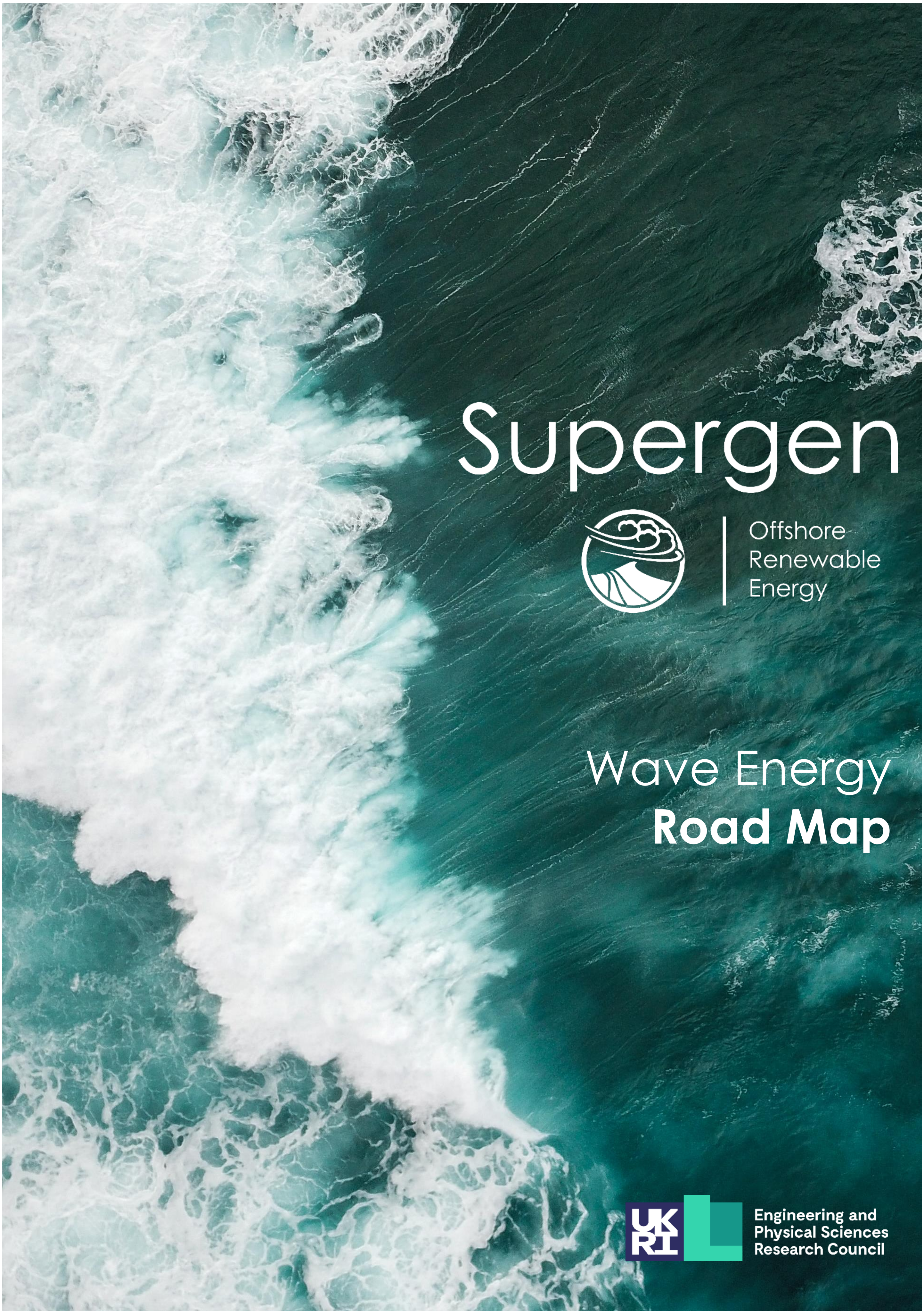


Supergen

Offshore Renewable Energy

Wave Energy **Road Map**

Engineering and Physical Sciences Research Council

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.

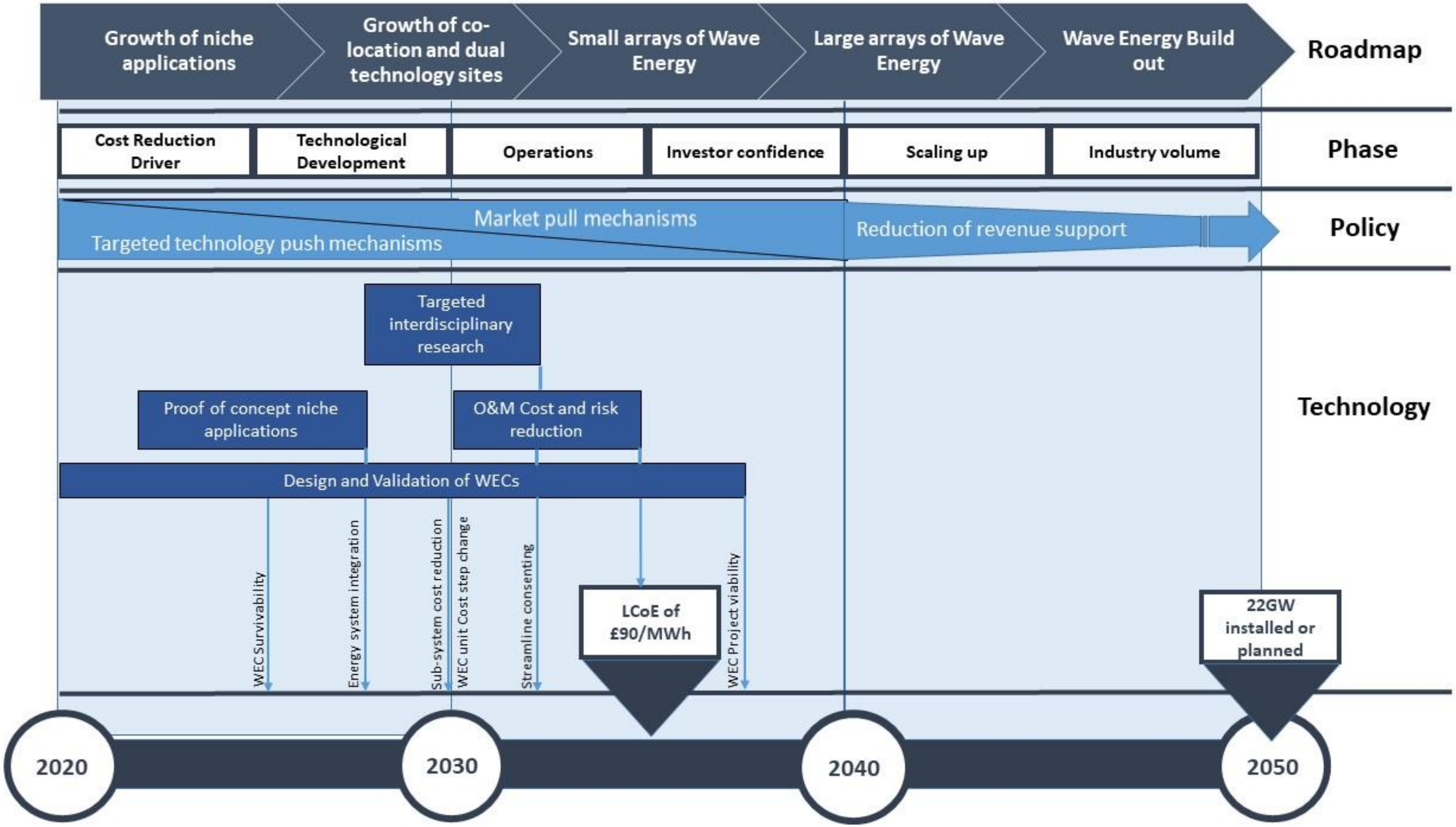
As an early leader, the UK Wave Energy sector has accumulated considerable experience, expertise and knowledge from the development and deployment of various prototypes and has a strong community of academics and industry. However, the development of Wave Energy will have to accelerate rapidly in order 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.



Growth of niche applications
Growth of co-location and dual technology sites
Small arrays of Wave Energy
Large arrays of Wave Energy
Wave Energy Build out
Roadmap
Cost Reduction Driver
Technological Development
Operations
Investor confidence
Scaling up
Industry volume
Phase
Market pull mechanisms
Targeted technology push mechanisms
Reduction of revenue support
Policy
Targeted interdisciplinary research
Proof of concept niche applications
O&M Cost and risk reduction
Design and Validation of WECs
Technology
WEC Survivability
Energy system integration
Sub-system cost reduction
WEC unit Cost step change
Streamline consenting
WEC Project viability
LCoE of £90/MWh
22GW installed or planned
2020
2030
2040
2050

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, policy-makers, 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 Annex A.

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.

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) [11], 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 in 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 are another way to increase 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.

Policy and financial support

Policy and financial support was highlighted in the workshops as a key enabler for the development of Wave Energy. It is 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. 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 [12], little effect on the displacement of animals apart from that associated with increased boat traffic [13], very little effect on ambient noise levels [14],[15], and very little effect on physical processes and on biomass [16] 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

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

Action:	Outputs:	Date:
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.	Revenue support mechanism for Technological Development	2020 – 2040
	Revenue support mechanism for Capacity Building	2020 – 2050
Incentivise local content in the development of Wave Energy deployment, particularly in fragile coastal communities	Wave Energy industry with significant UK content.	2030 – 2040
Build **supply chain** in synergy with Floating Offshore Wind build out, capitalising on new opportunities in digitalisation, robotics, sensing and autonomous systems.	Supply chain ready for growth in Wave Energy.	2040 - 2050

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.

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 WECs 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 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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Engineering and Physical Sciences Research Council

Annex A

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 here. Approximate values for Capture Width Ratio (CWR) and Characteristic Dimension (D) are given together with notes on typical deployment arrangements and technological challenges.

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 form a significant component of the cost.		
	Key challenge:	• Survivability. • Cost reduction in mooring system. • Tuning and control system.		

<table>
<tr><th>Categories</th><th colspan="4">Lessons Learnt</th></tr>
<tr><td rowspan="6">Pitching body: Oscillating Wave Surge Converter</td><td>Location</td><td>Orientation</td><td>CWR</td><td>D</td></tr>
<tr><td>Nearshore</td><td>Terminator</td><td>35%</td><td>30 m</td></tr>
<tr><td>Example:</td><td colspan="3">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.</td></tr>
<tr><td>Notes:</td><td colspan="3">• 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.</td></tr>
<tr><td>Key challenge:</td><td colspan="3">• Foundation design and installation for bottom fixed devices.
• Offshore operations and planning
• Extreme loads</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="5">Articulated body</td><td>Location</td><td>Orientation</td><td>CWR</td><td>D</td></tr>
<tr><td>Offshore</td><td>Attenuator</td><td>20%</td><td>100 m</td></tr>
<tr><td>Example:</td><td colspan="3">Pelamis: deployed at EMEC 2004 to 2014, and produced over 15,000 hours of operation with its second-generation from 2010 to 2014.</td></tr>
<tr><td></td><td colspan="3">• 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.</td></tr>
<tr><td>Key challenge:</td><td colspan="3">• Reliability of hinge joints.
• Design for wave loading in beam seas</td></tr>
</table>