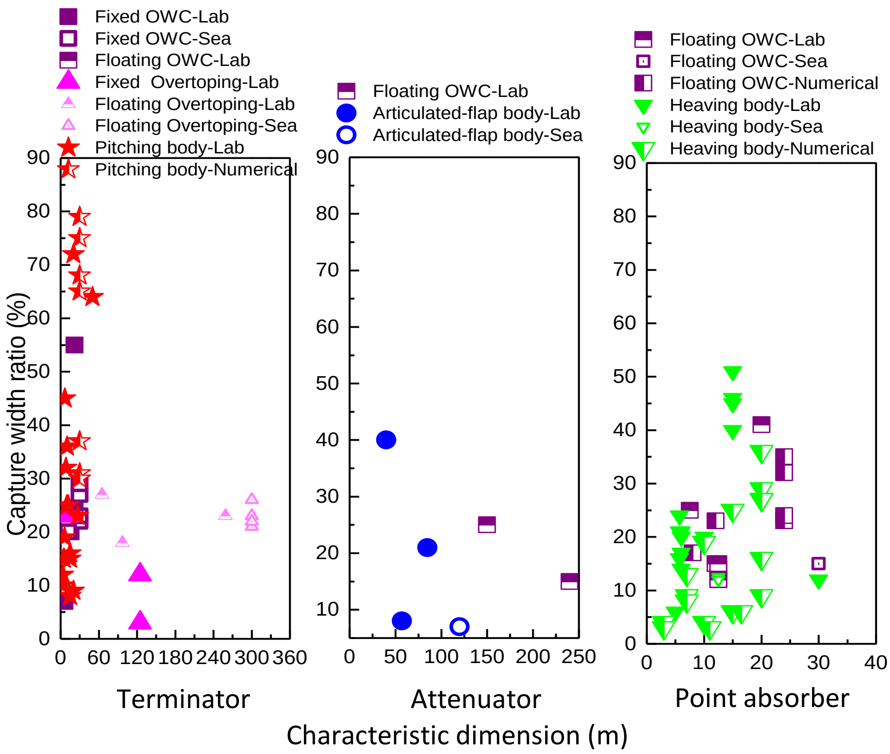

Figure C3. Capture width ratios of WECs as a function of characteristic dimension with respect to different WEC orientation.

Table C4. Indicative actual capture width ratio and characteristic dimension as a function of WEC size and orientation. The statistical analysis is based on the database shown in Table C2.

	Point absorber	Attenuator	Terminator
Mean characteristic dimension (m)	16	115	63
Mean capture width ratio (%)	19	19	30

1.2. 2 MW pilot WEC plant and 500 MW commercial WEC plant rough sizing

Assuming a 2 MW pilot WEC plant can be achieved in the next 5 years and a 500 MW commercial WEC plant by 2050 in the UK. By considering the installation at a site similar to EMEC with wave resource of 25 kW/m [10], the sizing of these two plants can be roughly designed as given in Table C5, with respect to different WEC concepts based on the results from Table C3.

To visualise the scale of a 2 MW WEC plant, we roughly compare the size a 2 MW wave plant to a 2 MW wind turbine. By comparison to a typical 2 MW wind turbine with diameter of 83 m and swept area of 5,410 m^2, a 2 MW heaving body WEC plant interacts with approximately 3,800m^2 water surface area (without consideration of the space between each WEC). As a result, it can be noted that the size of a WEC plant needs to be more or less of the same order as the swept area of a wind turbine to achieve the same capacity.

Table C5. Up-scaled design for a 2 MW pilot WEC plant and a 500 MW commercial WEC plant

Categories	Sub-categories	Number of WECs required for 2 MW plant	Number of WECs required for 500 MW plant
OWC	Fixed	14	3,500
	Floating	18	4,500
Overtopping	Fixed	8	2,000
	Floating	2	500
Oscillating body	Heaving	40	10,000
	Pitching	12	3,000
	Articulated body	6	1,500

2. Key challenges and lessons learnt

Table C6 lists details of ten leading WE technologies that have achieved or are on the verge of grid-connection in chronological order to demonstrate the significant steps in their development and current status.

Clearly, some operations have been closed, whilst some have been successfully commercialized in recent years or are developing into larger scale units and arrays. In the past, mismatches between financial and technical drivers have hampered progress in the sector, and costs remain high. Programmes that are still active are developing into grid applications at a steady pace, allowing for changes of direction and incremental improvements. Key technological and non-technological challenges remaining are given in Table 3 and Table 4 of the main document.

Table C6. Wave Energy development timeline for ten leading devices

WEC category			Timeline (<2000, 2005, 2010, 2012, 2014, 2016, 2018, 2020)			
OWC	Fixed	LIMPET	75 kW	world's first on-shore grid-connected WEC (at Islay, UK), 500 kW	operation closed	
OWC	Fixed	Mutriku Breakwater Wave Plant	initial design: breakwater	final design: OWC-breakwater	grid-connected at Mutriku, Spain 2 GWh in 2020	
OWC	Floating	OE Buoy	lab tests	OE12, 1:4 scale model (20 kW) sea tests	OE35 grid-connected at Hawaii, US	
Oscillating Bodies	Point Absorber	Pesedon Floating Power Plant	lab tests	build P37 (41 kW)	P37 grid-connected P80, ~ 10 MW >14,000h grid-connected in 2014	
Oscillating Bodies	Point Absorber	CETO	CETO1&2 (1:6 scale)	CETO3 80 kW CETO5 240 kW	CETO5 > 14,000h grid-connected in 2017 CETO6, ~ 1 MW	
Oscillating Bodies	Point Absorber	Seabased		Seabased at Maren 2x15 kW grid- connected	Sotenäs project, 1 MW grid-connected (34 units array)	
Oscillating Bodies	Point Absorber	Eco Wave Power		off-grid in Jaffa, Israel	Gibraltar project, 25-year power purchase	
Oscillating Bodies	Attenuator	Pelamis	1:80, 1:35, 1:7 scale	P1 (750 kW) at EMEC world's first offshore grid-connected in 2004; 3 x P1 off coast of Portugal in 2008; 2 x P2 at EMEC from 2012	operation closed	
Oscillating Bodies	Terminator	Oyster	lab tests	350 kW Oyster1 grid-connected in 2009 3x800 kW Oyster 800 grid-connected in 2012	operation closed	
Oscillating Bodies	Terminator	Waveroller	1:3 scale	2 x 15 kW units at EMEC	3 x 100kW at Peniche in Portugal, grid-connected	a 350 kW unit at Peniche
Overtopping	Floating	WaveDragon	1:45, 1:50, 1:4.5 scale	20 kW at Nissum Bredning, Denmark , grid-connected in 2003	operation closed	

Lessons learnt from review and analysis of numerical, laboratory and field test data of WECs with different working principles [3], [6], [7] to assess scalability (summarised in Figure C1 and Table C3) and identify remaining challenges is summarised in Table C7. Approximate values for Capture Width Ratio (CWR) and Characteristic Dimension (D) are given together with notes on typical deployment arrangements and technological challenges.

Table C7. Representative technical lessons learnt from Wave Energy projects

Categories	Lessons learnt			
OWC Oscillating Water Column	**Location**	**Orientation**	**CWR**	**D**
	Shoreline Offshore	Point absorber Terminator	20%	30 m
	Example:	Limpet shoreline OWC installation was in continuous operation producing power for over ten years from 2001 to 2012 before being decommissioned. Although designed with a 500 kW capacity, this was downgraded to 250 kW as a result of the low efficiency of the power take-off and lower than expected resource potential at the deployed site.		
	Notes:	• Shoreline installations will have better accessibility for O&M. • In floating applications, power production is limited by the available resource and does not increase with characteristic dimension.		
	Key challenge:	• Power take-off technology. • Evaluation of the exploitable wave resource.		
Overtopping	**Location**	**Orientation**	**CWR**	**D**
	Shoreline Offshore	Terminator	13%	200 m
	Example:	WaveDragon: A large overtopping WEC that is scaleable, but for which the ratio between output power and material volume is typically low. Prototype launched in 2003 and achieved more than 20,000 hours supply to the grid.		
	Notes:	• Shoreline installations will have easier accessibility for O&M than floating installations. • CWR is approximately constant irrespective of its characteristic dimension, which means that for these terminator WECs increasing the size of the device leads to increased power production.		
	Key challenge:	• Cost reduction through innovative materials		
Oscillating body	**Location**	**Orientation**	**CWR**	**D**
Heaving body	Offshore	Point absorber	20%	<30 m
	Example:	SeaBased/AquaBuOY: The 'End-stop' can be a big problem for heaving body WECs under large waves. SeaBased solved this problem by employing springs in the fore and aft ends of the linear generator and AquaBuOy using an elongated hose pump and piston assembly.		
	Notes:	• Poor accessibility for O&M, likely use of tow to shore strategy for maintenance. • Power production of point absorbers is limited to the site conditions and so, rather than increasing the characteristic dimension of a single device, many devices are needed in a wave power plant and the moorings a significant component of the cost.		
	Key challenge:	• Survivability. • Cost reduction in mooring system. • Tuning and control system.		

Categories	Lessons Learnt			
Pitching body: Oscillating Wave Surge Converter	**Location**	**Orientation**	**CWR**	**D**
	Nearshore	Terminator	35%	30 m
	Example:	Oyster: scalable terminator Oscillating Wave Surge Converter WEC deployed at EMEC 2009 to 2015 and accumulated over 20,000 hours of operation with the second generation Oyster 800 from 2011 to 2015.		
	Notes:	• Very poor accessibility for O&M and installation (typically submerged sea bed applications). • Although capture width ratio is limited by the wave conditions, when operating as a terminator WEC, power production increases with characteristic dimension.		
	Key challenge:	• Foundation design and installation for bottom fixed devices. • Offshore operations and planning • Extreme loads		
Articulated body	**Location**	**Orientation**	**CWR**	**D**
	Offshore	Attenuator	20%	100 m
	Example:	Pelamis: deployed at EMEC 2004 to 2014, and produced over 15,000 hours of operation with its second-generation from 2010 to 2014.		
		• Poor accessibility for O&M, likely use of tow to shore strategy for maintenance. • Power production performance is limited by the available resource and is not related to its characteristic dimension, which should be approximately equal to the wave length for attenuator WECs.		
	Key challenge:	• Reliability of hinge joints. • Design for wave loading in beam seas		

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Annex D - The development of Wave Energy Policy in the UK

1. History and Context

Since the early 2000's, the Wave Energy innovation policy landscape within the UK has been particularly complex, with various policies being managed by numerous different funding agencies across three levels of government, i.e. Scottish Government, the UK Government and the EU. There have also been rapid changes within policy, with a variety of new schemes being developed, each with their own eligibility criteria and objectives. The main changes within the policy landscape however has been the shift from commercially focused, full-scale device RD&D programmes in the mid-2000s and early 2010s, to innovation programmes supporting early-stage development through to largescale prototype demonstration, i.e. Wave Energy Scotland.

It must also be acknowledged that public funding investment for Wave Energy has been historically low and intermittent when compared to other renewable energy technologies. Since 1974, ocean energy has been allocated approximately $1.8bn (to both Wave Energy and Tidal Energy) of International Energy Agency (IEA) members' public energy R&D budget versus $25bn for solar PV and $7.5bn for wind energy [1]. Availability of funding for Wave Energy development has also been much more intermittent than most other energy technologies, mainly split across two phases during the 1970s and 1980s and the 2000s and 2010s.

Looking more recently, between 2000 and 2017, £545m of UK public grants were awarded to marine energy. Of the amount awarded to R&D activities, tidal stream received 47% (£178m), followed by wave at 27% (£102m) and cross-cutting marine R&D at 26% (£96m). Taking wave and crosscutting marine energy R&D together, £198m has been spent on Wave Energy-related projects, with a further £170m awarded to the installation, operation and maintenance of marine energy test infrastructure [2].

Table D1. Summary of UK public funds awarded for wave and tidal stream energy R&D 2000–2017

RD&D AREA	PUBLIC FUNDING (£M 2015)	SHARE
Wave	102.1	27%
Tidal stream	177.6	47%
Cross cutting	95.8	26%
Sub total	375.5	
Test-infrastructure	169.4	
Total	544.8	

However, despite a large number of UK government publications calling for the need to support Wave Energy and almost £200m of public funds being invested in the UK Wave Energy related innovation since 2000, the removal of formal Wave Energy targets in the 2010s and a decline in vocal support from UK government has been a contributing factor to Wave Energy technology remaining some distance away from full commercialisation.

2. Overview of Wave Energy policy mechanisms

Marine renewables policy mechanisms in the UK can be categorised into three broad areas, namely:

- Broad policy market drivers, i.e. increasing carbon reduction targets or energy mix/security
- Specific market enablers, i.e. production incentives, tariffs and subsidies
- Specific targeted grant programmes

Policies and interventions enacted at a Scottish Government, United Kingdom and European level have affected each of these three broad areas respectively.

2.1. *Broad policy market drivers*

In 2009 the EU released the original renewable energy directive, which established an overall policy for the production and promotion of energy from renewable sources in the EU. It required the EU to fulfil at least 20% of its total energy needs with renewables by 2020, which was to be achieved through the attainment of individual national targets, of which the UK was a part. In December 2018, a revised renewable energy directive entered into force, as part of the Clean energy for all Europeans package, aimed at keeping the EU a global leader in renewables and, more broadly, helping the EU to meet its emissions reduction commitments under the Paris Agreement [3]. The new directive established a new binding renewable energy target for the EU for 2030 of at least 32%, with a clause for a possible upwards revision by 2023 [4]

Subsequently in 2019, the UK Government became the first major economy in the world to pass laws to end its contribution to global warming by 2050. The 2050 target will require the UK to bring all greenhouse gas emissions to net zero by 2050, compared with the previous target of at least 80% reduction from 1990 levels [5]. Clean growth is also at the heart of the UK modern Industrial Strategy [6], with sector deals being agreed for Offshore Wind and a forthcoming Maritime Sector Deal, which will aim to deliver benefits to the UK economy, supported by the development of the tidal stream and Wave Energy industries [7]

In addition, set up in 2005, the EU Emissions Trading Scheme (EU ETS) is the world's first international emissions trading system, setting a price for carbon. It remains the biggest scheme, accounting for over three-quarters of international carbon trading. Currently about to enter its fourth phase (2021-2030) the EU ETS scheme will enable the EU to achieve the EU's 2030 emission reduction targets in line with the 2030 climate and energy policy framework and as part of the EU's contribution to the 2015 Paris Agreement [8].

2.2. *Specific market enablers*

Apart from the promotion of renewables, planning instruments and other specific levers devolved to the Scottish Government, energy policy is largely reserved to the UK government. Previously this included a subsidy framework offering multiple Renewable Obligation Certificates (ROCs) for each MWh generated for wave and tidal energy and was a significant driver of all UK renewables deployment from 2002. A regime of five ROCs for wave and tidal technologies provided a notional income level of around £300 per MWh [9]. However, following a government white paper in 2011 on Electricity Market Reform (EMR) and the subsequent Energy Act in 2013, multiple ROCs were removed and replaced by the Contracts for Difference (CfDs) framework. CfDs are a long-term contract between an electricity generator and LCCC (a body established by Government). The contract enables the generator to stabilise its revenue at a pre-agreed level (the strike price) for the duration of the contract [10]. In 2014, the strike price for marine (wave and tidal) was confirmed at £305/MWh (or 30.5p/kWh), similar to previous ROC payments. However, contracts were reduced to a 15-year period, which represented a 25% reduction in revenue compared to that under the 20-year ROC. Subsequently, in 2016 a strike price of £300/£295 MWh was agreed for Wave Energy, but the ring-fenced allocation of funding to guarantee deployment of marine renewables (minima) was removed within CfDs, requiring Wave Energy to compete with more mature technologies and larger projects, i.e. offshore wind, with prices of circa 10p/kWh and greater economies of scale in the same CfD round, which effectively made Wave Energy projects un-competitive

2.3. *Specific targeted grant programmes*

There have been a variety of grants and support mechanisms available to Wave Energy developers from a number of agencies within Scotland, the UK and at European level, including enterprise agencies, i.e. Scottish

Enterprise, Highlands and Islands Enterprise, InnovateUK and research and development programmes such as the EU's Horizon 2020 Programme. For Wave Energy, of note is the establishment of Wave Energy Scotland [11] by the Scottish Government, which is fully funded by the Scottish Government and can provide up to 100% funding to eligible technology projects to support the development of Wave Energy in Scotland [12]

3. Summary

The gearing of Wave Energy innovation support mechanisms towards full-scale demonstration in the mid-2000s by the UK government, as described in earlier sections, developed an overly positive view by both government and industry as to the speed at which Wave Energy could be commercialised, and did not consider the substantive difference in the engineering and environmental challenges faced in developing Wave Energy devices at scale and with high survivability rates. This led to the development of a sector culture that focused on developing higher TRL technologies at a quicker pace than the technologies and components could reasonably withstand (with over a third, £69m of £200m between 2000-2017, committed to late-stage technology demonstration rather than earlier stage R&D) [2] At the same time, the drive towards rapid commercialisation of Wave Energy attracted market incumbents, including OEMs, VCs and energy utilities, who were attracted by the global renewable energy resource potential of Wave Energy and its perceived ability to provide grid-scale renewable generation. This subsequently led to an over-commitment by developers within the sector as to the rate and scale of commercialisation that was possible, in order to secure private sector match funding required for securing public subsidies and subsequent investment. Finally, as the rate of the expected commercialisation slowed and ambitious targets failed to be fulfilled, investor expectations were unmet, leading to a reduction in the validity of Wave Energy technology as an investable proposition.

With a combination of low UK government and investor confidence, a reduction in UK government funding and the financial crisis of 2008, funds were withdrawn from the sector, creating a difficult financial environment for Wave Energy developers and leading to the failure of two Wave Energy market leaders in 2014 and 2015 respectively. From this point, the UK Government began to step back from Wave Energy, leading to its share of funding dropping from an average of 47% between 2000 and 2016 to just 31% in 2016 [2]. In contrast, the EU and the Scottish Government continued to increase their share of support for the technology.

Currently led by the Scottish Government through Wave Energy Scotland[11], learning from past policy mistakes in the Wave Energy sector has led to an innovation system that has helped to address many of the issues as set out previously. However, in the face of the withdrawal from the EU and reduction in levels of support to Wave Energy from UK government this system is still likely to face disruption, which could have an impact on the level of R&D support available. Notwithstanding this, this form of innovation support for Wave Energy has created a system far better placed to deliver a commercial technology than previous attempts, with measurable improvement across some key innovation indicators already being detected [2].

4. Policy recommendations

From previous work looking at the recommendations to support the growth of the Wave Energy sector within the UK there have been a number of suggestions. Hannon *et al.* (2017) [2] recommends the following 10 policy recommendations:

RETAIN ACCESS TO EU INNOVATION FUNDING POST-BREXIT

Brexit poses a major risk to EU Wave Energy funding, accounting for 27% (£53m) of all Wave Energy-related RD&D committed since 2000, and in 2016 EU funding (£6.3m) was greater than that from the UK Government (£6m). It is essential that the UK retains access to EU innovation funds following Brexit negotiations, especially EU Framework Programmes (FPs) (i.e. Horizon2020). This need for funding consistency was echoed in comments recorded at a 2-day Wave Energy workshop in January 2020, delivered by the Supergen ORE Hub and consisting of 40 industry, academic and policy stakeholders. The need for continuity in UK Government and EU funding support was highlighted as a key requirement for the development of the Wave Energy sector. Although, it was made clear during the workshop and subsequent interviews with industry stakeholders, that funding is required to be in the form of revenue support, rather than shorter term grant support.

This revenue support could be linked to the level of local content in developing Wave Energy devices, subsequently incentivising increased economic development.

ALLOW TIME FOR NEW UK WAVE ENERGY INNOVATION POLICY LANDSCAPE TO TAKE EFFECT

The UK Wave Energy innovation system has undergone a major reconfiguration over the past few years and the effects of this have not yet been fully felt. This new configuration must be given time to take effect before its efficacy is critiqued and decisions made to engage in any additional wide-scale restructuring.

DEVELOP A LONG-TERM SCOTTISH WAVE ENERGY STRATEGY IN A NEW POLITICAL ORDER

With the UK Government significantly reducing its support for Wave Energy and the threat of EU funds being withdrawn after Brexit, the Scottish Government could find itself acting alone in developing Wave Energy technology. Consequently, a strategy must be put in place that presents a credible path towards delivering a commercial Wave Energy device in Scotland that is resilient to the potential withdrawal of UK Government and/or EU funds.

IMPROVE CO-ORDINATION OF UK ENERGY INNOVATION POLICY LANDSCAPE

There are still significant opportunities to improve the degree of co-ordination of Wave Energy RD&D support both within and across different levels of government. It is recommended that, to ensure coordination with bodies operating at different levels of government, these new networks engage closely with both the devolved administrations (e.g. the Scottish Government) and the EU. Furthermore, a top-down body responsible for Wave Energy at UK level, similar to Scotland's WES model, could also improve coordination of Wave Energy RD&D.

SHARE AND SYNTHESIZE LESSONS FROM PAST AND PRESENT WAVE ENERGY INNOVATION PROGRAMMES

Outputs from publicly funded later stage Wave Energy RD&D projects have not traditionally been made available for public consumption because of issues around IP protection and private sector match funding. In contrast, the Scottish Government's WES programme and the EU's FPs require awardees to share their key findings via project reports, enabling the wider sector to learn lessons from past projects and avoid making the same mistakes. It is critical that this approach is applied across all future publicly funded Wave Energy RD&D programmes in the UK and efforts should also be made to capture knowledge generated from past public RD&D projects

ACKNOWLEDGE THAT SUPPORT FOR WAVE ENERGY HAS BEEN HISTORICALLY LOW AND INTERMITTENT

Since 1974, ocean energy has been allocated approximately $1.8bn3 of IEA members' public energy RD&D budget versus $25bn for solar PV and $7.5bn for wind energy. Furthermore, funding for Wave Energy has been much more intermittent than most other energy technologies, split across two phases during the 1970s and 1980s and the 2000s and 2010s, increasing the likelihood of significant knowledge depreciation between these periods of concentrated investment

AVOID COMPETITION FOR SUBSIDIES WITH ESTABLISHED LOW CARBON ENERGY TECHNOLOGIES

Emerging technologies, such as Wave Energy, can be out-competed for subsidies on a cost basis when in direct competition with significantly more mature technologies. Specific examples include separating Wave Energy from the same EMR CfD allocation as significantly cheaper technologies such as offshore wind energy and avoiding Wave Energy becoming bundled into wider marine energy RD&D programmes where it must compete with more mature technologies such as tidal range and tidal stream. This was

AVOID NEED FOR PRIVATE SECTOR MATCH FUNDING TO SUPPORT WAVE ENERGY RD&D

The need to secure private sector investment to be awarded public grants has placed intense pressure on Wave Energy developers to 'fast track' their innovation timeline and avoid knowledge exchange in a bid to protect their IP. Furthermore, the financial crisis and Wave Energy's slow progress saw private sector funds become more difficult to secure, in turn making access to public funds difficult. State aid compliant procurement frameworks such as WES can avoid the need for private sector match funding, offering a 100% intervention rate.

SUPPORT WAVE ENERGY NICHE MARKET FORMATION

A shift towards demonstrating Wave Energy devices in niche markets (e.g. off-grid islands, aquaculture) enables developers to learn valuable lessons through 'learning by doing' in both real-world ocean and market environments, as well as providing both government and investors with greater confidence in the technology's prospects. When Wave Energy is ready for full-scale demonstration, funds for Wave Energy RD&D should facilitate deployment in 'real-world' niche markets. This support for niche market formation was also echoed in the Supergen ORE Hub Wave Energy workshop in January 2020. Niche markets were identified as one route for developers to test designs and adapt devices to prove reliability and survivability, raising confidence in Wave Energy as a reliable energy source.

ENABLE EASY ACCESS TO WAVE ENERGY TEST FACILITIES

Access to the UK's world-class test facilities has required developers to secure public sector funds via open competitions, and the corresponding levels of private sector match funding. This process involves significant time and effort, channeling developers' resources away from RD&D. To ensure developers can quickly and easily access these facilities, a state aid compliant UK-wide 'innovation voucher' scheme should be established to enable 'free at the point of use' access to those that have passed through preliminary stage-gated phases of development with independently verified positive results, building upon lessons learnt from the Europe-wide test infrastructure access schemes such as FORESEA and MARINET.

There has also been recent work compiled and published by Scottish Renewables (2019) [7], which sets out a proposed route to market for marine energy (including Wave Energy), and looks to address the policy and financial barriers as discussed in earlier sections. The paper proposes three interlinked support models, illustrated in Figure 1 in the main document, which fit with the different stages of current technology development and UK government policy, to bring marine energy to a cost competitive position and allow for technology progression, namely:

An innovation Power Purchase Agreement (iPPA)

The iPPA can be used to support technology developers to deliver projects of up to 5MW whilst protecting consumers from costs by providing off-takers a tax rebate when buying marine energy. This would allow marine projects to sell their power over the market rate, with the off-takers reclaiming excess costs against tax, with this cost declining over time.

An innovation Contract for Difference (iCfD)

The iCfD is a bridging mechanism that enables utility scale projects to through in the current CfD mechanism. This would allow for a new 'pot' within the CfD framework for all new technologies such as wave, tidal stream, and Advanced Combustion Technologies to complete among themselves. This could be funded through the underspend on the CfD budget, an additional iCfD budget or through a tax rebate for energy buyers who are paying the excess costs.

Cost Competitive Solution

Finally, there will be a cost competitive solution within the existing CfD rounds, for when emerging technologies are able to compete directly with other established technologies.

Finally, following a two-day workshop in January 2020, organised by the Supergen ORE Hub and conducted with 40 industry, academic and policy stakeholders and subsequent follow on interviews with key industry stakeholders, the following key policy recommendations were highlighted:

- Establish a policy framework and revenue support mechanism that recognises Wave Energy and Tidal Energy separately from more established offshore renewable energy technologies, as set out in the CfD regime.
- Link time limited revenue support mechanisms to Commercial Readiness Levels, as opposed to Technology Readiness Levels, in order to create future domestic and international markets.

- Simultaneously provide revenue support for the development of niche Wave Energy markets to establish a mechanism for testing and demonstrating reliable Wave Energy devices, ensuring that fundamental research at lower Technology Readiness Levels is supported and that future scaling up of devices for capacity requirements is managed efficiently and cost effectively.
- Provide relevant tax breaks to incentivise local content in the development of Wave Energy deployment, particularly in fragile coastal communities.
- Replicate the Wave Energy Scotland staged technology approach within England and Wales.
- Establish a 10-year timeframe for revenue support mechanisms to reflect the period of technological development in the 2020 to 2030 period, with the capacity building period following from 2030 onwards.

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Annex E – Wave Energy Road Map

Executive Summary

Wave Energy has the potential to provide a significant source of renewable energy and economic growth for the UK and to contribute to the UK Government's climate change objectives [1]. The UK has the necessary infrastructure, markets, technology, legislation and regulation in place and, with key strategic interventions, a successful Wave Energy sector can be delivered with significant benefits to the UK.

We need a diverse renewable energy resource for the UK's net zero 2050; Wave Energy will be an essential component of the mix and brings valuable grid-balancing energy system benefits. Exploitable wave resource in the UK has the potential to deliver in-grid electricity of 40-50 TWh/year, contributing approximately 15% of the UK's current electricity demand, and to have 22GW installed capacity by 2050 [2]. Wave Energy is one of the few domestically led technology sectors that advances our low carbon economy with significant UK content (estimates suggest that the wave industry could secure approximately 80% UK content in the domestic market [2]). The resource maps directly to fragile coastal communities, generating significant impact on community identity, delivering economic benefit and creating high value jobs and economic growth. 8,100 new jobs are estimated in Wave Energy by 2040 [3] and industry support would deliver a GVA benefit ratio of 6:1 [2]. Furthermore, Wave Energy is an abundant local energy resource for the UK, it is well matched to demand and delivers security of supply chain infrastructure.

As an early leader, the UK Wave Energy sector has accumulated considerable experience, expertise and knowledge from the development and deployment of various prototypes and has a strong community of academics and industry. However, the development of Wave Energy will have to accelerate rapidly in order to reach its potential contribution to the UK's net zero target by 2050. This Road Map for Wave Energy sets out the logical steps to be taken through targeted technology development and support mechanisms needed to encourage inclusivity, collaboration and sharing in order to reach the milestones of £90/MWh Levelised Cost of Energy (LCoE) by 2035 and 22GW installed capacity by 2050. This technology push should be complemented by market pull mechanisms that increase as the technology is proven and the market begins to develop, and then shrink as the market becomes established and self-sustaining.

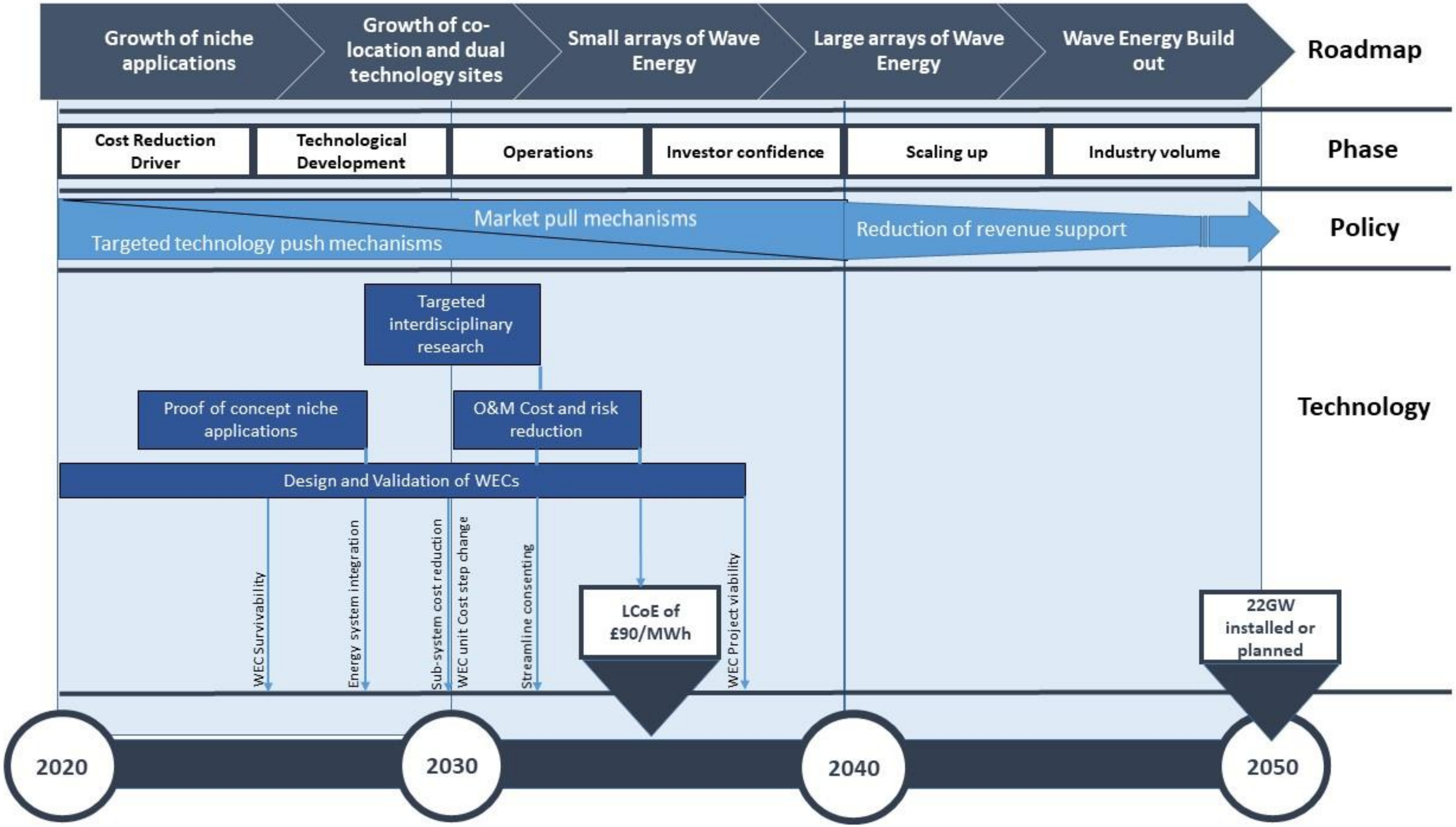
Achieving a step change reduction in the Wave Energy technology unit cost is fundamental to unlocking further investment and development. This is addressed in the early stage of the Road Map, with a focus on design and validation of Wave Energy Converter (WEC) technologies to prove availability and survivability at reduced unit cost. This may be achieved through design innovation and use of alternative component technologies in existing WECs or novel WEC concepts. Targeted research to demonstrate survivability with significant cost reduction is the first step, followed by demonstration of the viability of pilot WEC farms.

Although the main focus of Wave Energy's contribution to net zero targets is at utility scale, niche markets in Wave Energy have developed rapidly and are seen as an important stepping-stone and an effective route to demonstrating the benefit of integrating Wave Energy within the energy system alongside other renewables. Here, niche applications are targeted in parallel with utility-scale WEC design.

As the volume of in-sea Wave Energy demonstration and deployment increases, interdisciplinary research is targeted to improve understanding of interactions with marine ecology and environment, achieve cost reductions in impact assessment and to streamline policy, planning and consenting. Opportunities to exploit technology transfer from other sectors will also grow as deployments increase, enabling lowering of LCoE and risk reduction in operations management, maintenance and safety.

From 2040 onwards, large-scale deployment of Wave Energy will deliver the most dramatic LCoE reductions, with research and innovation continuing in parallel to further improve performance and drive costs down. The global potential for Wave Energy is vast and, with strategic investment, Wave Energy could not only be a significant contributor to our future renewable energy mix but also a lucrative export market for the UK.

Wave Energy Roadmap



Wave Energy Road Map

This Wave Energy Road Map is intended to summarise the views of the Wave Energy Sector on steps needed in the next 10-15 years to accelerate development of Wave Energy and to realise its potential contribution to the UK climate change objectives and economy by 2050. It has been compiled following consultation through scoping workshops and a series of structured interviews with academics, policymakers, funding bodies and industry professionals. This document should be read in conjunction with the Wave Energy Innovation Paper, which sets out the role of Wave Energy in our future Energy System, its current status and recommendations to achieve its potential. Framed within the UK Government's overall strategy to cut emissions, increase efficiency and help to reduce the amount consumers and businesses spend on energy, whilst supporting economic growth, it shows that, with targeted action, Wave Energy can meet the Government's Clean Growth Strategy tests [1] and provide a significant source of renewable energy and growth for the UK economy.

Delivering net zero	Achieving value for money	Supporting communities	Maintaining energy security	Advancing the low carbon economy
• Deliver in-grid electricity of around 40-50 TWh/year • Contribute approximately 15% of the UK's current electricity demand and valuable grid-balancing energy system benefits • 22GW by 2050 in UK [2]	• One of the few domestically-led technologies in the net zero mix which advances our low carbon economy with significant UK content. • Benefit to industry support creates GVA ratio of 6:1 [2]	• Wave Energy resource maps directly to fragile communities • Impact on community identity, reflecting local environmental and economic context. • 8,100 new jobs in Wave Energy by 2040 [3]	• Security of supply chain infrastructure • Abundant local energy resource that is well matched to demand.	• Economic benefit, high value jobs and growth to support coastal communities. • Wave Energy industry with 80% UK content. [2]

Here, we review lessons learnt from the development of the sector so far, followed by a summary of remaining challenges and recommended actions designed to achieve a step change in technology and demonstrate a pathway to cost reduction, thus providing the evidence needed for further investment.

Lessons Learnt

Modern research and development of Wave Energy in the UK was pioneered from the mid-1970s in response to the oil crisis. World-first large-scale deployments were made in the UK, achieving over 35,000 hours of operation and generating significant experience and knowledge that has been assimilated into the community and informs ongoing research and development in Wave Energy. In the past, mismatches between financial and technical drivers have hampered progress in the sector, and costs remain high. However, two recently concluded Horizon 2020 projects achieved respectively 50% and 30% reduction in energy cost of their wave devices [4], [5]; demonstrating progress towards the European SET-Plan LCoE target for Wave Energy of £90/MWh by 2035 [6].

Lessons learnt from review and analysis of numerical, laboratory and field test data of WECs with different working principles [7], [8], [9] to assess scalability and identify remaining challenges [10] is summarised in Table C7 (*Annex C*).

Remaining Challenges

The UK, as an early sector leader, has accumulated considerable experience and know-how from the deployment of various WEC prototypes. Effort should now focus on remaining challenges to achieve the step change needed in Wave Energy LCoE. The key technological and non-technological challenges remaining are summarised in Table 3 and Table 4 of the main document.

Actions

Targeted research and innovation will play an important role in the journey to commercialisation of Wave Energy. A comprehensive programme of fundamental research to address remaining technical challenges will generate a step change in technology costs and a pathway to further cost reductions. Laboratory scale and at-sea testing of concepts and components will further reduce costs, build investor confidence and secure cheaper capital. This phase will culminate in the deployment of at-sea grid-connected demonstration arrays, in which several full-scale devices operate in real-sea conditions without interruption. These demonstration arrays will reinforce investor confidence and achieve further cost reductions via 'learning by doing'. Large-scale deployment of Wave Energy will deliver the most dramatic cost reductions, following the path of offshore wind. During this period, research and innovation will continue in parallel, as lessons learnt from deployments are fed back into the laboratory to continue improving performance and driving costs down. Research and innovation need to be supported by policy and financial interventions designed to suit the development stage of the new technology to provide incentive for private investment and industry engagement.

Policy

<table>
<tr><th>Action:</th><th>Outputs:</th><th>Date:</th></tr>
<tr><td rowspan="2">• Establish a policy framework and revenue support mechanism that declines over time.
• The revenue support is a combination of technology push and market pull. The mechanism starts with technology push in 2020 and runs through the period of technological development, reducing from a maximum in 2020 to zero in 2040.
• The market pull mechanism increases from zero in 2020, becomes the dominant support mechanism from 2030 onwards during the capacity building phase, reaches a maximum in 2040 and reduces from then towards 2050.</td><td>Revenue support mechanism for Technological Development</td><td>2020 – 2040</td></tr>
<tr><td>Revenue support mechanism for Capacity Building</td><td>2020 – 2050</td></tr>
<tr><td>Incentivise local content in the development of Wave Energy deployment, particularly in fragile coastal communities</td><td>Wave Energy industry with significant UK content.</td><td>2030 – 2040</td></tr>
<tr><td>Build supply chain in synergy with Floating Offshore Wind build out, capitalising on new opportunities in digitalisation, robotics, sensing and autonomous systems.</td><td>Supply chain ready for growth in Wave Energy.</td><td>2040 - 2050</td></tr>
<tr><td colspan="3">Establish a policy framework and revenue support mechanism that recognises Wave Energy and Tidal Energy separate from one another and also separate from more established offshore renewable energy technologies, and reflects the period of technological development in the 2020 to 2030 period, with the capacity building period following from 2030 onwards. Link support mechanisms to performance measures and evaluation and reduce the support from 2040 as the Wave Energy sector becomes self-sustaining.

Link time limited revenue support mechanisms to Commercial Readiness Levels as well as Technology Readiness Levels (TRL), in order to create future domestic and international markets.

Support Wave Energy niche market formation: provide revenue support for the development of niche Wave Energy markets to establish a mechanism for testing and demonstrating reliable Wave Energy devices, ensuring that fundamental research at lower TRL is supported and that future scaling up of devices for capacity requirements is managed efficiently and cost-effectively.</td></tr>
</table>

Technology

1. Target research effort to achieve a step change in Wave Energy technology cost.

Action: Research to address:	**Outputs**: Design and Validation of WECs:	**Date**:
• Alternative technology, novel WECs. • Survivability and reliability. • Innovative materials. • PTO and control systems.	WEC design survivability and cost reduction	2020 – 2025
• Mooring and connection systems. • Foundation design and installation for bottom fixed devices.	Sub-system cost reduction	2025 - 2030
• Demonstration of WEC in real sea conditions.	WEC unit cost step change demonstrated.	2025 - 2030
• Demonstration of pilot WEC farm in real sea conditions	WEC project viability demonstrated.	2030 - 2038

A step change in Wave Energy technology unit cost is a major milestone needed to progress the industry, and together with addressing the storm wave survivability challenge and proving technology at sea for lengthy periods, would unlock investor confidence in the sector. This may be achieved through a programme of research effort focused on technological challenges and building on lessons learnt. Targeted innovation to achieve survivability at reasonable cost may involve new materials, modular devices, modular construction and novel fabrication and installation processes. Research funded through the programme would be required to have strong industry engagement and demonstrate cost reduction through design so that promising developments are supported further towards commercialisation. It was also recommended in the workshops that PhD studentships and Research Fellowships could be dedicated to achieving a step change in Wave Energy technology cost.

2. Target research effort to support Wave Energy niche markets and integration in the energy system.

Action: Research to address:	**Outputs**: Proof of concept niche applications:	**Date**:
• Developing and demonstrating the application of Wave Energy in niche markets. • Quantifying and demonstrating grid-scale benefits of ocean energy	Integration in the Energy System.	2022 – 2028

Wave Energy is closer to cost-competitive in certain niche markets, and these may be an effective route to building experience in Wave Energy as a stepping-stone and essential developmental step to utility scale. Niche applications also provide the opportunity to demonstrate the benefits of Wave Energy integration within the Energy System. The correlation of Wave Energy intermittency with that of solar and wind power will reduce the need for storage, transmission and demand-response. Other benefits such as grid resilience to security threats may also be significant. Research targeted at providing reliable estimations of these benefits would help better inform policy and investment decisions.

3. Target interdisciplinary research effort to take whole system approach

Action: Research to address:	**Outputs**: Whole system cost reduction:	**Date**:
• Marine observation modelling and forecasting to optimise design and operation of WECs. • Open-data repository for Wave Energy.	Data Collection & Analysis and Modelling Tools	2028 – 2033
• Improved knowledge of the environmental and socioeconomic impacts of ocean energy.	Streamline policy, planning and consenting	2028 – 2033

The diverse mix of technologies in Wave Energy and a lack of long-term deployments makes Environmental Impact Assessment and project consenting difficult. Building on WEC demonstration and niche deployments, targeted interdisciplinary research will ensure that ecological and social factors are integrated into technology design and do not become barriers to development.

4. Target research effort to exploit technology transfer from other sectors

Action: Research to address:	**Outputs**: O&M Cost and risk reduction:	**Date**:
• Optimisation of maritime logistics and operations. • Instrumentation for condition monitoring and predictive maintenance including digital tools.	Operations management, maintenance and safety	2030 - 2035

As WEC technology moves to small array and pilot farm demonstration, the synergy between offshore wind, wave and tidal technologies can be exploited and advances shared between sectors. Research and development of ORE technologies together will benefit from sharing of developments, and step changes in Wave Energy may come from breakthroughs in other sectors. Collaboration and technology transfer with aligned sectors, such as offshore networks, storage, robotics, autonomous systems, sensing and digital tools will benefit from new developments and achieve further cost reductions.

5. Development of at-sea technology/component test bed

Action:	**Outputs**:	**Date**:
• Establish multi-disciplinary component test facility for technology, ecological and physical environment studies	Demonstration of components.	2025 – 2050

An at-sea test bed for components will enable different component technologies to be tested for survivability and reliability in a realistic environment without the expense of the entire prototype WEC and enabling these component technologies to be utilised in different WEC designs. This is an essential facility to support the targeted technology development and demonstration.

Support Mechanisms

Support mechanisms are needed to enable the research and innovation to be achieved as quickly and effectively as possible. Essential aspects of this are collaboration with international partners; collaboration with industry and other stakeholders; access to research facilities and infrastructure; support and development of the Wave Energy research and innovation community.

1. Promote and facilitate international collaboration

Encouraging the participation of UK researchers in international projects will accelerate the research and development of Wave Energy.

2. Engage industry with early stage research.

Close collaboration between researchers and industry is essential to ensure that research is directed into areas of most impact and that research findings are disseminated effectively and translated into practice.

3. Enable easy access to Wave Energy test facilities.

The UK has established excellent facilities for all scales of development testing, and UK facilities are in demand from national and international research groups and developers. Large scale laboratory facilities designed for marine energy are used for proof-of-concept and medium-scale testing of Wave Energy concepts and arrays under controlled conditions.

At sea nursery test sites are used to test installation and deployment of prototypes at approximately half scale, and grid-connected at-sea sites provide demonstration at full scale and with the generated electricity provided to the grid. Structured support for these facilities will enable them to be sustainable, to share knowledge and expertise, provide training and help accelerate the development of Wave Energy.

4. Establish UK Centre for Wave Energy

A UK Centre established by 2022 to accelerate and promote the sector and to secure a Sector Deal when cost reductions have been achieved to the 2035 target. It is recommended by the community that a structured innovation approach is adopted, such as was developed within WES [11]. Rather than focus on designing the complete technical solution in isolation, the approach aims to develop more efficient sub-systems that could be implemented across different WECs. WES tailored a new funding scheme using pre-commercial procurement (PCP) in conjunction with a stage-gate development process. Funding calls are targeted at specific topics, and at each stage, winning projects are selected to move on to the next funding phase, with technologies converging towards the final stages. The aim is to secure advances and share them between developers, ensuring that solutions for common components and design aspects may be appropriately utilised by the Wave Energy sector as a whole.

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