2021-06

Wave energy in the UK: Status review and future perspectives

Jin, S

10.1016/j.rser.2021.110932
Renewable and Sustainable Energy Reviews
Elsevier

Wave energy in the UK: status review and future perspectives

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ARTICLE INFO

Keywords:
UK wave energy
Government and industry support
Progress and status
Utility-scale and niche applications
Recommendations

ABSTRACT

This review aims at giving a picture of the progress of the UK wave energy and suggesting key steps needing to be taken for its contribution to the Net Zero greenhouse gas emissions target by 2050. It follows consultation through scoping wave energy workshops held by the Engineering and Physical Sciences Research Council (EPSRC) in August 2019 and by Supergen Offshore Renewable Energy (ORE) Hub in January 2020 and a series of structured interviews with academics, policy-makers, funding bodies and industry professionals. It is believed that the UK has excellent wave resources and advanced techniques that need to be rapidly developed to achieve the target of 22 GW of installed capacity by 2050 [1]. The wave energy resources in the UK are reviewed, summarising wave energy hotspots for development and identifying openly accessible wave data. The progress and achievements of wave energy development in the UK are reviewed and described to underline the important roles that UK government and industry support have to play in securing a leading position in wave energy. The potential benefits of wave energy for the decarbonisation of UK industry (including utility scale and niche markets) to achieve Net Zero target by 2050 are presented, as well as the steps that need to be taken in the next 30 years to achieve its potential.

Nomenclature

BEIS	Department for Business, Energy & Industrial Strategy
CfD	Contract for Difference
EPSRC	Engineering and Physical Sciences Research Council
GHG	Greenhouse Gas
IEA	International Energy Agency
LCoE	Levelised Cost of Energy
MoU	Memorandum of Understanding
MPS	Marine Power Systems, Ltd.
NFFO	Non-Fossil Fuel Obligation
OPT	Ocean Power Technologies, Ltd.
OWC	Oscillating Water Column
ORE	Offshore Renewable Energy
RO	Renewable Obligation
ROC	Renewable Obligation Certificate
SRO	Scottish Renewable Obligation
WEC	Wave Energy Converter
WES	Wave Energy Scotland

1. Introduction

In response to concerns over climate change, a total of 192 countries signed the Kyoto Protocol in 1997 in a working global agreement to fight climate change [2]. Since then, renewable energy has been acting as an increasingly crucial part of the energy mix as shown in Figure 1, which is summarised from the data in the World Energy Balances 2018 report by the International Energy Agency (IEA) [3]. The UK, as one of the major economies in the world, is at the forefront of utilising renewables, having achieved nearly 30% of renewable electricity generation in 2017.

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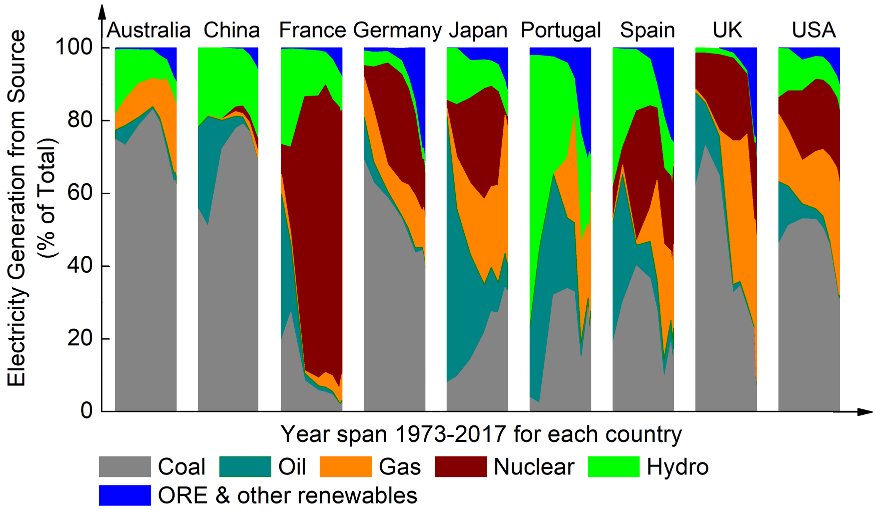


Figure 1: Evolution of the worldwide electricity generation by source between 1973 and 2017. The results are summarised from the data presented in the report of World Energy Balances 2018 by the IEA [3].

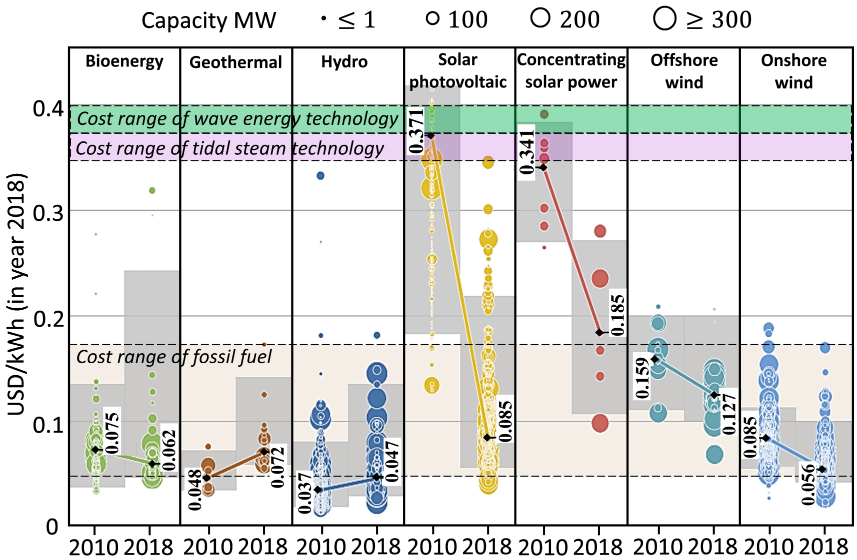
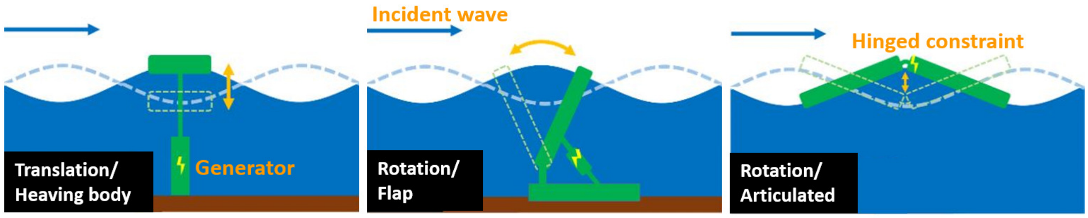


Figure 2: Evolution of the levelised cost of energy (LCoE) by renewable source between 2010 and 2018. The diameter of the circle shows the capacity of a project, with the central point representing the cost of the project on the Y axis and year on the X axis. The values in the white boxes are the weighted-average LCoE values of different renewable energy generation technologies in year 2010 and 2018. The grey bands for each technology and year represent the 5th and 95th percentile LCoE bands. The orange, purple and green bands represent the estimated cost ranges of fossil fuel, tidal steam and wave energy technology, respectively. The diagram is adapted from the data given in [4–6].

Renewable energy comes in a number of forms, including hydroelectric dams, wind (onshore/offshore), solar, biomass, geothermal, tidal and wave, etc. Wind and solar have been rapidly developed in the past 10 years and are competitive with the fossil fuel presently, as shown in Figure 2 (summarised from the data presented in [4, 5]). In comparison, wave energy is far behind with approximately £300/MWh of levelised cost of energy (LCoE) presently, as estimated in [6] in 2018. Although still at early stage, wave energy has great potential as an important contribution for energy mix resilience as it features of high energy density (probably the highest among renewable energy sources

[7]) and provides compensation for the use of wind and solar energy [8]. It is expected that if the exploitable global wave energy resource is harnessed fully (estimated up to 29,500 TWh/year [9]), this could satisfy the annual electricity generation of the world (26,700 TWh in 2018 [10]).

The device that captures and converts energy in the waves to useful power is called a wave energy converter (WEC). Different approaches have been used to classify WEC concepts and the most commonly used definitions can be found in [11–13]. Here, we classify WEC by the working principle, as illustrated in Figure 3. (1) Oscillating body converts wave motions into device oscillations to generate electricity. Two main sub-categories are further given according to the dominant oscillating modes: translation (heaving or horizontal movement) and rotation (flap and articulated, etc). (2) Oscillating water column (OWC) uses trapped air above a water column to drive turbines for electricity generation. Fixed and floating types are available which are further classified based on the dynamic feature of the supporting structure. (3) Overtopping device applies reservoirs to generate a head flow to drive turbines for electricity generation and can be further divided into fixed and floating type. (4) Novel concepts fall outside of the above categories, such as the devices using flexible membrane and hybrid technologies.



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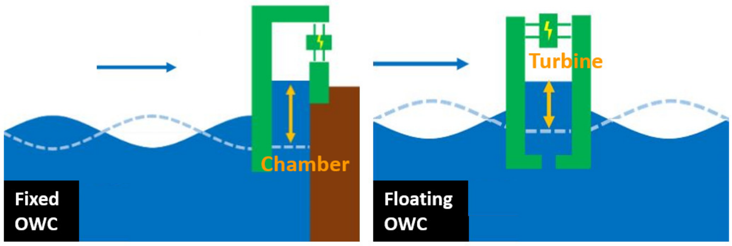

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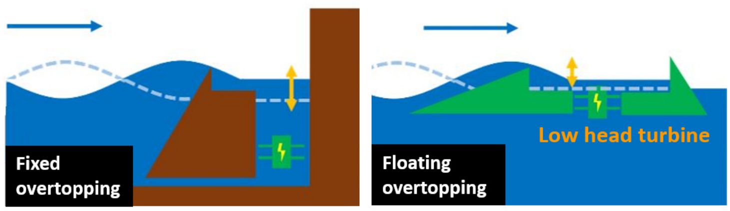


(c)

Figure 3: Schematic diagrams of WEC concepts by working principles. (a) Oscillating body. Three popular applications are shown, including heaving body, flap-type body and articulated body. (b) OWC. Two sub-categories are given based on the device is fixed or floating. (3) Overtopping. Two sub-categories are given based on the device is fixed or floating. The active WEC projects related to each WEC concept can be found in Table 1.

Table 1 and Figure 4 provide summaries of the globally active WEC technologies at the time of writing to demonstrate the evolution of the installed & planned capacity by country between 2000 and 2019. The data are compiled from various sources including published papers, reports and individual company websites [14–26, 28–45]. Clearly,

Table 1: An overview of some of the active WEC projects in the world.

Category	Sub-category	Device	WEC developed in	Device capacity [kW]	Project start year/current status
Oscillating body	**Translation/ heaving**	PB3 PowerBuoy® [14]	USA	3	1997/field test in North Sea for Premier Oil, UK
		CETO6 [15]	Australia	1000	1999/Garden Island Microgrid, Australia
		Atmocean [16]	USA	10	2006/sea test for desalination, Peru
		Seabased [17]	Sweden	30	2006/grid-connected 1 MW wave array SOTENÄS, Sweden
		Oceanus 2 [18]	UK	162	2007/sea trail at Wave Hub, UK
		Corpower [19]	Sweden	300	2009/1:2 scale test at EMEC, UK; full scale test plan at Agucadoura, Portugal
		BOLT LifeSaver [20]	Norway	30	2010/test at Navy's Wave Energy Test Site (WETS), USA
		Neptune 6 [21]	Canada	20	2010/test off Point Grey, Canada; wave-wind hybrid is ongoing
		Waveswing [22]	UK	25	2010/test plan at EMEC, UK
	Translation/ horizontal	Wavepiston [23]	Denmark	100-200	2013/tests at Gran Canaria, Spain and Sardinia, Italy
		40South Energy H24 [24]	Italy	50	-/grid-connected at Marina di Pisa, Italy
	Rotation/ flap	WaveRoller® [25]	Finland	350	1993/grid connected near Peniche, Portugal
		CCell-Wave [26]	UK	n/a	2015/apply advanced composites, UK
		LAMWEC [27]	Belgium	200	-/test at EMEC, UK
		bioWAVE™[28]	Australia	250	-/Port Fairy Pilot Wave Energy Project, Australia
	Rotation/ articulated	SeaPower Platform [29]	Ireland	n/a	2008/1:5 scale winter trials off Ireland
		SeaRay [30]	USA	5	2004/test in Puget Sound, USA; megawatt StingRay is ongoing
		Blue Horizon [31]	UK	n/a	2014/1:2 scale test plan at EMEC, UK
		Blue Star [31]	UK	2-4	2014/teams up with subsea sector, UK
		M4 WEC [32]	UK	n/a	-/test plan at Shenzhen, China
	Rotation/ other	WaveSub [33]	UK	4500	2008/1:4 scale test at FaBTest, UK; full scale test is ongoing
		Wello WEC2 [34]	Finland	1000	2008/test at EMEC, UK
		ISWEC [35]	Italy	50	2009/power Eni's PC80 oil & gas platform at Ravenna, Italy; 100 kW device is ongoing
		WaveNet [36]	UK	7.5-750	2009/45 kW device test at Mingary, UK
		FPWEC [37]	Korea	300	-/sea test off Jeju Island, Korea
OWC	**Fixed**	Mutriku [38]	Spain	296	2008/accumulated 2 GWh production by February 2020
		REWEC3 [38]	Italy	2500	2014/consent authorised
		Uniwave ®[39]	Australia	200	2016/King Island project
		Yongsoo OWC [38]	Korea	500	2017/operational
	Floating	OE Buoy [40]	Ireland	500	2006/test at US Navy's WETS, 2019; OE50 Buoy of 2.5 MW is ongoing
		MARMOK-A-5 [38]	Spain	30	-/test in Biscay Marine Energy Platform, Spain
Overtopping	**Fixed**	OBREC [38]	Italy	1	2016/operational
Other	**Flexible membrane**	AWS-III [22]	UK	4000	2010/1:2 scale test at Orkney, UK; full prototype is ongoing
		mWave™ [41]	Australia	1500	2012/deployment plans at East Pickard Bay, UK and west of La Santa, Spain
		PolyWEC [42]	UK	n/a	-/operational
	Hybrid	P37 [43]	Denmark	63	2004/wave-wind hybrid; two floating parks using megawatt-scale P80 are under development in the UK
		Eagle Wanshan [44]	China	100	2015/wave-solar hybrid system
		DualSub [45]	UK	15000	2008/secured £4.3m to develop wave-wind hybrid system

numbers of coastal countries have been active in the development of WEC technologies, such as Australia, China,

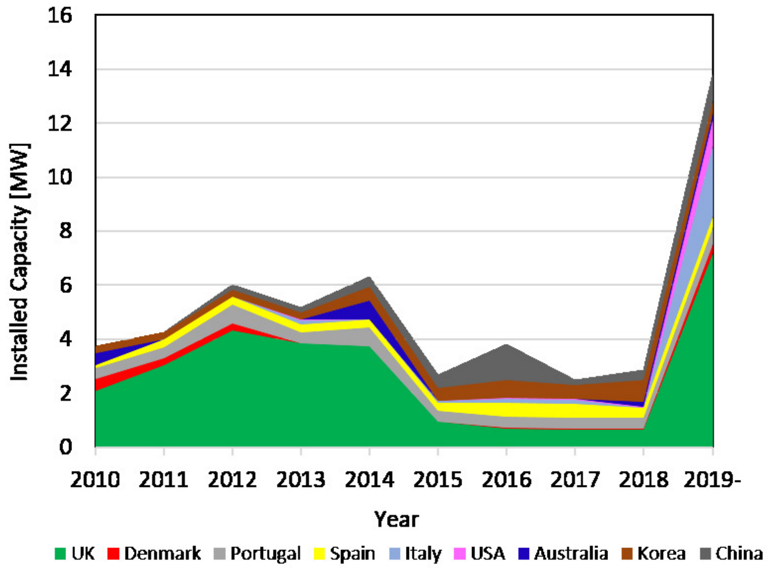


Figure 4: Evolution of the worldwide installed & planned capacity of wave energy by country between 2010 and 2019. The results are summarised from the data given in the OES reports [38].

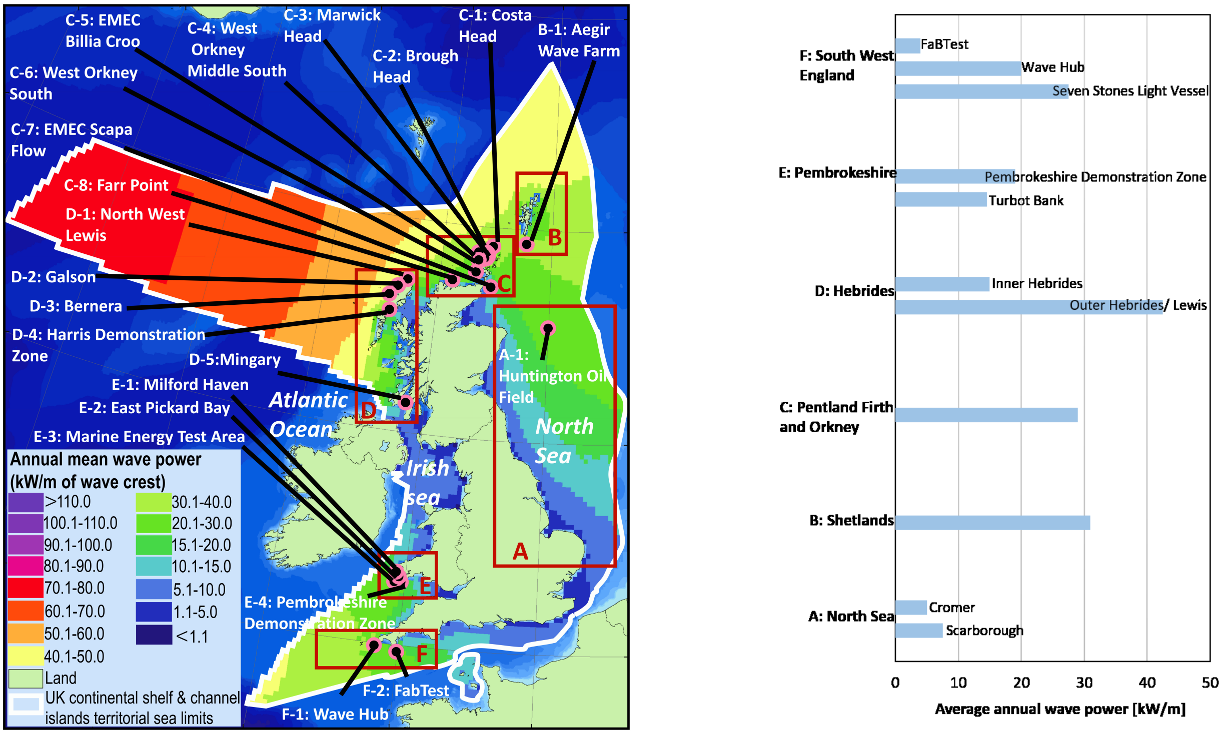
Denmark, Italy, Korea, Portugal, Spain, UK, USA, etc., among which the UK shows to be leading the global pace in wave energy development. As presented in Table 1, the UK has some of best at-sea test centres in the world, EMEC, Wave Hub and FabTest which have attracted numbers of worldwide developers to test their WEC technologies in the UK waters. Between 2010 and 2014, the UK performed the strongest potential in developing wave energy with up to 4 MW of installed capacity, far ahead other countries (see Figure 4). Between 2015 and 2018, the UK's level dramatically dropped to about 0.7 MW, whereas the capacities of Spain, Korea and China increased. Year 2019 shows to be a turning point for the UK's wave energy with the sign of an upward trend.

The UK Government has been implementing wave energy policy (since the mid 1970s) and market incentive support (since the late 2000s) throughout the country to pull the technology into commercialisation. In 2019, the Net Zero target by 2050 was passed into the UK legislation, making the UK the first major economy to set a target of 100% of greenhouse gas (GHG) reduction by 2050 [46]. In response to the Net Zero target, Engineering and Physical Sciences Research Council (EPSRC) released the Wave Energy Road Map in 2020, demonstrating the steps towards the targets of £90/MWh LCoE by 2035 and 22 GW installed capacity by 2050 [47].

For comparison, in Australia, the lack of national targeted policy and market incentive support (e.g., capacity targets, or Feed in Tariffs) can be a major challenge for the wave energy sector [48]. However, in 2020, in response to the Marine and Coastal Act (2018) in Victoria State, the Victorian Government released a statewide marine and coastal policy to support the local marine development in the next 10-15 years. The policy will be accompanied by a marine and coastal strategy to be released in 2021. In China, the Government has been paying attention to developing marine energy, under the national strategies of 'Building China into Sea Power Nation' and 'One Belt, One Road' and 'Twenty-first Century Maritime Silk Road', etc., in the past decade [49]. In the 13th Five-Year Plan (2016-2020), a series of polices have been implemented to accelerate the development, demonstration and deployment of the domestic marine energy and the international collaboration. Additionally, at the UN General Assembly in 2020, China, has pledged to achieve carbon neutrality by 2060 to tackle climate change, which can be a signal for targeted wave energy strategies in the coming 14th Five-Year Plan (2021-2025). In the US, the Office and Science Technology Policy, released in 2018 the Science and Technology for America's Oceans: A Decadal Version, setting goals to advance US ocean science & technology and the Nation in the coming decade (2018-2028) [50]. Carried out by the US Department of Energy Water Power Technologies Office, the long-term Marine Energy Program (formerly known as Marine and Hydrokinetics Program) initiated in 2009, has been aimed at addressing barriers to the commercialisation and deployment [51]. In US, a series of market incentives are available through federal, state and local government for wave energy, which can be found in [52]. For detailed information of different countries' wave energy strategies, see the series of literature reviews and reports in [38, 47–49, 53].

As one of the few domestically led and world leading renewable technologies in the UK, wave energy has been supported in its development over a long period of time, from the mid 1970s. However, it is far behind offshore wind and even tidal technology in its commercial readiness at present. Recently, the Government has been paying attention to facilitating the UK's wave energy development and strengthening its world leading position. Wave energy workshops were held by the EPSRC in August 2019 and by the Supergen Offshore Renewable Energy (ORE) Hub in January 2020, to discuss the wave energy roadmap for 2020-2050 to achieve wave energy's potential contribution to the Net Zero target. This paper follows the key discussions and suggestions at these workshops, aiming to review the UK's progress and current status of wave energy and in turn summarise the experience learnt from the past for future development. Although this is a UK based review work, the authors hope that the experience obtained from the UK can be valuable for all the other countries developing wave energy. The remainder of the paper is organised in the following way: the UK's wave energy resource is discussed in Section 2; the UK Government and industry support is summarised in Section 3; the UK's wave energy progress and status is given in Section 4; the potential role of wave energy contributing to the UK's Net Zero target is discussed in Section 5 and finally the conclusions and recommendations are given in Section 6.

2. The UK's wave energy resource



(a) (b)

Figure 5: Wave energy resource in the UK. (a) Average annual mean wave power (adapted from `http://www.renewables-atlas.info` ©Crown Copyright) and summary of the wave energy hotspots in the UK. The regions marked in A, B, C, D, E and F represent the North Sea, Shetlands, Pentland Firth and Orkney, Hebrides, Pembrokeshire and South West England, respectively. (b) Average annual mean wave power by region (results are summarised from [12, 54–57]).

The UK has an excellent wave resource, estimated at 35% of Europe's, and 1% of the global wave resource [58]. The Carbon Trust has evaluated that (1) the UK's total wave resource is around 230 TWh/year with the majority found in the deeper offshore parts of the UK's exclusive economic zone; (2) the practical wave resource is up to 70 TWh/year for the offshore zone and 5.7 TWh/year for the nearshore zone; and (3) the exploitable wave resource is 40–50 TWh/year [59, 60]. This can contribute at least 15% of the current electricity generation in the UK (323.7 TWh in 2019 [61]).

Figure 5a shows the spatial distribution of wave energy in the UK. The data are summarised from [12, 54–57, 62]. As observed, most of the UK's wave energy arrives from the Atlantic to the west, with the annual mean values generally in the range of 10–50 kW/m and some of the highest values up to 80 kW/m in the offshore Scottish waters. Shelter from Ireland significantly reduces the wave energy resource in the Irish Sea to a level lower than 10 kW/m. The typical energy levels are shown to be up to 30 kW/m in the North Sea, relatively smaller than that in the north west and south west.

Table 2: Crown Estate leased sites and hotspots for wave energy development in the UK [12, 54–56, 63, 64].

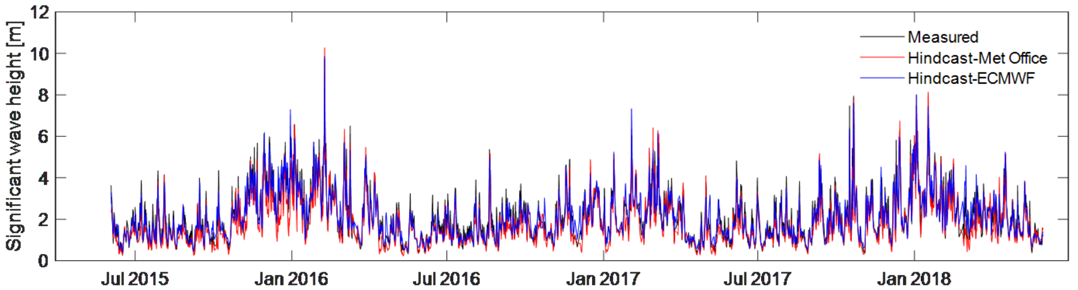
Region	Site	Site area [km^2]	Site status	Capacity of the site [MW]	In-grid	Active/planned projects in the site
North Sea	Huntington Oil Field	n/a	Operational	n/a	No	OPT's PB3 PowerBuoy® 3 kW
Shetlands	Aegir Wave Farm	2	Cancelled	10	n/a	n/a
Pentland Firth and Orkney	Costa Head	24	On hold	200	Yes	n/a
	Brough Head	n/a	On hold	200	Yes	n/a
	Marwick Head	n/a	Cancelled	50	Yes	n/a
	West Orkney Middle South	30	Cancelled	50	Yes	n/a
	EMEC Billia Croo	n/a	Operational	7	Yes	Laminaria's LAMWEC 200 kW; Wello's WEC2 1 MW
	West Orkney South	30	Cancelled	50	Yes	n/a
	EMEC Scapa Flow	n/a	Operational	n/a	No	Mocean Energy's Blue Horizon; AWS's Waveswing
	Farr Point	2-3	Cancelled	10	Yes	n/a
Hebrides	North West Lewis	n/a	On hold	30	Yes	n/a
	Galson	n/a	On hold	10	Yes	n/a
	Bernera	n/a	Cancelled	10	Yes	n/a
	Harris Demonstration Zone	100	In development	Yes	n/a	n/a
	Mingary	n/a	Operational	n/a	No	Albatern's WaveNet 45 kW
Pembrokeshire	Milford Haven	n/a	Operational	n/a	No	Wave-tricity' Ocean Wave Rower
	East Pickard Bay	n/a	Operational	n/a	n/a	Bombora's mWave™ 1.5 MW
	Marine Energy Test Area	n/a	Operational	n/a	No	n/a
	Pembrokeshire Demonstration Zone	90	In construction	180	Yes	n/a
South West England	Wave Hub	8	Operational	48	Yes	Seatricity's Oceanus2 160 kW
	FaBTest	2.8	Operational	n/a	No	MPS's WaveSub

To provide an overview of the relationship between wave energy development and wave resource distribution, the leased wave sites by the Crown Estate and the active hotspots [12, 54–56, 63, 64] are reviewed and summarised in Figure 5 and Table 2. As can be seen, six regions have been active in wave energy development, including: North Sea, Shetlands, Pentland Firth and Orkney, Hebrides, Pembrokeshire and South West England. Between 2010 and 2015, the UK Government had ambition to accelerate Pelamis Wave Power's Pelamis and Aquamarine Power's Oyster into commercialisation. As a result, Crown Estate leased the first batch of field sites in Shetlands, Pentland Firth and Orkney, and Hebrides where the wave energy resources are relatively abundant (see Figure 5b), to support the development and demonstration of Pelamis and Oyster. Following the closure of Pelamis Wave Power (in 2014) and Aquamarine Power (in 2015), the proposed wave sites were cancelled or put on hold, as shown in Table 2. The operational or on-going sites in Table 2 are mainly test centres, used for project demonstration but not for long-term commercial application. One exception is the Huntington Oil Field, where the OPT's PowerBuoy® was installed in 2019, mainly due to the

Table 3: Overview of accesses for available wave data of the UK.

Source	Period	Coverage	Buoy	HF radar	Satellite	Model
British Oceanographic Data Centre	n/a	UK	✓			✓
Cefas WaveNet	n/a	UK	✓		✓	
Channel Coastal Observatory	n/a	England	✓			
ECMWF/ERA5	1979-present	Global				✓
EMEC	2010-present	EMEC	✓			
ERS-2	1995-2011	Global			✓	
ERS-1	1995-2011	Global			✓	
IFREMER/HOMERE	1994-2015	English Channel				✓
Jason-3	2016-present	Global			✓	
Jason-2	2008-present	Global			✓	
Jason-1	2001-2003	Global			✓	
JMA/JRA-55	1958-present	Global				✓
MARENDATA	n/a	Europe	✓	✓		
Met Office	n/a	UK	✓			✓
TOPEX/Poseidon	1992-2005	Global			✓	
Sentinel 3	2016-present	Global			✓	
University of Plymouth	2011	Wave Hub		✓		
Wave Hub	2015-2018	Wave Hub	✓			
WAVEWATCH III®	1979-2019	Global				✓

local electricity demand from the oil & gas sector (Premier Oil), although the wave resource in this location is relatively small (as shown in Figure 5).



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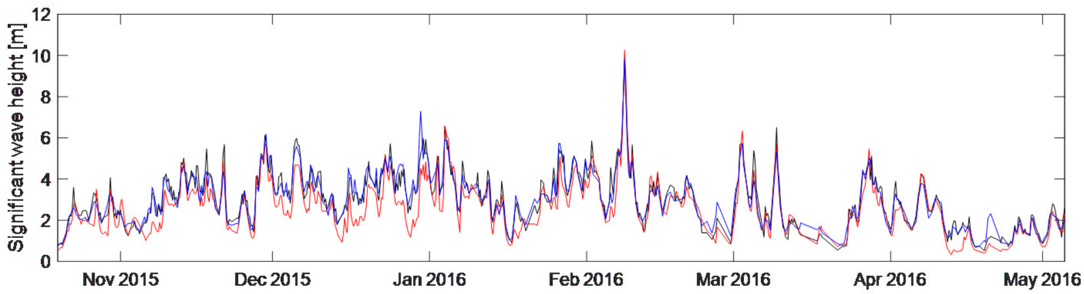


(b)

Figure 6: Comparison of the measured significant wave height and the hindcasts by Met Office and ECMWF, for the EMEC Billia Croo site. (a) Data between 06/2015 and 06/2018. (b) Data between 11/2015 and 05/2016.

Obtaining high quality and reliable wave data is of fundamental importance to optimising wave farm siting decisions, power production and design of WECs to withstand wave loads during the project lifetime. Wave-rider buoys, satellites, high frequency (HF) radars and wave numerical models are the most commonly used sources. Wave-rider buoys can offer high-quality in-situ data but are limited by the sparse distribution in the open sea. Remote measurements (like satellites and HF radars) and improved wave numerical models may be good alternatives [65]. HF radar for wave measurement has been widely used in countries like USA [66] and Australia [67] but not so widely in the UK. The University of Plymouth and University of Sheffield have done studies on the HF radar measurements in Liverpool Bay (2004-2011) [68] and Wave Hub (2012 [69, 70]. HF radars are able to provide measurement over 100 km from the coast with the resolution typically 1-7 km [71]. Hindcast models are preferred for return period analysis of maritime engineering design, due to the advantage of offering long-term wave data [72]. The ERA5 released by ECMWF provides hindcast wave data from 1979 to present, with resolution of 1 hour and 31 km in global coverage [73]. In addition, hindcast wave data between 1980 and 2018 with resolution of 3 hours and 8 km in the UK sea limits are available from Met Office. To evaluate the two wave hindcast datasets, physically measured waves between 2015 and 2018 at EMEC Billia Croo site (offered by EMEC) are used for comparison, in Figure 6. Clearly, the two hindcast datasets can well describe the measure data. Table 3 presents the overview of the available datasets for the UK's wave resource.

3. The UK's Government and industry support for wave energy

3.1. Government support

In the long term, funding for wave energy development can be mainly supported by private companies when the wave energy market achieves commercialisation. At the current stage, Government policy and support play a significant role for sector development, as the wave energy sector is not yet mature. By reviewing past projects [74, 75], it is clear that there exist numbers of public funding bodies that have invested funding into the UK wave energy, as summarised in Table 4. As seen, the funding bodies are operating at different levels of governance, such as the UK, Scotland, Wales and EU, although Brexit will have an impact on the UK's access to EU funding in the future.

Table 4: An overview of the funding bodies for the UK's wave energy development [74, 75].

Funding body	Governance
Carbon Trust	UK
Department for Business, Energy & Industrial Strategy (BEIS)	UK
Energy Technologies Institute (ETI)	UK
EPSRC	UK
Innovate UK	UK
Natural Environment Research Council (NERC)	UK
UK Government	UK
Highlands and Islands Enterprise (HIE)	Scotland
Scottish Enterprise	Scotland
Scottish Government	Scotland
Welsh Government	Wales
Welsh European Funding Office (WEFO)	EU
European Commission	EU

The overview of the support target by funding body and the evolution of the UK's wave energy programmes against Government policy in the past 20 years are presented in Figure 7. The data are summarised from [74–79]. The following findings can be drawn:

- The wave energy funding landscape is complex. The support from different institutions target different priorities, from basic fundamental research to pre-commercial demonstration and full scale deployment.
- The EU, UK Government and Scottish Government have played consistent roles in supporting the UK wave energy over the past 20 years with the Welsh Government actively supporting wave energy from 2014.
- The UK and Scottish Government's support target of wave energy has changed over time. By the mid 2010s both the UK and Scottish Government appeared to have the greatest interest and ambition to push wave energy into commercialisation. As a result, large numbers of funding programmes emerged between 2010 and 2015 and most of the spending (estimated at approximately 80% [76]) focused on funding the demonstrations of WEC arrays or prototype deployments, such as the Marine Renewables Deployment Fund (MRDF), Wave and Tidal Energy Support Scheme (WATES), Marine Renewables Commercialisation Fund (MRCF), Marine Energy Array Deployment (MEAD). From 2015 onwards, the number of wave energy focused funding programmes supported

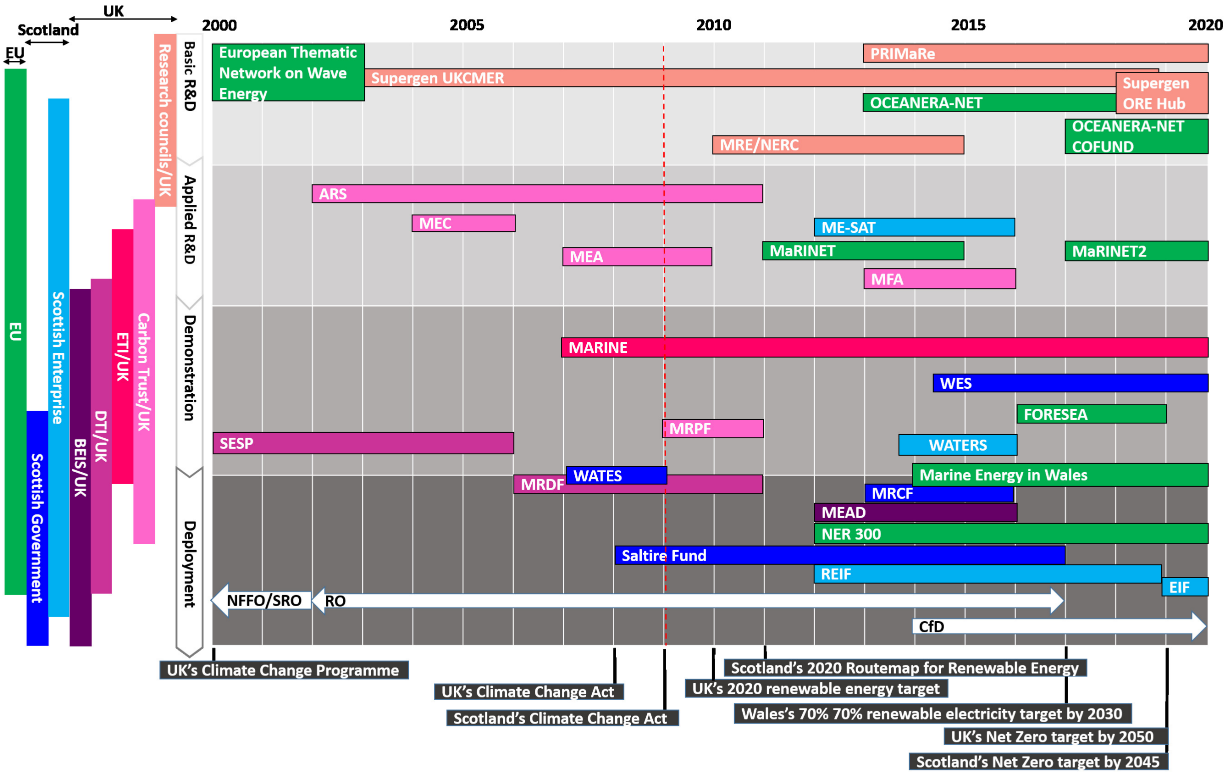


Figure 7: Diagram illustrating supporting target by funding body and the corresponding programmes considering wave energy support between 2000 and 2020. Abbreviations: Marine Renewable Energy (MRE); Applied Research Scheme (ARS); Marine Energy Challenge (MEC); Marine Energy Accelerator (MEA); Marine Energy – Supporting Array Technologies (ME-SAT); Marine Farm Accelerator (MFA); Wave Energy Scotland (WES); Funding Ocean Renewable Energy through Strategic European Action (FORESEA); Marine Renewables Proving Fund (MRPF); Sustainable Energy Supporting Programme (SESP); Wave and Tidal Energy: Research, Development and Demonstration Support (WATERS); Wave and Tidal Energy Support Scheme (WATES); Marine Renewables Deployment Fund (MRDF); Marine Renewables Commercialisation Fund (MRCF); Marine Energy Array Deployment (MEAD); Renewable Energy Investment Fund (REIF); Energy Investment Fund (EIF).

by UK and Scottish Government reduced dramatically. Meanwhile, both of the Governments shifted away from commercially deployment focused programmes towards innovation targeted research and demonstration, such as Supergen ORE Hub [77], Wave Energy Scotland (WES) [80] and Marine Wave Energy (launched at the time of writing). The details of some of the currently active funding programmes are presented in Table 5.

- The UK Government has been encouraging electricity generation from renewables during the last 30 years, according to the Non-Fossil Fuel Obligation (NFFO) and Scottish Renewables Obligation (SRO) between 1990 and 2002 [81]; Renewable Obligation (RO) from 2002 [82] and Contract for Difference (CfD) from 2014 to replace RO [83]. Under RO framework, 5×Renewable Obligation Certificate (ROC) was proposed for wave energy, approximately at £300/MWh in 2010 [84, 85]. In 2014, under the CfD framework, £305/MWh of strike price (for delivery year 2018/2019) was confirmed for wave energy in the first round [86], similar to the RO level in 2010, but with 15 year contracts (25% less revenue than the 20 year contracts under RO). In addition, wave energy has to compete with more mature technologies like offshore wind and biomass to obtain CfD, as they are in the same budget pot (less established technologies). As a result, at the time of writing, there have been no accreditations for wave power in round 1-3 CfD [87–89]. In 2019, round 3 of the CfD, £281/£268 MWh of strike price was allocated for wave energy (for year 2023/2024 and 2024/2025) [90]. In comparison, biomass's strike price is £121/£121 MWh and offshore wind's level is £56/£53 MWh, significantly cheaper than that of wave.

Table 5: Active public funding programmes for the UK's wave energy development.

Coverage	Programme	Funding body	Period	Budget
Wave energy	Marine Wave Energy	EPSRC	2020-2024	£4m
	Wave Energy Scotland (WES)	Scottish Government	2014-ongoing	£40m
Marine energy	Maine energy in Wales	European structural funds/EU Commission	2014-2000	€100m
	MARINE	ETI	2007-ongoing	n/a
	OCEANERA-NET COFUND	EU Commission	2017-2021	€24m
ORE	MaRINET2	Horizon 2020/EU Commission	2017-2021	€10m
	Supergen ORE Hub	EPSRC	2018-2022	£9m
Energy	Energy Entrepreneurs Fund	BEIS	2012-ongoing	£75m
	Energy Investment Fund	Scottish Enterprise	2012-ongoing	£20m
	Energy catalyst round 8	Innovate UK, EPSRC, Department for International Development	2020-ongoing	£20m
Coastal	Coastal Communities Fund round 5	UK Government	2017-2021	£90m

The current CfD consultation of round 4 is putting fixed offshore wind in a pot on its own and leaving floating offshore wind with wave, tidal and others to increasing the competitiveness of wave energy and enhancing the supporting diversity [91].

- In the last 20 years, the evolution of wave energy funding schemes and wave energy development are highly related to the Government's policies of climate change and decarbonisation. Early interest in wave energy happened in the early 1970s due to the oil crisis [92]. The next swell of wave energy programmes happened in response to the UK and Scottish Government's announcement of the Climate Change Act in the late 2000s, aiming for at least 80% of reduction of the GHG by 2050 [93]. As a result, the number of wave energy programmes and the installed capacity were highest between 2010 and 2015 as shown in Figure 7 and Figure 4. In 2017, Welsh Government announced the 70% renewable electricity target by 2030 in Wales [94]. In 2019, a new legislation was announced to push the reduction of GHG emission to a higher level of 100% by 2045 for the Scottish Government and by 2050 for the UK Government [46], which may bring a new upturn for wave energy in the UK (as indicated in Figure 4).

3.2. Supply chain

A strong supply chain is fundamental for the growth of the UK's wave energy. Table 6 presents an overall view of the supply chain status in the UK based on the reports from EMEC, Wave Hub, ORE Catapult and WES [95–98]. As can be seen, the UK has sufficient capacity and capability from universities and companies which can provide consultancy for wave energy technology. Large numbers of active WEC developers have deployed or are planning to test their WECs in UK waters which will accumulate significant technological experience. Thanks to the mature oil & gas and wind (onshore/offshore) sectors, the UK has good capacity and capability in marine operations, vessels, health and safety, control systems, electrical infrastructures, foundations and mooring systems, which have been applied in the wave energy sector. However, establishing a cost effective and tailored supply chain for wave energy sector is required to improve the competitiveness of wave energy against other renewables. For example, novel anchor and mooring technologies are required to secure the dynamics of floating WECs and improve the efficiency of connection and disconnection resulting in a more viable O&M strategy and lower costs, which is the focus of the fifth call within the WES programmes [99].

4. The UK's wave energy progress 1970–2020

The progress and current status of the wave energy technologies developed in the UK are comprehensively described below.

Table 6: Supply chain for UK's wave energy.

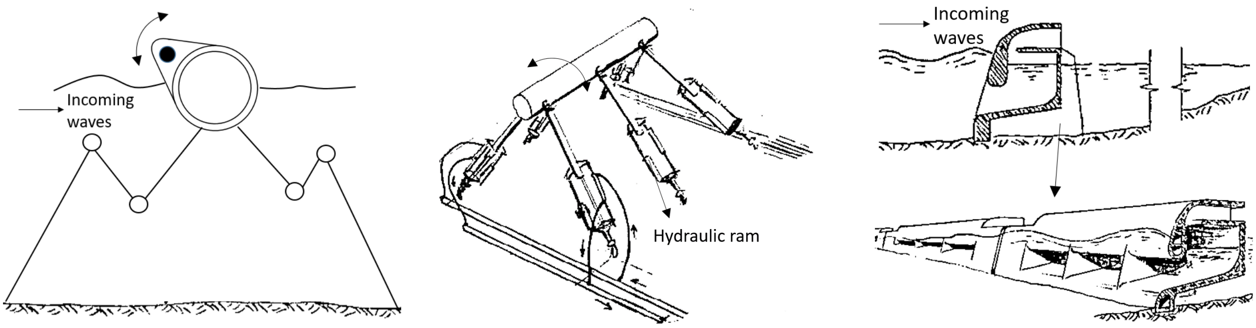
Category	Sub-category	Supplier
Consultancy and R&D supply		UK universities (such as Edinburgh, Exeter, Plymouth, Strathclyde, etc.), Aquatera, BVG Associates, Regen, ORE Catapult
Device supply	**Wave energy developers**	Albatern, AWS Ocean Energy, Bombora, Carnegie, Corpower, CCell, Fred. Olsen, M4, Mocean Energy, MPS, OPT, Seabased, Seatricity, Wave-tricity, Wello Oy, etc.
	Engineering design	4C Engineering, Black Fish, etc.
Manufacture & components supply	**Device fabrication**	Globe Energy Group, Mainstay Marine Solutions, SUPACAT, etc.
	Moorings and foundations	BiFab, Bluewater, North West Marine Services Ltd, Deep Sea Mooring, Sustainable Marine Energy, Mooring Systems Ltd, etc.
	Substations and cables	ABB, GE Power Conversion, Siemens Transmission Products, Draka, JDR Cable Systems, Bpp Cable Solutions, Hydro Group, etc.
Installation supply	**Test sites**	FaBTest, Marine Energy Test Area, EMEC Scapa Flow, EMEC Billia Croo, Wave Hub, Pembrokeshire Demonstration Zone
	Installation ports	Falmouth, Hayle, Bristol, Pembroke, Mostyn, Swansea, Scrabster, Orkney ports,etc.
	Mooring, foundations and cables	Green Marine (UK) Ltd, Leask Marine Ltd, Scotmarine Ltd, Gareloch Support Servic, Bryan J Rendall (Electrical) Ltd, etc, James Fisher and Sons plc, etc.

4.1. 1970s-1980s

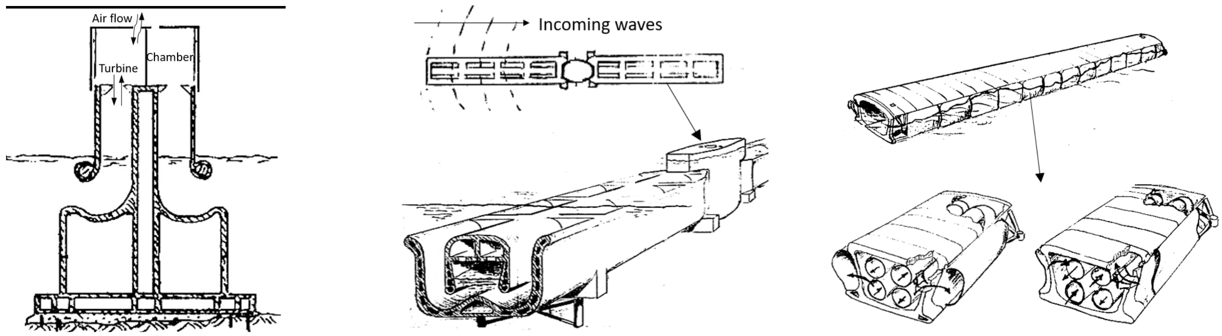
Modern research and development of wave energy in the UK was pioneered from the mid-1970s in response to the oil crisis [92, 101]. In 1974, Stephen Salter of the University of Edinburgh published the Edinburgh Duck WEC [102], which experimentally demonstrated impressive mechanical efficiencies of up to 80%. In the same year, the UK Government launched the first Wave Energy Programme with an ambitious aim of a 2 GW wave energy plant [92]. More than ten technologies were supported including: Edinburgh Duck, Bristol Cylinder, Lancaster Flexible Bag, National Engineering Lab (NEL) OWCs, Belfast OWC, Vickers OWCs, Lanchester Clam, Cockerell Raft, PS Frog, etc. Figure 8 shows the schematic diagrams of some of the funded technologies. Detailed descriptions of different technologies can be found in [100, 103]. At the same time, the fundamental theories for wave power absorption were established by pioneers all over the world, like Budar and Falnes [104], Evans [105, 106], Newman [107–109], Salter [102], etc. In 1981, Evans, from University of Bristol in the UK, reviewed the research work across the world in [110]. In 1982, the UK Department of Energy made an assessment of the funded WEC projects and concluded that the overall economic prospects for wave energy were poor [100]. Meanwhile, with the end of oil crisis, the UK Government abruptly scaled down the British wave energy programme in 1983 and moved to other more efficient energy sources like nuclear [92]. As a result, no full-sized wave energy prototype was constructed. The University of Edinburgh has been conducting work on collating the surviving reports from this government funding scheme. Details can be found in Energy Technology Support Unit [111].

4.2. 1990s

Although the Wave Energy Programme was closed, wave energy technologies continued to be developed in the UK. Some representative devices were invented in this period, such as the Sloped IPS Buoy [112, 115, 116] (Figure 9a), the Circular SEA Clam [113, 117] (Figure 9b), especially the 75 kW pilot Shoreline OWC on Islay, Scotland (commissioned in 1991 and operated for approximately 10 years) [114] (Figure 9c). In 1999, the UK Government relaunched the wave programme as a part of Sustainable Energy Supporting Programme (SESP), at a much smaller scale than that in 1974, but resulting in a more significant effect on the development of wave energy. Three wave devices including: Wavegen's LIMPET, Pelamis's P1 and Sea Power International's Floating Wave Power Vessel were awarded in the third round of the SRO to supply electricity to the National Grid [92]. Finally, only LIMPET, a 500 kW shoreline OWC was commissioned in 2000 and connected to the UK's national grid in 2001. LIMPET continuously operated for a decade before it was decommissioned in 2013 (see Figure 10a). LIMPET operated as a fixed OWC, as illustrated in Figure 3b.



(a) (b) (c)



(d) (e) (f)

Figure 8: Representative WEC technologies supported by the UK Wave Energy Programme between 1974 and 1983 [100]. (a) Edinburgh Duck. (b) Bristol Cylinder. (c) NEL fixed OWC (sitting in perpendicular to the wave direction as a terminator). (d) Belfast fixed OWC. (e) Vickers fixed OWC (sitting in parallel to the wave direction as an attenuator). (f) Lancaster flexible membrane WEC.

(a) (b) (c)

Figure 9: Representative WECs developed in 1900s in the UK. (a) Sloped IPS Buoy developed by University of Edinburgh [112]. (b) Circular Sea Clam [113] under test on Loch Ness, Scotland. (c) 75 kW pilot Shoreline OWC on Islay, Scotland, UK [114] (with permission from Elsevier).

4.3. 2000s to the mid 2010s

From the early 2000s onwards, with the concerns of climate change, renewable technologies like wave power were revisited. Large numbers of wave energy programmes were allocated in the period, with the focus on large-scale deployment, WEC array deployment and construction of test infrastructures, as stated in Figure 7. As an example, led by the strong support from Scotland, the first grid-connected test centre EMEC was established in 2003 [12]. In 2004, the world's first offshore floating WEC prototype, Pelamis P1 (750 kW), was deployed at EMEC and connected to the UK grid. The Pelamis device is an articulated type oscillating WEC, referring to Figure 10b. In 2009, the first wave energy array (2.25 MW) was tested in Portugal based on three Pelamis P1. In the same year, another well

(a) (b) (c)

Figure 10: Representative WECs which were connected to the UK's national grid. (a) 500 kW LIMPET on the island of Islay, Scotland, UK [114] (with permission from Elsevier). (b) Pelamis P1 under sea test [118] (with permission from ©2011 The Royal Society). (c) Schematic diagram of Oyster 315 kW [119] (with permission from ©2011 The Royal Society).

known device, Oyster 315 kW developed by Aquamarine Power was installed at EMEC. Oyster is a flap type WEC, as shown in Figure 10c. In 2010, the Crown Estate launched the world's first commercial wave and tidal leasing round in Pentland Firth and Orkney Waters (PFOW). The Crown Estate entered into agreements for lease with 11 projects in the PFOW with a potential capacity of up to 1.6 GW, among which 6 projects were for wave with 6 MW of capacity [120–122]. In the same year, the second grid-connected test centre Wave Hub was installed off Cornwall [54]. From 2010 to 2014, two Pelamis P2 machines were tested at EMEC, accumulating over 15,000 hours of operation before it went into administration in 2014. From 2011, Oyster 800 kW was installed at EMEC, completing 20,000 hours of operation before the programme was halted in 2015. The failures of the market leaders Pelamis and Oyster depressed the sector significantly with various players exiting this market during this period [85]. A discussion on these two projects and factors leading to their closure can be found in the report released by EU in 2017 [123] and the Wave Energy Road Map released by EPSRC in 2020 [47]. It is suggested that the failure of Pelamis and Oyster could highly result from the mismatch between the financial and technical drivers that forced the WEC developers to embark on costly large-scale demonstrations too early in their development. Currently, WES own the IP of Pelamis and Oyster. They have been conducting the Project Know-How, where more lessons, knowledge and key experiences captured from Pelamis and Osyter are secured [124].

4.4. Mid 2010s to present

4.4.1. Wave energy in Scotland

In 2014, the Scottish government set up WES [80] to provide continued support for the wave energy developers in Scotland. WES purchased the IP of Pelamis (2014) and Oyster (2015) and captured the learning and considerable experience gained in their development and deployment. Rather than focusing on the design of the complete technical solution in isolation, WES developed a structured innovation approach within Project SEAWEED [125] (a similar approach has also been studied in [126, 127]), aiming at the development of more efficient sub-systems that could be implemented across different WECs. Five funding areas have been released with each one targeting a specific component, i.e. power take-off systems, novel WECs, structures and materials, control systems and quick connection systems. A new funding scheme using pre-commercial procurement (PCP) in conjunction with a stage-gate development process was applied. At each funding stage, only winning projects are selected to move on to the next funding phase, with technologies converging towards the final stage. To date, nearly £40m of investment has been allocated for 55 projects through the programme, with five control projects, two material projects, two control projects and two

Figure 11: Concept diagram of ‘Blue Horizon’ from Mocean Energy, one of the winners of WES (image courtesy of Mocean Energy Ltd.).

WEC developers reaching the final phase.

Two WEC developers from Scotland, AWS Ocean Energy and Mocean Energy Ltd. have secured £7.7m to deploy their half scale models at EMEC in 2020. The ’Archimedes Waveswing’ from AWS is a submerged heaving oscillating body generating electricity via a direct-drive generator. The ’Blue Horizon’ from Mocean Energy is a floating articulated type WEC (see Figure 11) with a unique geometry which is indicated to significantly improve the performance compared to the traditional articulated WECs and increase the survivability by diving through the largest waves. Both WEC companies have built collaborations with other sub-system technologies developed and proven independently through the parallel WES programme investments or the other programmes. For example, AWS has been collaborating with Arup (one of the structure and material winners under the WES programme) to apply reinforced concrete material to the structure to reduce the cost and improve the durability in the sea. Overall, the WES programme plays a significant role in facilitating wave energy development in particular the development of supply chain tailored for wave energy. Additionally, the successful and efficient structure innovation approach applied in WES can be widely applied in other funding programmes.

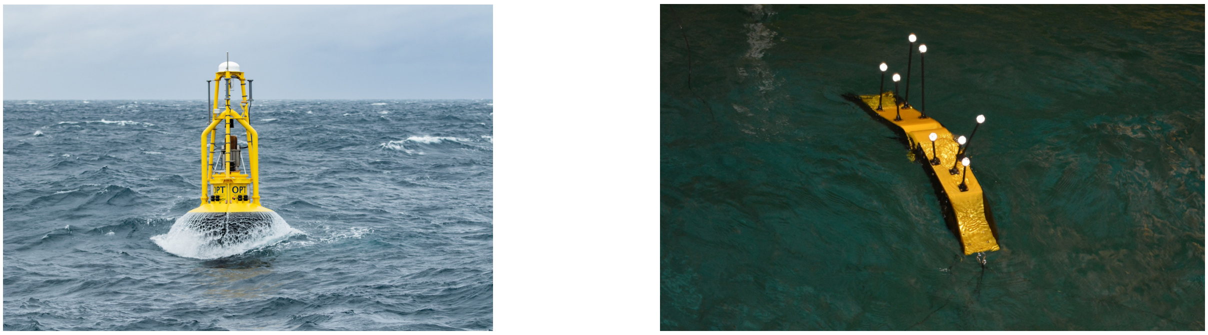
4.4.2. Wave energy in Wales

From 2014 onwards, the Welsh Government has been rapidly developing wave energy in Wales, €100.4m of European Structural Funds was secured to develop Wales as a world class centre of marine energy [56]. The world’s largest grid-connected test site located off the South Pembrokeshire coastline: the Pembrokeshire Demonstration Zone (PDZ) is under construction to be completed in 2021 [56]. 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 has the potential to support the demonstration of 90 MW of wave arrays and 90 MW of floating offshore wind technologies. In addition, the Marine Energy Test Area (META) is a newly established off-grid test site area located in the Milford Haven Waterway in Pembrokeshire which can be used to test pre-commercial devices. META Phase 1 was officially opened in September 2019.

Three main wave energy projects have been developing in Wales: Bombora’s mWave™, MPS’s WaveSub and Wave-tricity’s Ocean Wave Rower. The Australian company Bombora secured a £10.3m WEFO grant in 2018 to deploy the 1.5 MW mWave™ at East Pickard Bay, approximately 1 km from Freshwater West beach, Wales [41]. The mWave™ is a novel WEC using flexible membrane (see Figure 12a, the concept diagram of mWave™). It features air-inflated rubber membranes mounted on the fixed structures, generating air flow to drive a turbine for electricity generation. The Wales based company MPS has secured a £12.8m EU funding to deploy a full scale WaveSub at sea in 2022 [33]. WaveSub is a submerged platform equipped with multiple floaters, each of which acts as an oscillating body to efficiently capture the orbital energy flow of the waves. WaveSub has the potential to generate multi-megawatt power capacity aimed at being comparable with modern wind turbines. Figure 12b shows the 1/4 scale of WaveSub at FaBTest, UK. Wave-tricity received £4 million from the WEFO for the device Ocean Wave Rower. A concrete barge was refitted and refurbished to be used as the platform of Ocean Wave Rower, where a point absorber was mounted for power generation. Sea trials were conducted in the Milford Haven area in 2017.

(a) (b)

Figure 12: Representative WECs developed in Wales, UK. (a) mWave™ from Bombora (image courtesy of Bombora Ltd.). (b) 1/4 scale of WaveSub from Marine Power Systems (MPS) under test at FaBTest, UK (image courtesy of MPS Ltd.).



(a) (b)

Figure 13: Representative WEC technologies that have attracted attentions from other markets. (a) OPT PB3 PowerBuoy® operating in the North Sea of UK for Premier Oil to demonstrate its ability to serve as a self-powering site-monitoring systems for offshore oil & gas platform (image courtesy of OPT Ltd.). (b) 1/20 scale 'Blue Star' from Mocean Energy, under test at Ocean Basin of University of Plymouth (image courtesy of Mocean Energy, Ltd.). The device is designed to act as a stand-alone power station for sub-sea facilities [31].

4.4.3. Participation of other markets

Although still dominated by start-up wave energy companies, other engineering firms are beginning to enter the wave energy market like aquaculture, oil & gas and offshore wind, etc. The Scotland based company Albatern is collaborating with two leading aquaculture companies, Mowi Scotland and Scottish Salmon Company to demonstrate the capability of the kilowatt-scale 'WaveNet' WEC to replace diesel for power supply of the fish farms. The device has been tested at Mingary, Scotland. In 2018, Albatern signed an memorandum of understanding (MoU) with Chinese partner Qingdao Seven Ocean Marine & Offshore Engineering Co Ltd to develop wave energy as part of Seven Ocean's offshore fish farm systems and financing packages for the fast developing offshore fish farming sector in Asian and global waters [128]. The M4 WavePower from University of Manchester has been validated with impressive performance under 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% [129]. 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, China. 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 [130]. With their experience in offshore wind sector, 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. In collaboration with ORE Catapult, Bombora is investigating the feasibility of integrating the mWave™ technology into offshore floating wind structures [41] (see Figure 16b). In response to the exploration of decarbonisaton in the UK's oil & gas sector, wave power is regarded as a competitive candidate to power the subsea facilities. In 2019, Premier Oil has deployed OPT's PB3 PowerBuoy® at Huntington field in the North Sea of UK to provide communications and remote monitoring services [14] (see Figure 13a). Mocean Energy has developed a relatively small size WEC (length of 20 m), 'Blue Star' (2-4 kW) to power a range of sub-sea applications, from subsea control systems to fully autonomous underwater vehicles and has attracted funds of £200,000 from Scottish Enterprise and the Oil & Gas Technology Centre in Aberdeen for the development [31]. Figure 13b shows the 1/20 scale model of 'Blue star' tested at Ocean Basin of University of Plymouth. The aim is to study the device performance under extreme waves. The 1 MW Wello WEC2 is at the time of writing under test at the EWEC Billia Croo sea test site. By utilising the long experience in offshore engineering, oil company Saipem has signed a MoU with Wello Oy to further enhance the Penguin WEC2 technology by optimising the installation procedure and operability offshore [34].

To summarise WEC development in the UK, the capacity evolution of the WECs tested or to be tested in UK waters is presented and discussed here. As indicated in Figure 14 and Figure 4, in the early years before 2011, the UK market was far ahead of other countries by approximately 1 MW device installed capacity with devices such as Pelamis's P2 750 kW and Aquamarine Power's Oyster 800 kW. After Pelamis and Aquamarine went into administration, the market dramatically scaled down to relatively small scale devices lower than 200 kW. From 2015 onwards, the market seems to be converging in two directions: large megawatt scale grid-connected utilities (Wello's 1 MW WEC2, Bombora's 1.5 MW mWave, AWS's 4 MW AWS III, MSP's 4.5 MW WaveSub) and kilowatt scale niche applications (OPT's 3 kW P3 PowerBuoy®, Mocean Energy's 2-4 kW Blue Star, Albatern's 50 kW WaveNET, Seatricity's 160 kW Oceanus2). In addition, it is clear that the UK's wave energy market was largely supported by domestic developers during the early years (2000-2010). From 2010 onwards, the sector has been attracting more and more worldwide developers to test or develop their devices within the UK. This indicates the UK's leading position in developing wave energy in the world and the positive prospect of a significant wave energy market and sector in the UK.

5. Potential role of wave energy in the UK

To achieve the Net Zero 2050, the UK is at the rapid pace of decarbonisation [46]. Diverse renewable energy resources are needed to achieve the target. Wave energy although on a nascent stage, is considered to have an essential role in the long-term decarbonisation of the UK as stated in the UK's Clean Growth Strategy [131]. As indicated in Figure 14, here we suggest the two valuable roles of wave energy for decarbonisation: contribution to the energy mix at utility scale and niche markets.

5.1. Energy mix

The UK is rapidly developing renewable energy, in particular wind, solar and biomass to contribute to the UK's energy mix, as shown in Figure 15 (summarised from the data published by BEIS in [132, 133]). However, relying on wind and solar alone is not recommended as they are intermittent. This can be solved by the introduction of wave energy and other diverse renewable energy sources. Wave energy has great potential to complement wind and solar. As indicated in [57, 134], the peaks of wave climate trail the wind peaks by several hours and the UK's solar energy is higher in the summer, whereas wave energy is much higher in the winter. In consequence, the combination of wave, wind and solar in the energy mix can lead to a more continuous, reliable and smoother power supply. In addition, the integration of offshore wind, wave and solar can offer higher power capacity and lower cost of energy by sharing infrastructures, such as support structure, mooring, grid connection, installation and O&M.

To prove the benefits of wave energy to the energy mix, an increasing number of projects have focused on developing technologies of hybrid devices and mixed microgrids. The Danish developer Floating Power Plant (FPP) was the pioneer for hybrid wave-wind technology. In 2008, a scale model P37 was tested off the Denmark sea, hosting 33 kW wind and 30 kW capacity of wave [43]. FPP is now developing the commercial scale P80 with capacity up to 8 MW. In the UK, WEC developers such as, MPS and Bombora are developing wave-wind hybrid technology (see Figure 16). MPS secured £4.3m by the European Regional Development Fund to further develop the DualSub (wave-wind hybrid system) with 20+ MW capacity target. Bombora is collaborating with ORE Catapult to integrate mWave™ into

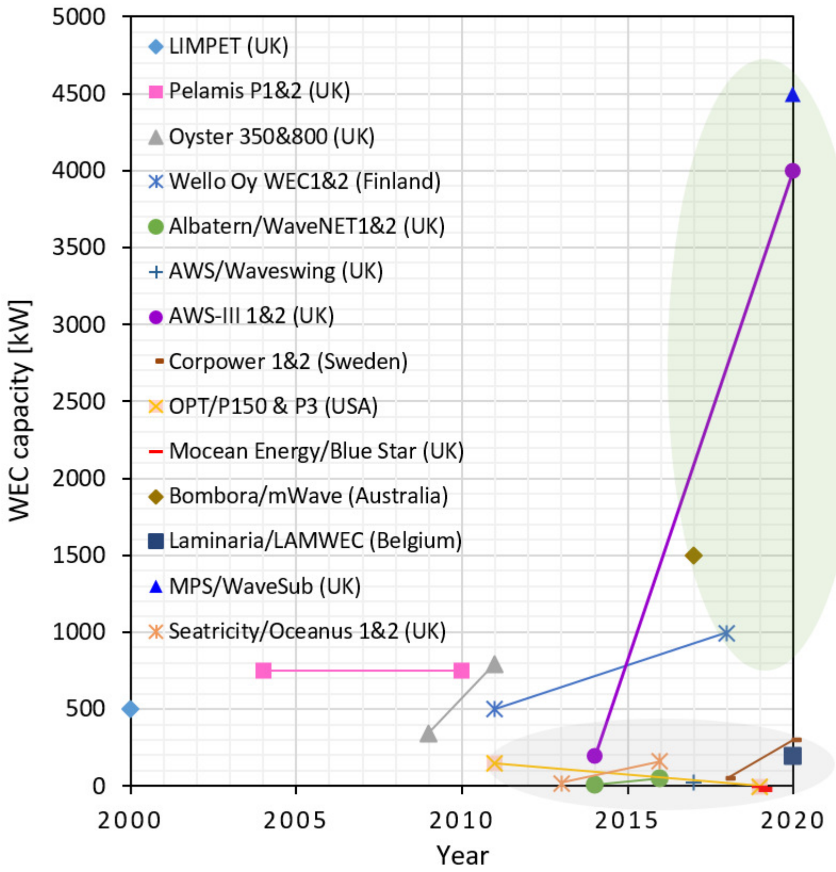


Figure 14: Evolution of the WEC capacity in the UK. Each symbol represents a WEC device that has been tested or is planned to be tested in the UK waters, with its capacity on the Y axis and test year on the X axis. The two ovals indicate the two different WEC sizes that appear to be converging: the large megawatt scale WECs in green and the kilowatt scale niche applications in grey.

offshore wind structures. Two Australia-based projects: King Island co-located wind-wave-solar and Garden Island co-located wave-solar are ongoing to demonstrate the role of wave energy within mixed renewables. In King Island, a 200 kW fixed OWC developed by Wave Swell Energy is under construction and is expected to be integrated with the existing high penetration wind and solar microgrids on King Island [39]. Carnegie Clean Energy has completed the commission of the microgrid plant in Garden Island, Western Australia. The microgrid consists of three 1 MW CETO6, a 2 MW solar PV array, a 2 MW battery and a desalination facility. The plant started to produce green electricity for Australia's largest naval base, HMAS Stirling on Garden Island in 2019.

5.2. Niche markets

As shown in Figure 14, unlike the early stages of megawatt-scale utility applications, wave energy for kilowatt-scale niche applications have developed rapidly in the past 10 years. More importantly, compared to the Government support dependent megawatt-scale WECs, wave energy niche applications have been attracting significant support from a greater diversity of sources, including industry, such as aquaculture companies and oil & gas companies. It is believed that the rapid growth in wave energy niche applications can be an important stepping-stone to facilitate the development of utility-scale devices by accumulating field experience, demonstrating integration of wave energy with the energy system and building confidence for investors. Benefiting from the diversity of WEC technologies, the niche markets in wave energy are diverse and are summarised in below and in Table 7.

- WEC-Integrated breakwaters: Embed WEC devices into breakwater structures to save cost, improve structure reliability and provide green power to the facilities in vicinity [114, 135–138].

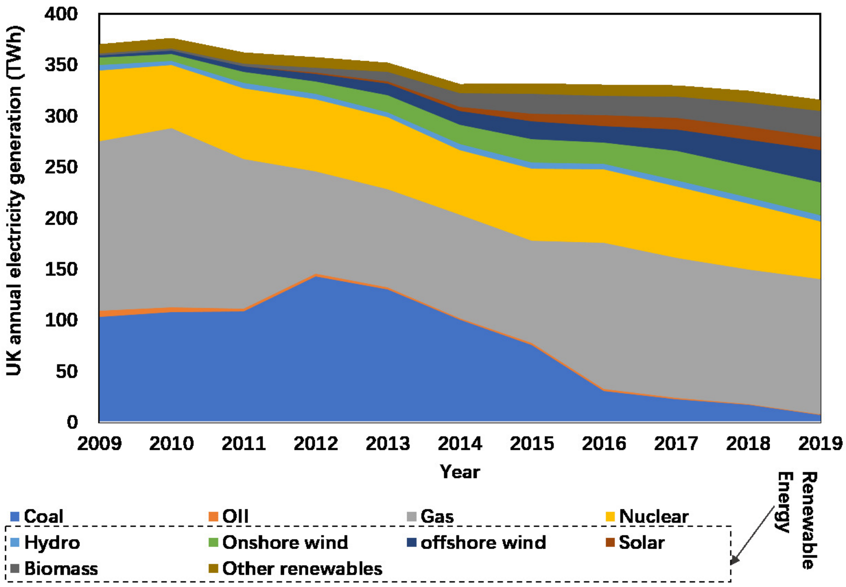


Figure 15: Evolution of electricity generation by different sources in the UK.

(a) (b)

Figure 16: Concept diagrams of the wave combined systems developed based in the UK. (a) DualSub (wave-wind hybrid system) from MPS (image courtesy of MPS Ltd.). (b) Bombora floating mWave™ + wind hybrid solution (image courtesy of Bombora Ltd.).

- WEC for desalination: Use WEC devices in place of the conventionally used diesel generator to drive desalination system to converter sea water into fresh water. This can be necessary for coastal regions and isolated islands [139–141].
- WEC for mariculture: Use WEC devices to power mariculture farms, such as offshore aquaculture farms to address the increasing demand for seafoods [36]; artificial reef farms to protect the coastlines and improve marine ecosystem [26]; macroalgae farms to provide biomass for biofuel production to compete the terrestrial biomass like crops [142].
- WEC for offshore oil & gas applications: Use WEC devices to provide green power for the offshore oil & gas platforms or their sub-sea facilities to improve the decarbonisation of oil & gas sector.

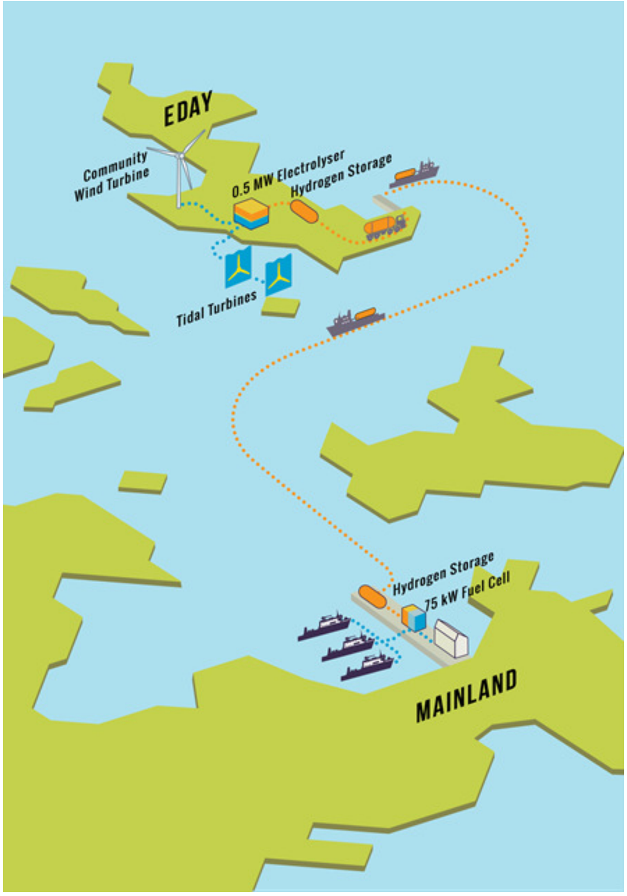


Figure 17: Schematic diagram of offshore renewables-powered hydrogen generated at EMEC, UK [12] (image courtesy of EMEC). In 2017, EMEC achieved the first tidal-powered hydrogen.

- WEC for island microgrids: Build local wave microgrids or wave-integrated renewable microgrids to provide green power on remote and economically poor communities and to release the fiscal burdens and potential marine environmental pollution caused by importing fossil fuel.
- WEC for military and surveillance: Provide green electricity to navy bases or operate as an offshore stand-alone power and communication stations for unmanned sub-sea facilities for military use.
- WEC for combined energy systems: Integrate wave into wind or solar for higher and smoother power output.
- WEC as navigation buoys: Power the light, air horns, radar reflectors, etc., on a buoy to act as a navigational aid, such as the well known Masuda's navigation buoy [143].
- WEC for oceanography services: Act as a wave-rider buoy to collect ocean data [144].
- WEC for mining seawater minerals and gasses: Use wave power to drive systems (like passive absorption, electrochemical and electrolytic processes) to extract useful elements, minerals and gases (like hydrogen) [145]. As an example, EMEC has achieved the world's first tidal generated hydrogen using power from tidal energy, as shown in Figure 17.
- WEC for luxury resorts: Provide green electricity to luxury resorts by WECs or wave-wind/wave-solar hybrid systems. Research [146] has highlighted that applying wave energy to power facilities of luxury resorts can be a promising market for wave energy commercialisation due to the fact that most resorts are privately owned and WEC implementations will not highly depend on support and acceptance from local government.

Table 7: Representative cases for wave energy niche applications.

Niche market	Case	Country	WEC type	Capacity	Status
WEC-integrated breakwaters	OWC sloping caisson	Japan	Fixed OWC	60 kW	n/a
	Mutriku	Spain	Fixed OWC	296 kW	Active
	REWEC3	Italy	Fixed OWC	2.5 MW	Active
	OBREC	Italy	Fixed overtopping	1 kW	Active
WEC for coastal protection	Lab test of DEXA	n/a	Articulated WEC	n/a	n/a
	Numerical test of wave dragon	n/a	Floating overtopping	n/a	Inactive
	Numerical test of DEXA	n/a	Articulated WEC	n/a	Inactive
	Numerical test of WaveCat array	n/a	Floating overtopping	n/a	Inactive
WEC for desalination	Delbuoy	Puerto Rico	Heaving WEC	1100 litres/day	Inactive
	OWC-RO	India	Fixed OWC	10,000 litres/day	n/a
	Garden Island project	Australia	Heaving WEC	n/a	Active
	Odyssée	Canada	Heaving WEC	10,000 litres/day	n/a
	SAROS	USA	Heaving WEC	11,000 litres/day	Active
	ATMOCEAN	USA	Heaving WEC	n/a/day	Active
	Wavepiston	Denmark	Horizontal WEC	28,000 litres/day (150 kW)	Active
	Resolute Marine	USA	Flap type	n/a	Active
	Seatricity	UK	Heaving WEC	162 kW	Active
WEC-integrated microgrids on islands	Garden Island microgrid	Australia	Heaving WEC	1 MW	Active
	King Island microgrid	Australia	Fixed OWC	200 kW	Active
WEC for mariculture	WaveNET	UK	Rotational WEC	50 kW	Active
	CCELL	UK	Flap type	n/a	Active
	eForcis	Spain	Heaving WEC	n/a	Active
WEC for offshore oil & gas applications	PB3 PowerBuoy®	Italy	Heaving WEC	3 kW	Inactive
	PB3 PowerBuoy®	UK	Heaving WEC	3 kW	Active
	ISWEC	Italy	Rotational WEC	100 kW	Active
	Wave Star	UK	Articulated WEC	2-4 kW	Active
WEC for military and surveillance	BOLT LIfeSaver	USA	Heaving WEC	30 kW	Active
	Garden Island project	Australia	Heaving WEC	1 MW	Active
	OPT fibre optic mooring cable	USA	Heaving WEC	3 kW	Active
WEC for combined energy system	P37	Denmark	Heaving WEC	30 kW	Inactive
	DualSub	UK	Rotational WEC	20 MW	Active
	mWave+wind	UK	Flexible membrane	n/a	Active

- WEC for coastal protection: Weaken the nearshore waves to protect shorelines from coastal erosion and flooding [147–149].

As summarised in Table 7, first, most of the niche markets have achieved pre-commercial or on the verge of commercial deployment, excluding WEC application for coastal protection which is still at the research stage. For example, the commercial-scale 100 kW ISWEC developed by ENI oil company is going to be connected to a medium-scale oil & gas platform for power supply. Secondly, the kilowatts to hundreds of kilowatts scale can be enough to meet the requirements of niche markets. For example, in the desalination market, a 150 kW Wavepiston can generate approximately 28,000 litres of freshwater per day which can meet the daily demand of nearly 190 people. Thirdly, all types of WECs can be applicable to most of the niche markets. Only a few niche markets have formed a preference for WEC type; for example, fixed WECs are preferred for breakwater integration where fixed OWC and overtopping WECs have been in use. Novel types of wave technology like flexible membrane types have been proposed for breakwaters integration due to the benefit of low cost [150]. Located offshore, floating WECs are preferred for oil & gas applications.

In summary, niche markets are rapidly developing and stimulating the development of the wave energy sector and should be supported in parallel with the utility-scale WEC development. As stated in the newly announced £4.5m Marine Wave Energy by EPSRC in 2020, novel design for niche application is one of the key areas for funding support.

6. Conclusions and recommendations

This paper presents an overview of the UK's wave energy sector in the last 50 years 1970-2020, following the work based on the consultation through scoping wave energy workshops held by EPSRC in August 2019 and by Supergen ORE Hub in January 2020 and a series of structured interviews with academics, policy-makers, funding bodies and industry professionals. The work covers the review of the UK's wave energy resource, Government and industry support, the progress and current status as well as the potential role of wave energy for the UK's industry. Based on the review, following key findings can be given:

- The UK has valuable exploitable wave resources (40-50 TWh/year) which has the potential to contribute at least 15% of the current (2019) annual electricity generation. Six regions active in wave energy development are suggested here, including: Shetlands, Pentland Firth and Orkney, Hebrides, Pembrokeshire, South West England and North Sea. In addition to the existing EMEC in Scotland, Wave Hub and FaBTest in South West England, two Welsh test centres: META and PDZ have been newly established. For reference, there exist numbers of sources offering openly accessible wave energy data of the UK.
- Long-term effective Government and industry support play a significant role in facilitating wave energy commercialisation. Four significant opportunities are highlighted in the paper to illustrate the importance of Government and industry support to the UK's wave energy development. (1) The first technology push from government happened in the early 1970s, in regard to the oil crisis and Government's need for new energy alternatives. However, the programme ended with no prototype constructed because the oil crisis ended and Government policy shifted towards other energy solutions. (2) In the late 2000s, in response to the Climate Change Act (80% of GHG reduction by 2050), the UK and Scottish Government renewed interest in wave energy and urged the sector to be commercialised, although the technology was still not mature at that time. The Government invested approximately 80% of public funding to support large-scale, array deployments and test infrastructures [76], but the sector was highly depressed by the failures of the two market leaders Pelamis and Aquamarine with numbers of players existing the market in the mid-2010s. (3) From then on, capturing experience from Pelamis and Oyster programmes, Government shifted away from commercially focused RD&D funding back to innovation-focused research and demonstration, such as the WES, Supergen ORE Hub programs. (4) Since 2019, a new upward trend is evident for wave energy with the announcement of the legislation of Net Zero targeting at 100% of GHG reduction by 2050 for the UK Government and by 2045 for the Scottish Government. In addition, other mature industrial sectors are seeking collaborations with wave energy, like oil & gas, aquaculture and military, etc.
- Market incentive support for the UK's wave energy has started since 1990, through the NFFO and SRO (1990-2002), RO (from 2002) and CfD (from 2014 to replace RO). In 2019, in round 3 of the CfD for the less established technologies pot, wave energy's strike price (for year 2023/2024 and 2024/2025) was £281/£268 MWh and offshore wind's level was just £56/£53 MWh. To increase the competitiveness of wave energy and enhance the support diversity, the CfD round 4 released in 2021, is planning to put fixed offshore wind in a pot on its own, leaving wave, tidal, floating offshore wind and other less established technologies in a pot.
- The existing supply chain for the UK's wave energy, covering marine operations, vessels, health and safety, control systems, electrical infrastructures, foundations and mooring systems, mainly incorporate expertise from the supply chains of oil & gas and offshore wind sector. However, the requirements are different in these sectors. It is therefore important to develop cost effective, tailored supply chains for the wave energy sector.
- According to Fig.4, the UK has been leading the globe in wave power development and installation, achieving nearly 23 MW (note that the value includes the devices that are no longer operational) of cumulative installed capacity since 2010, far ahead the other countries. An ambitious 22 GW of wave energy capacity is expected by 2050 in the UK to contribute the Net Zero target [1]. WEC technologies have been converging to some extent. Most of the installed deployments and ongoing constructions use oscillating body WECs, followed by OWC, novel concepts (like flexible membranes and hybrid systems) and overtopping WECs.
- It is suggested that the failure of Pelamis and Oyster could highly result from the mismatch between the financial and technical drivers that forced the WEC developers to embark on costly large-scale demonstrations too early in their development. Therefore, continued technological innovation and development is highly necessary for the wave energy sector.

- Unlike the main focus on developing 1 MW devices seen before the mid 2010s, the UK's wave energy sector is developing in two directions presently: megawatt-scale utility devices and kilowatt-scale niche devices. In the UK waters, representative wave energy technologies are being developed to complement and compete with the wind turbines in the energy mix. 12 types of WEC niche markets are summarised in the paper. Compared to the utility-scale devices, most of the WEC niche applications are more advanced and have achieved or are on the verge of commercialisation.

According to the review of the UK's wave energy between 1970 and 2020, the following recommendations are given for future development:

- Innovation research, demonstration and large-scale deployments, all play significant roles in wave energy development and more importantly, each helps to accomplish the other. It is therefore important for the UK Government to balance the funding ratio among targeted innovation research, pre-commercial demonstrations and commercial deployments.
- A tailored supply chain based in the UK is one of the significant aspects for the development of wave energy sector. In particular, the specific sub-components of wave energy sector such as accurate wave energy resource assessment, novel technologies for foundations, mooring systems and power take-off need to be focused on.
- Niche applications are developing rapidly alongside utility-scale devices in the UK presently, and many are on the verge of commercialisation. Thus, niche technologies can be regarded as an important stepping-stone and effective way to demonstrate the competitiveness of wave energy for the UK energy mix alongside other renewables. Therefore, we recommend support for niche market applications in parallel with utility-scale WEC technologies.

As one of the pioneers in developing wave energy technology, the UK is an important contributor in the world wave energy community. The UK's test facilities attract and support developers from all around the world, accumulating valuable field experience in operation, deployment and maintenance; EMEC is supporting Qingdao Pilot National Laboratory to develop the first wave and tidal test centre in China. The authors hope the experiences of WEC development, policy making and market incentive summarised in this review paper can also be useful for the wave energy development in other countries.

Acknowledgment

This work was conducted within the Supergen ORE Hub, a £9 Million programme (2018 – 2022) funded by EPSRC. The authors would also like to thank Dr. Yang Qin for useful comments provided and the companies and authors for the permissions of using their device images in the article. The authors also would like to thank Met Office, ECMWF and EMEC for providing the hindcast and measured data used in this paper. Furthermore, the authors would like to thank all the reviewers for their constructive suggestions.

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