Marine Renewable Energy

SUBSEA ENGINEERING OPPORTUNITY
International Market Insights Report Series

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Scottish Enterprise

Contents

1. Introduction

This report is part of a series of reports considering the opportunities for the Scottish oil and gas (O&G) subsea supply chain in other subsea and related markets. The report is a desk review considering the international activity of each of the sectors including where there is current activity and where there is the potential for activity based on published targets and available resource and opportunity. The report also considers the particular synergies of the given sector and the subsea oil and gas supply chain. These opportunities cover where there is a direct cross over and also where there are opportunities for collaboration to provide innovative solutions.

The marine renewable energy (MRE) sector, also known as Ocean Energy, harnesses the power of the oceans to generate renewable energy, there are a number of technology categories that fall within the MRE definition including: tidal stream/currents, tidal range, ocean currents, wave energy, ocean thermal energy conversion (OTEC) and salinity gradient. MRE provides a source of renewable energy that is highly forecastable and predictable which is important for energy management.

Waves originate from the transfer of the wind's kinetic energy to the upper surface of the ocean, and the wave's energy is proportional to the square of its height and period of motion.[1,2] The energy is then captured using Wave Energy Converters (WECs) and converted into electrical energy. This industry is still at an early stage however various technology solutions have been tested in real sea conditions, including attenuators, oscillating water columns and point absorbers. As well as energy production, wave energy is associated with water drawing, heat supply, seawater desalination and hydrogen production.[2] Examples of wave energy include the Mutriku OWC plant in the Basque Country, Spain, which has a capacity of 296 kW and has generated 1.3 GWh to the grid as of April 2017.[3]

Tidal Range is exploiting the difference between the rise and fall of the tides, which are derived from the gravitational forces of the Moon and Sun and the Earth's rotation. Energy is captured using a barrage across an estuary, trapping the water at high tide and releasing through turbines to generate electricity, some barrages also generate electricity as the tide floods into the estuary although this isn't as efficient as generating on the ebb flow. An example is La Rance Tidal Barrage in France which started operating in 1966 and has a capacity of 240 MW. There are limited locations globally that support this technology, but they can offer a highly predictable form of renewable energy.

Tidal Streams come from the currents resulting from the filling and emptying of coastal regions as a result of the tidal rise and fall, and it is noteworthy that bathymetry and coastlines have an impact on the strength of tidal streams. Areas that experience the biggest tidal streams have constrained passages such as through island archipelagos and coastal features such as peninsulas. An example of a tidal stream project is the Nova Innovation's Shetland Tidal Array, which will have a capacity of 300 kW, currently two 100 kW turbines have been deployed in Bluemull Sound.[4]

Ocean Currents are derived from ocean circulation caused by forces such as wind, thermohaline circulation, salinity gradients and the Earth's rotation. They are predictable, continuous and move in one direction. They are less explored in terms of technology applications than tidal currents, but potentially provide a huge resource in areas where they occur. To date, there has not been a full-scale demonstration of this technology, but there has been some work on prototypes.[5]

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[1] World Energy Council, Marine Energy, World Energy Resources, 2016.
[2] Wang, S., Yuan, P., Li, D. and Jiao, Y., An overview of ocean renewable energy in China, *Renewable and Sustainable Energy Reviews*, **15** (2011) 91–111
[3] Tethys, Knowledge base, Mutriku Wave Power Plant, 2018
[4] Nova Innovation Website, Sites, Bluemull Sound, Shetland. Accessed January 2018
[5] Bureau of Ocean Energy Management, Ocean Current Energy

Ocean Thermal Energy Conversion (OTEC) is the extraction of energy from the temperature difference between the solar warmed upper ocean layers and the colder deeper ocean water, typically below 1,000 m. This technology is limited to regions where the monthly average seawater temperature difference between the water at 20 m and 1000 m depth always exceeds 18degC. This region is typically between 30°N and 30°S. deep water tropical sites where the greatest temperature difference can be found.[6]

Salinity Gradients are derived from the difference in salinity of fresh water and ocean water found at river mouths. The electricity is generated from the potential difference created across a membrane in areas such as fjords and deltas.

Marine renewable energy is still a developing sector, but although the concepts have been around for a number of decades, the commercialisation of the technology is still happening. Full scale demonstrations of technologies have occurred with promising results. Cost reduction however is a vital step in developing the technology. Some countries have supportive policies in place such as enhanced feed-in tariffs for MRE generated electricity, and these act as a stimulus to the development of the sector to reap the economic benefits as well as making use of indigenous resources. Figure 1 shows an overview of the technology readiness of each of the six MRE areas. It is worth noting that within each of these sectors there will be a range of technologies that have achieved a range of TRLs.

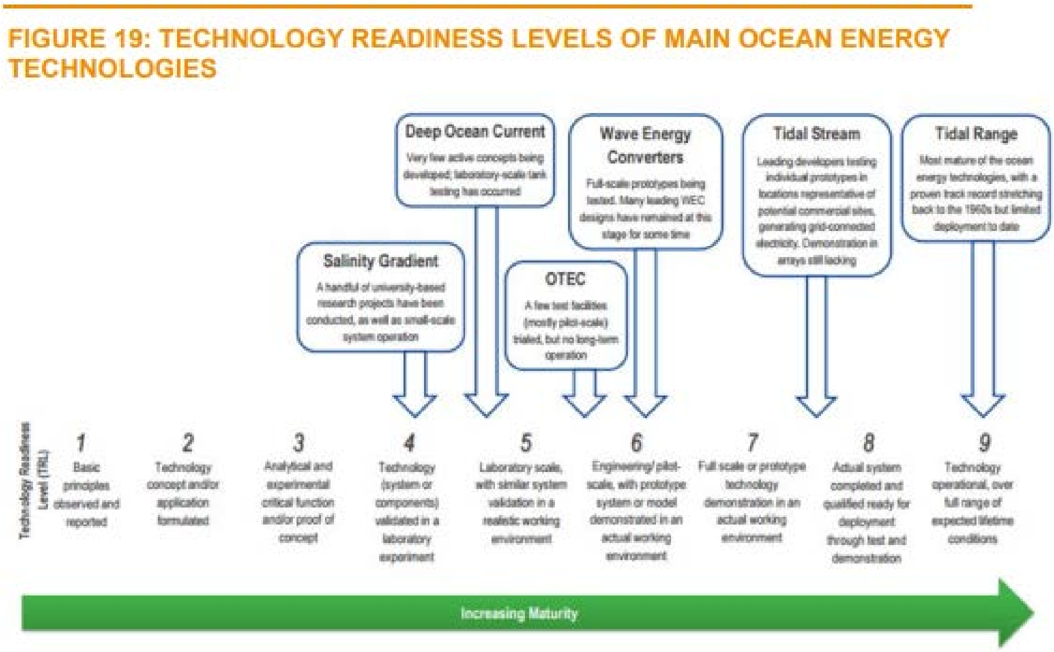


Figure 1: Technology readiness levels of the various MRE technology areas. technologies within these areas will have their own TRLs, this is a summary. Source: WER2016/Mofor et al. 2014

Table 1 summarises the global resource for MRE, including the type of resource that is available; current installed capacity (to the end of 2016); the resource potential, where it is known; and any published targets for the country in question.

[6] Rajagopalan, K., and Nihous, G. C., An Assessment of Global Ocean Thermal Energy Conversion Resources with a High-Resolution Ocean General Circulation Model, *Journal of Energy Resources Technology*, **135** (2013)

Table 1: Global opportunities for MRE including types of MRE, installed capacity, potential resource and national targets. Source: Various.

Country	Resource Type	Installed Capacity (end 2016)	Potential	Target
Argentina	Wave and tidal stream			
Australia	Wave, tidal stream		Wave: 280 GW Tidal stream: 200 MW	
Belgium	Wave			Primarily research and development
Brazil	Wave, tidal stream, ocean current, OTEC		Wave: 122 GW Tidal stream: 27 GW Ocean current: OTEC:	
Canada	Tidal stream, tidal range, wave	Tidal range: 20 MW Tidal stream: 2.5 MW (FORCE) Wave: 11 kW	Wave: 27.5 GW extractable) Tidal stream: 6.3 GW	
Caribbean	OTEC			
Chile	Wave		Wave: 240,000 MW Tidal stream: 3,000 MW	
China	Wave, tidal stream, tidal range, ocean current, OTEC and salinity gradient	Tidal range: 4.1 GW Tidal current: 1.78 MW Wave: 600 kW	Tidal Range: 22.3 GW Tidal Current: 1.6 GW Wave: 1.5 GW OTEC: 25.7 GW Salinity Gradient: 11.3 GW	
Cuba	OTEC			
Denmark (plus Greenland)	Wave	Wave: 130 kW	Wave: 3.4 GW	
France (Including French offshore territories)	Tidal range, wave, tidal stream, OTEC	Tidal range: 240 MW Tidal stream 2.25 MW	Wave: 14 GW Tidal: 3 GW	
Ghana	Wave	Wave: 400 kW		
India	Tidal stream, tidal range		Tidal stream and range: 12 GW Wave: 40 GW OTEC: 180 GW	
Indonesia	Wave, tidal stream, OTEC		Wave: 1.2 GW Tidal stream: 4.8 GW OTEC: 43 GW	3.1 GW by 2025, 4.5 GW by 2030
Ireland	Wave, tidal stream	Tidal stream 1.2 GW	Wave: 29 GW Tidal stream: 100 MW	
Italy	Tidal stream, waves	Tidal stream: 60kW Wave: 150 kW		

Japan	Wave, ocean current		Wave: 31-36 GW	1.5 GW by 2030
Mexico	Wave, tidal stream		Tidal stream: 100 MW+	
Netherlands	Wave, tidal stream	Tidal stream: 1.55 MW Salinity: 50 kW	Wave: Tidal stream: 50 – 100 MW Tidal range: 60 – 100 MW	
New Zealand	Wave, tidal stream		Wave: 7 GW Tidal stream: 500 MW	The plan for 2020 would be to reach 1 to 2% of electricity from marine energy (Energy Outlook to 2030).
Norway	Tidal stream, wave, Salinity gradient		Wave: 29 GW Tidal stream: Salinity gradient:	
Philippines	Wave		OTEC: 265 MW Tidal stream: 40-60 GW Wave: TOTAL: 170 GW	Department of Energy target for ocean energy installation is up to 71 MW by 2030 with the first ocean facility operational by 2020
Portugal	Wave	Wave: 400 kW	Wave: 15 GW	
Russia	Wave, tidal		Tidal: 23 GW	
South Africa	Wave and ocean current		Wave: 69 GW	
South Korea	Wave, tidal stream, tidal range, OTEC	Tidal stream: 500 kW Tidal barrage: 1 MW Wave: 665 kW OTEC: 220 kW	Wave: 7 GW Tidal stream: 1 GW Tidal range: 6.5 GW OTEC:	
Spain	Wave	Wave: 526 kW	Wave: 20 GW	
Sweden	Wave	Wave: 3.3 MW		
Taiwan	Wave, ocean current		Highest Ocean current, low for wave, OTEC and tidal	
UK	Wave, tidal stream, tidal range	Tidal stream: 3.4 MW	Wave: 43 GW Tidal stream: 32 GW Tidal range:	
USA	Wave, tidal stream	Wave: 50 kW	Wave: 223 GW Tidal stream: 350 MW	

Throughout the technology and project development process for all aspects of MRE there will be opportunities for the subsea oil and gas supply chain including innovation through collaboration as well as transfer of knowledge and technology.

2. MRE Sectors Overview

It is estimated that by 2050 there could be up to 337 GW of Marine Renewable Energy (MRE) installed worldwide, this deployment could create an estimated 300,000 direct jobs.[7] The size of the global market is expected to be €108bn (£95bn) annually in 2050.[8]

The figure below shows the installed and consented capacities of all MRE in the International Energy Agency Ocean Energy Systems (IEA-OES) member countries in 2015.

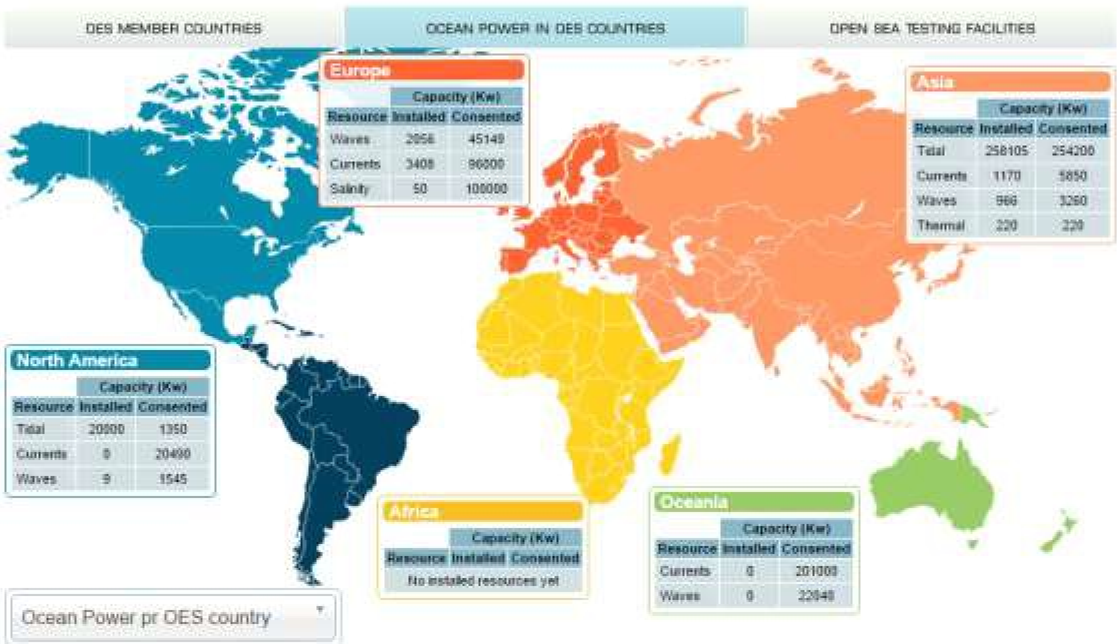


Figure 2: Global MRE capacities. Source: OES 2015 Annual Report

The sections below aim to summarise the type of technology within each of the six MRE sectors, the global resource of each of the sectors and the current or proposed projects, where the information is available.

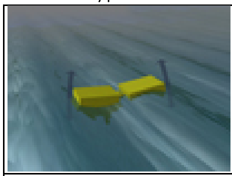
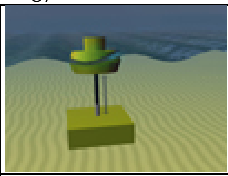
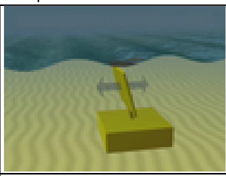
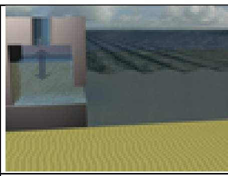
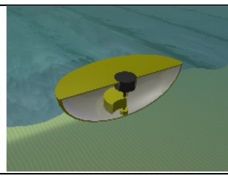
2.1. Wave

2.1.1. Technology

Wave energy converters aim to extract the energy from the waves in the near shore environment. A number of devices have been developed to make use of this energy. Historically, oscillating water columns (OWCs), described in Table 2, are the most abundantly deployed including sites in Portugal, Scotland, Japan, India and Norway.[9] In more recent times, other technologies, as described in Table 2, have been developed with some being tested at part and full scale in test tanks and the real sea environment.

[7] Ocean Energy Systems, Annual Report 2015
[8] Lizhen Xu, The Ocean Energy Sector Report, knowRES, 2015
[9] Aquaret, Technology Selection – Wave, 2012

Table 2: Types of wave energy converters. Source: Aquaret

				
Wave attenuator	Point source absorber	Oscillating wave surge converter	Oscillating water column (OWC)	Rotating mass
Uses the bending motion of hinged joints between floating sections, caused by the waves passing under the device, to drive a hydraulic motor and generate electricity	Bottom mounted, this WEC has a tethered buoy either floating on the surface or suspended in the water column which rises and falls with the wave swell. Electricity is generated through hydraulic motors, or through driving water to shore where it passes through hydroelectric turbines to generate electricity.	A near shore seafloor mounted device. A submerged paddle which is moved forward and back by the wave surge, generates electricity through a hydraulic motor.[10] Other examples use the motion to pump water ashore to pass through a hydroelectric generator.	Installed at the shoreline or in a breakwater, the device contains a chamber which fills with water from the wave surge. Air is expelled from the chamber, as the water floods in, through an air turbine in top of the chamber which in turn generates electricity. The turbines may also generate on the reverse as air is drawn into the chamber as the water retreats.	An asymmetric hull is used which when subject to the movement of the waves creates a gyrating motion, this induces the mass located inside the hull to rotate and directly generate electricity.[11]
E.g. formerly Pelamis	E.g. Seabased's WEC, Carnegie Wave Energy's CETO	E.g. AW Energy's Waveroller	E.g. Mutriku wave power plant; Pico OWC plant	E.g. Wello's Penguin
Other technologies include: Wave overtoppers, Submerged pressure differential device, bulge devices				

2.1.2. Resource

The theoretical wave power resource globally is 2.11 Terrawatts (TW) to 95% confidence, the breakdown of this is shown in Table 3 below, where it is seen that there is roughly an even split of theoretical resource between the Northern and Southern hemispheres. The authors of the resource study, Gunn and Stock-Williams, comment that only a small portion of this is extractable. Although not all the energy can be practically extracted, the amount available will significantly depend on the technology and type of deployment such as the spacing of devices, type of device and other considerations. The values should be treated as theoretical, but show that there is significant resource to be tapped globally. Countries with the greatest wave resource are those that have long coastlines facing open sea with a large fetch, such as the UK, Ireland and Norway's north Atlantic coastline.

[10] AW Energy company website, http://aw-energy.com/waveroller/, accessed February 2018
[11] Wello company website, https://wello.eu/about/, accessed February 2018

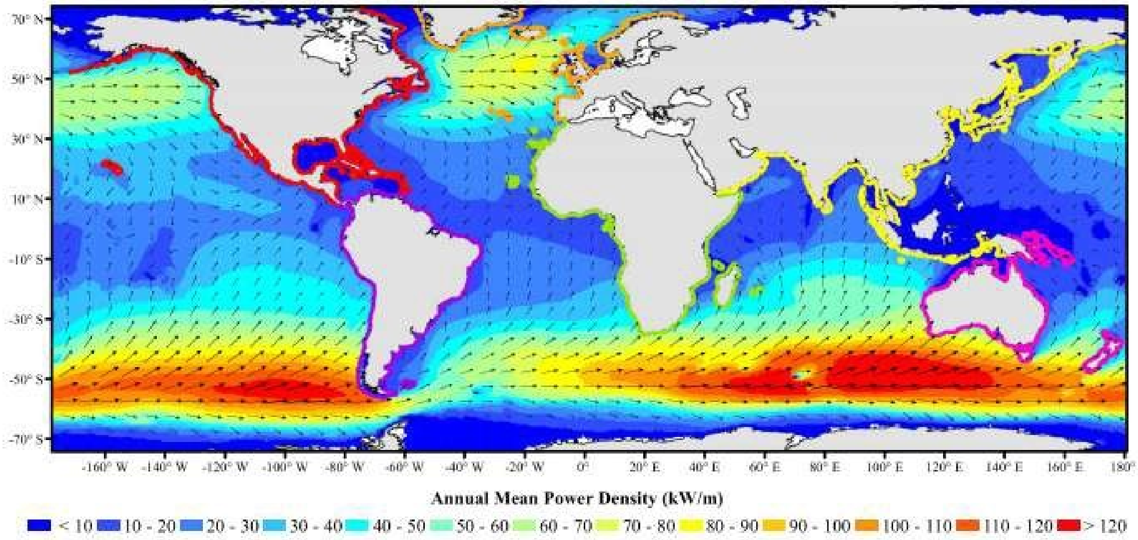


Fig. 1. Annual mean wave power density (colour) and annual mean best direction (→). The land buffers used to quantify the resource are also shown, coloured by continent (see Section 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 3: Global map of annual mean wave power density and the annual mean best direction (denoted by the arrows). Source: Gunn & Stock-Williams

Figure 3 shows the global annual mean wave power density, the figure highlights that the strongest waves are situated roughly between 30°N to 50°N and 30°S to 50°S. The global coastlines of the greatest resource are therefore west coast North America; western Europe, the Southern reaches of South America (Chile); South Africa, Southern Australia and New Zealand.

Table 3: Theoretical Wave Resource globally. Source: Gunn and Stock-Williams

Hemispheres	Theoretical wave resource
Northern Hemisphere	1.07 TW
Southern Hemisphere	1.05 TW
Continents	
North America	427 GW
Oceania	400 GW
South America	374 GW
Africa	324 GW
Asia	318 GW
Europe	270 GW
Countries	
Australia	280 GW
United States	223 GW
Chile	194 GW
New Zealand	89 GW
Canada	83 GW
South Africa	69 GW
United Kingdom	43 GW
Ireland	29 GW
Norway	29 GW
Spain	20 GW
Portugal	15 GW
France	14 GW

2.1.3. Global Wave Energy Projects

In terms of wave energy projects globally, the World Energy Council[1] in 2016 reported that there are forthcoming developments, totalling 839 MW, including:

- Consented - 20 MW
- Early planning - 94 MW
- Early concept - 725 MW

A number of these projects are shown in Table 4 below.

Table 4: Overview of current wave energy projects including those operating, in planning and early concept. Source: World Energy Council, ReNews Global Marine Special Report 2017.

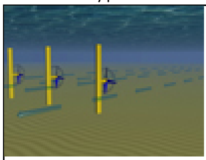
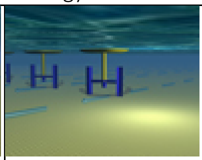
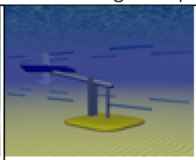
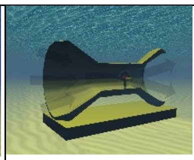
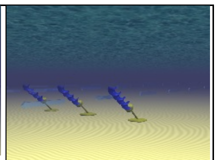
Project country	Company & Technology	Size	Status	Number of devices
Sotenas, Sweden	Seabased	1.05 MW	Under construction	42
Ghana	Seabased	400 kW	Installed	6
Garden Island, Australia	Carnegie CETO 5	240 kW	(pre-commercial demo project)	3
Mermaid/Bligh Bank, Belgium		20 MW	Consented	
Sontenas	Seabased Phase II	9.5 MW	Early planning	378
Ghana	Seabased Phase II	14 MW	Early planning	560
Peniche peninsula, Portugal	SWELL project Oscillating wave surge converters	5.6 MW	Early planning	16
Australia	OPT	Combined total almost 100 MW	Early concept	
Australia	OPT		Early concept	
Australia	OPT		Early concept	
Scotland	AWS Ocean Energy phase I	10 MW	Early concept	4
Scotland	AWS Ocean Energy phase II	190 MW	Early concept	76
WaveHub, UK	Carnegie CETO 6	10 – 15 MW	Pre-commercial stage	
	Fortum	10 MW	Early concept	
	Seabased	10 MW	Early concept	
Garden Island, Australia	Carnegie CETO 6		On hold due to Albany project	
Killard Point, Ireland	WestWave project	5 MW	Due for commissioning 2018	
Albany, Australia	Carnegie CETO 6	1.5 MW	Due to be installed 2020	1
Ghana	Seabased / TC Energy	100 MW	Early concept	

2.2. Tidal Stream

2.2.1. Technology

Tidal stream deploys technology that is, in the most part, analogous to offshore wind turbines, i.e. horizontal axis multibladed turbines. Other technology solutions that have been developed include: contra-rotating turbines; underwater kites; vertical axis turbines; oscillating hydrofoils; ducted turbines (horizontal axis); Archimedes screws and multiple turbine devices. A number of these are described in Table 5 below.

Table 5: Types of Tidal energy converters. Source Images: Aquaret

					
Horizontal Axis turbine. Either bottom fixed or floating; single turbine or multiple turbines per structure.	Vertical Axis turbine. Either bottom fixed or suspended from a floating structure.	Oscillating hydrofoil	Other horizontal axis, e.g. ducted or open centre	Underwater kite	Archimedes screw
Kinetic energy is extracted from the current moving across the horizontal axis rotor. As water is 832 times denser than air the swept area of the rotor can be significantly smaller than a wind turbine. E.g. the AR1500 deployed at Meygen 1A are 1.5 MW turbines with a rotor diameter of 18m[12], compared to a GE 1.5 MW wind turbine with a 82.5m diameter rotor[13]. These are the most widely demonstrated tidal stream	Similar to the horizontal axis turbines, the vertical axis turbines sit in the flow of the water and convert the currents kinetic energy to electricity through a generator, but with the rotational axis perpendicular to the flow. The blades on these TECs can either be straight or helical. Where straight blades are used these can be of fixed or variable pitch. Similar designs exist for wind power turbines.	The oscillating hydrofoil is positioned in the tidal flow and moves up and down in the current. The motion drives reciprocating hydraulic rams which use high pressure hydraulic fluid to turn a hydraulic motor and then an electrical generator. The angle of the hydrofoil can be used to improve efficiency.	Such TECs are similar to the horizontal axis tidal turbines, but have features such as a) ducting surrounding the turbine to increase energy extraction by increasing the mass flow rate through the turbine and directing the flow. b) open centre turbines allow for inductive direct drive (no gear box) generators to be housed in the turbine rim.[14]	The underwater kite is tethered to the sea floor and uses the hydrodynamic lift generated on the wing to fly the kite in a predetermined figure of eight motion. Electricity is generated as the current passes through the turbine situated below the wing. This technology is suitable for low velocity currents.[15]	This TEC uses helix screws to generate electricity in low velocity tidal streams <1 m/s.[16] It is adapted from technology deployed in run of river schemes. The turbines are fixed to the seabed.

[12] Simec Atlantis Energy, Our Turbines webpage, accessed February 2018
[13] Wind Turbine Models.com, General Electric GE 1.5xle, accessed February 2018
[14] Allsop, S., Peyrard, C., Thies, P. R., Boulougouris, E. and Harrison, G. P., Hydrodynamic analysis of a ducted, open centre tidal stream turbine using blade element momentum theory, *Ocean Engineering*, **141** (2017) pp531 - 542
[15] Minesto company website, www.minesto.com/our-technology, accessed January 2018
[16] Marine Energy.biz, Image of the day: Flumill tidal energy system, 2015

technology.					
E.g. Atlantis Resources; Nova Innovation; ScotRenewables; and Schottel Hydro	E.g. EC-OG	E.g. Stingray	E.g. OpenHydro (open centre turbine)	E.g. Minesto	E.g. Flumill

Given the range of technology that is shown in Table 5, it is difficult to state exact figures for capital costs for a tidal stream farm. Figure 4 below, gives an indication of the split of the where the capital costs would occur. All parts of this breakdown will have a subsea element, if not entirely subsea, due to the nature of where the technology is deployed.

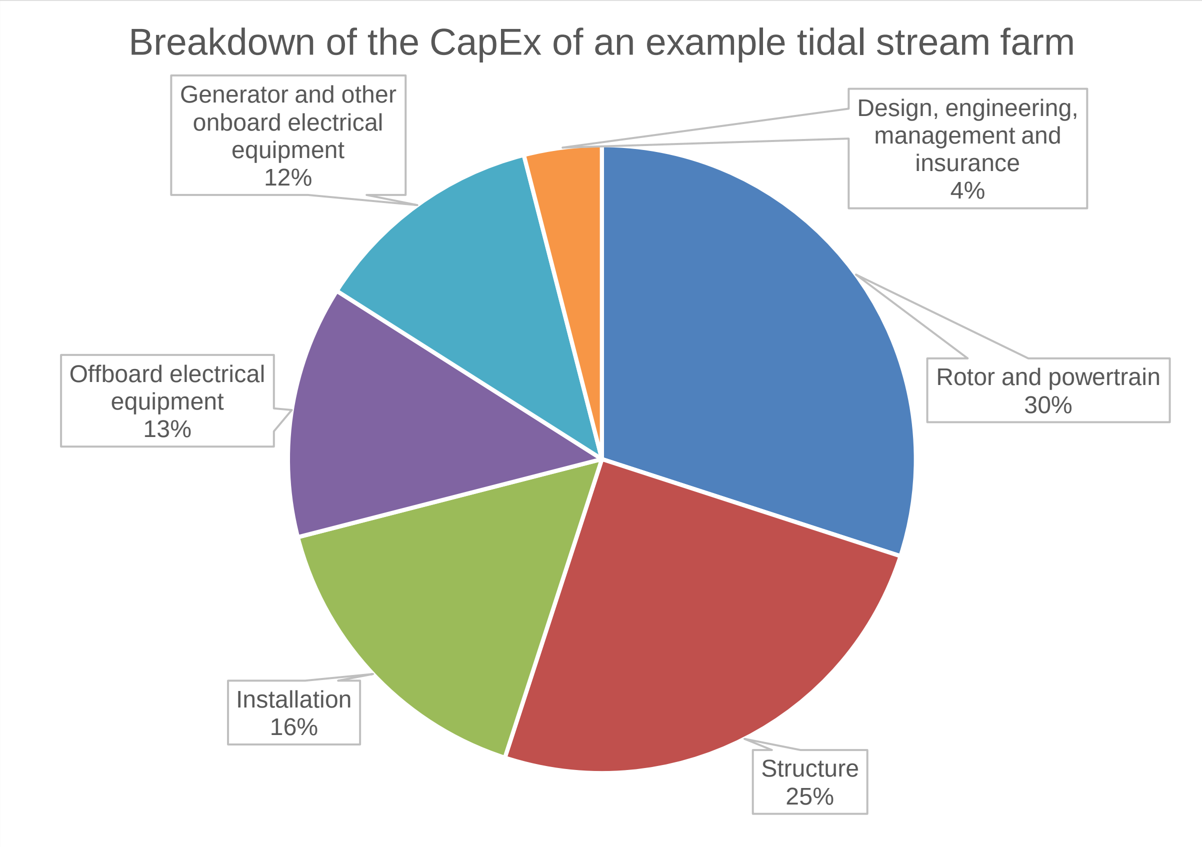


Figure 4: Breakdown of capex for tidal stream farm. Source Aquaret

2.2.2. Resource

Theoretical global potential for tidal stream is predicted to be about 1 TW[17], it is estimated that the global *practical* resource is in excess of 120 GW[18]. Figure 5 below shows some of the main areas of potential resource for tidal stream, the highest resource is the UK which boasts approximately 50

[17] Lewis, A., S. Estefen, J. Huckerby, W. Musial, T. Pontes, J. Torres-Martinez, 2011: Ocean Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[18] MarineEnergy.biz, Estimate of global potential tidal resources, 2015

percent of the European resource. Japan, China and Canada are the areas of the next highest resource.

The best tidal stream resource is found in areas where there is a constraint on the tidal flow, such as through a strait between islands or an island and the mainland; or around a headland. The Pentland Firth in Scotland is widely regarded as one of the most energetic tidal resources as the tidal flow from the Atlantic and North Seas is forced through a small channel. It is estimated that the Pentland Firth could provide approximately half of Scotland's energy needs. The Bay of Fundy in Canada also boasts a significant tidal stream resource. Figure 5 below shows the countries with significant tidal energy resource.[18]

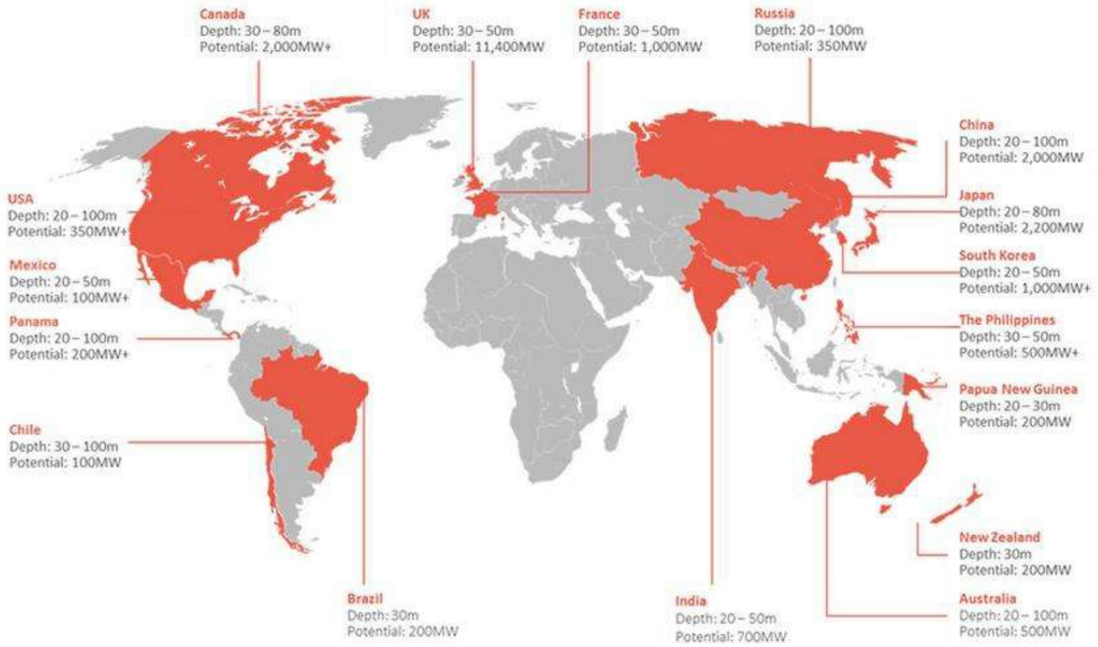


Figure 5: Map showing an estimate of potential tidal resources globally. Source: Tidal Energy Today/Atlantis Resources Corporation.

2.2.3. Global tidal stream projects

The UK is seen as a pioneer in wave and tidal stream energy, largely due to ambitious targets; supportive legislative landscape; and a once supportive subsidy mechanism. However, as Table 6 shows, there are many other countries who are developing projects and demonstrating technology. The major deployment of tidal stream technology has been in Scotland, either in the test berths of the European Marine Energy Centre (EMEC) or the two arrays that are under construction in Shetland and Caithness, amongst others at various stages of planning.

From the world energy council 2016 report, the breakdown of global tidal stream energy projects is, further details are provided in Table 6:

- Installed – 4.3 MW
- Under construction – 10.5 MW
- Consent granted – 44 MW
- Consent application – 42 MW
- In planning – 1 GW
- Early planning – 1.5 GW

Table 6: Overview of global tidal stream projects. Source: various.

Project, Country	Project Capacity	Project Status	Number of Devices
Federico II, University of Naples, Italy		Demonstration project	
Tocardo, Netherlands		Demonstration project	
Korea East West Power Co, Korea		Demonstration project	
Uldolmok Tidal Power Station, South Korea		Operational	
SeaGen, Northern Ireland	1.2 MW	Decommissioned	1
Meygen Phase 1a, Scotland	6 MW	Under construction	4 (3x Andritz Hammerfest HS1500 and 1x Lockheed Martin designed Atlantis AR1500)
Cape Sharp, Bay of Fundy, Canada	4 MW	Under construction	2x 2 MW openhydro turbines
Shetland Tidal Array, Scotland	300 kW	Operational	3x 100 kW Nova Innovation turbines (community ownership model)
Sabella, Brittany, France	500 kW	Under construction	1
Paimpol Bréhat, France	1 MW	Pre-commercial demo	2x 500 kW DCNS/Open Hydro ducted turbines
Scotrenewables	2 MW	Pre-commercial demonstration	1x 2 rotor floating turbine SR2000 MW1 With EU funding secured for a second SR2000 to be deployed alongside the first.
Bluewater, Netherlands	200 kW	Pre-commercial demonstration	BlueTEC
Meygen Phase 1b	82 MW (project total 86 MW)		
Meygen Phase 2	312 MW (project total 398 MW)		
St Davids Head, Wales	10 MW	Consented / under construction (first 400 kW is installed, an analysis on the performance will be undertaken before the others are deployed.	9 devices each holding 3 turbines rated at 400 kW
Normandie Hydro Project (General Electric)	5.6 MW		4x
Raz Blanchard	14 MW		7x Openhydro
Sound of Islay	10 MW		10 x Andritz Hydro Hammerfest

2.3. Tidal Range

2.3.1. Technology

Tidal range projects deploy proven technology in that the devices use a dam with hydroelectric turbines spaced along the length. The power plant works by the dam or 'barrage', built across the opening of an estuary, allows the flow of water into the bay, and then traps it there, creating additional head. The water is then released back through the barrage, where the movement of the water through the barrage spins the turbines which in turn generate electricity. Barrages can work on the *flood*, as the water enters the tidal basin; the *ebb* as the water returns to the sea; or in both directions. Figure 6 shows the ebb configuration.[19] Another configuration considered is a Tidal Lagoon, where the impounded water is offshore, or connected to the shore, in an artificially constructed lagoon.[20] A version of this, a tidal fence, is less restrictive to water movement than a barrage in terms of the structure, could be built for example between islands. Tidal fences are more likely to use vertical axis turbines such as those shown in Table 5, although there is yet to be one built.

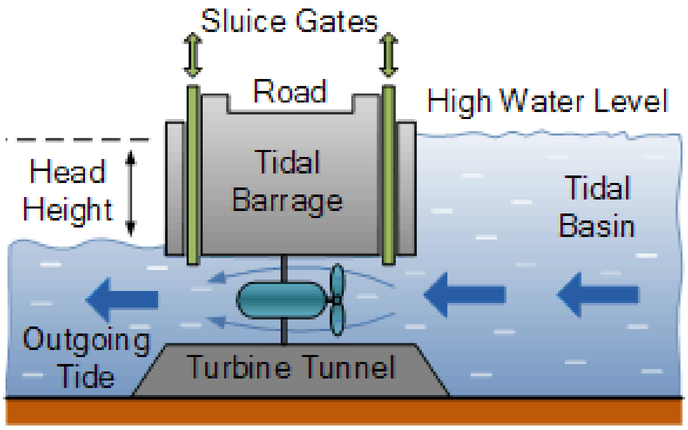


Figure 6: Example of a tidal barrage configuration. Source: Alternative Energy Tutorials.

Tidal barrages can also provide additional benefits to the local infrastructure, such as acting as a breakwater, flood defence and also the potential to provide transport links across an estuary.

2.3.2. Resource

The combined theoretical tidal range and tidal stream resource is predicted to be in the order of 3 TW (3,000 GW) globally of which 1 TW is thought to be close to shore in shallower waters.[17] The useable resource from this will be lower, but this gives an indication of the size of the prize. Studies have shown that the annual tidal range resource worldwide could be 25,880 TWh/yr.[20]

Although individual tidal range power plants provide the opportunity for large scale projects, there are limited locations worldwide that are suitable. Suitability is determined by tidal range, grid connectivity, geomorphology, seabed conditions, and the size of impoundment area available.[20] The environmental considerations of tidal range projects also need to be considered, including the impact of the project on the estuarine ecosystem, including potential loss of habitat and changing of flood

[19] Alternative Energy Tutorials, Tidal Barrage Generation, Accessed January 2018.

[20] Neill SP, Angeloudis A, Robins PE, Walkington I, Ward SL, Masters I, Lewis MJ, Piano M, Avdis A, Piggott MD, Aggidis G, Evans P, Adcock TAA, Židonis A, Ahmadian R, Falconer R, Tidal range energy resource and optimization – Past perspectives and future challenges, *Renewable Energy* (2018), doi: 10.1016/j.renene.2018.05.007

and ebb regimes, as well as the impact on migratory fish that use the impacted routes.

One of the biggest impacts on suitable locations for a tidal barrage or lagoon is the tidal range that is achievable at a location. Good locations for tidal barrages have estuaries or bays where the geomorphology creates a natural oscillatory frequency which resonates with the tidal periodicity to achieve an increased tidal range. Examples of high tidal ranges include the Bay of Fundy, Canada at 17m tidal range; the Severn Estuary, UK at 15 m; and Baie du Mont Saint Michel, France at 13.5 m. At the other end of the scale, the Mediterranean Sea only experiences a tidal range of 1m.[17]

Tides are created by the effect of the moon's gravity on the Earth's water bodies, and so tidal ranges are affected by the relative position of the Sun, Moon and Earth. These effects are well documented and predictable therefore meaning that the energy generation from tidal barrages is highly predictable.[17]

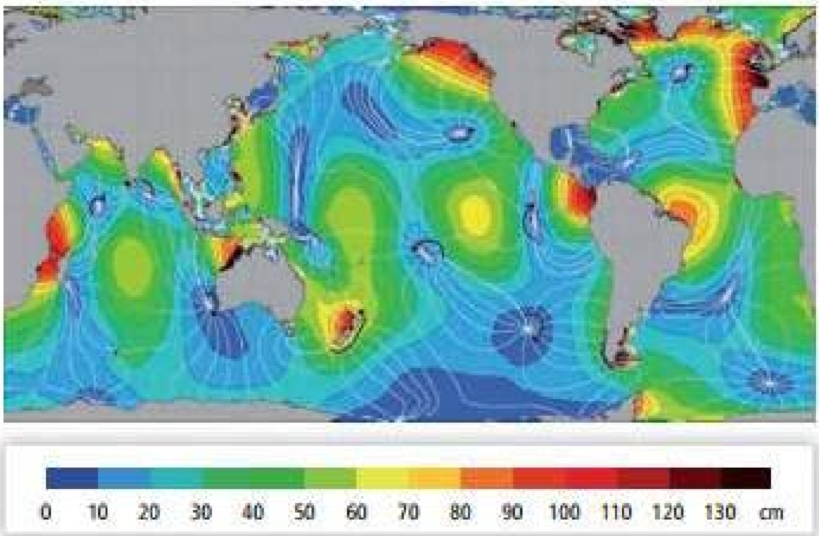


Figure 7: Map showing the M2 tidal amplitude globally, indicating areas with potential tidal range resource. Source: IPCC

2.3.3. Global tidal range projects

The first large-scale tidal range power plant was built in France in 1966, La Rance Tidal Power Station. There are now five operating tidal range power plants globally, detailed in Table 7, with a combined capacity of approximately 521 MW. There are two others under construction, totalling 1.7 GW, and numerous others planned, which could add a further 13.7 GW of tidal range capacity including:[1,21]

- Consent granted – 700 MW
- Consent application – 320 MW
- In planning – 10.7 GW
- Early planning – 2.8 GW
- Early concept - 29.3 GW

6.7 GW of the non-consented planned capacity is in the UK, using Tidal lagoon technology. The other main countries with activity are South Korea, who have 2 GW of planned projects and further development in Canada in the Bay of Fundy.[1]

[21] O'Rourke, F., Boyle, F., and Reynolds, A.: Tidal Energy Update 2009. Applied Energy. Volume 87, Issue 2, Pages 398-409. February 2010. doi:10.1016/j.apenergy.2009.08.014

Table 7: Table showing the operational and consented tidal range power plants globally. Source: various

Project	Location	Capacity	Status
La Rance Tidal Power Station	Brittany, France	240 MW	Operational since 1966
Kislaya Guba	Russia	1.7 MW (upgraded from 400 kW)	Operational since 1968
Annapolis Royale	Canada	20 MW	Operational since 1982
Sihwa tidal plant	South Korea	254 MW	Operational
Jiangxa tidal power plant	China	4.1 MW	Operational (upgrade)
Incheon Tidal Power Plant	South Korea	1.3 GW	Under construction
Saemangeum Reclamation Project	South Korea	0.4 GW	Under construction
Tidal Lagoon Swansea Bay	United Kingdom	320 MW	Consented

2.4. Ocean Currents

2.4.1. Technology

Ocean currents occur across the worlds oceans due to a combination of solar heating, salinity gradients, bathymetry, wind and the Earth's rotation. They tend to be slow moving, typically 1 - 2.5 m/s, but given the density and volume of water this is a huge potential energy resource.[22] To give an example, the Gulf stream moves at an average of 1.7 m/s, and transports four billion cubic feet of water per second.[23] Unlike tidal currents, ocean currents only move in one direction and are continuous, therefore although the water speed is slower, there is a constant movement, rather than a tidal periodicity.

There has been no commercial or demonstration of ocean current energy extraction to date, in part due to the resource being further offshore and therefore more expensive to obtain. However, the technologies that can be used to extract such energy will be based on those employed for the extraction of energy from tidal streams, such as those discussed in Table 5. Modifications will need to be made to accommodate slower flows, such as increasing the swept area of a horizontal axis turbine and changes to gear ratios. These projects are also likely to be in deeper waters and adequate moorings or foundations will be required for this.

2.4.2. Resource

The currents that exist in the ocean, shown in Figure 8, occur all around the globe and are a potentially huge marine energy resource. The Ocean Energy Council, based in the US, suggest there is worldwide potential of 450 GW.[24] The fastest currents ~2 m/s exist in the:[17]

- Agulhas/Mozambique Currents off South Africa
- Kuroshio Current off East Asia
- East Australian Current
- Gulf Stream off eastern North America

[22] Minesto, Feasibility of Ocean Current Power, Renewable Energy Caribbean, 2014
[23] National Oceanic and Atmospheric Association, How fast is the Gulf Stream?
[24] Ocean Energy Council, Ocean Current Energy, accessed February 2018

The Florida Current of the Gulf Stream has been studied and predictions of a technical potential of 25 GW, with a core region 15 – 30 km from the coast. The Swedish TEC developer Minesto has signed an MoU with Florida Atlantic University to investigate the feasibility of demonstration and commercial ocean current projects in the Florida Current.[17,22]

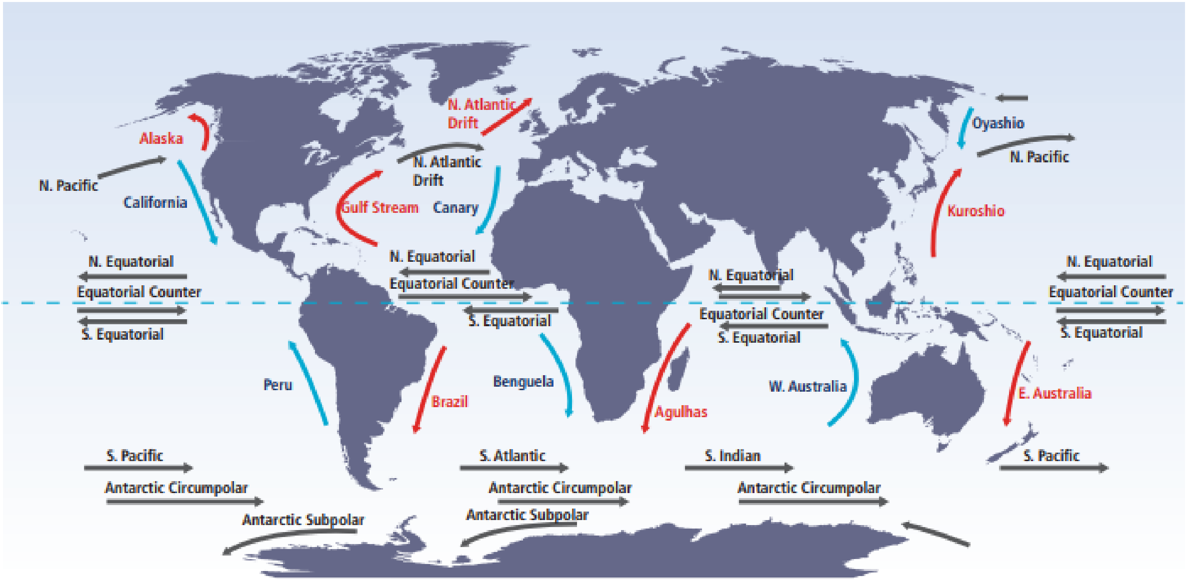


Figure 8: Map showing global surface ocean currents, warm are shown in red and cold in blue. Source: IPCC.

2.5. Ocean Thermal Energy Conversion

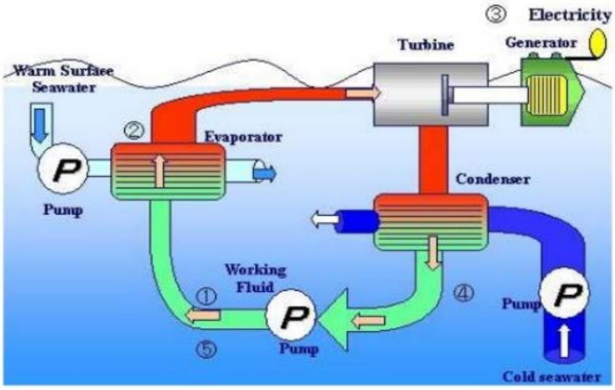
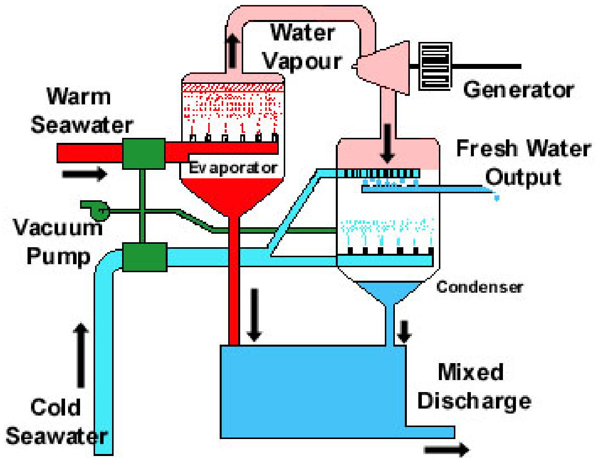
2.5.1. Technology

Ocean Thermal Energy Conversion (OTEC) is the use of the temperature gradient between warm equatorial surface waters and cold deep ocean water to generate electricity. OTEC also has options for use for cooling systems and water desalination. The technology used to achieve this was first built in the 1930s, although it wasn't until the 1970s that a net generation of electricity was achieved. There are three configurations for OTEC systems, closed cycle, open cycle and combined, as shown in Table 8.

The principle of OTEC is that warm surface water in the ocean is used to heat a fluid through a heat exchanger, to produce steam which turns a turbine which subsequently drives a generator to produce electricity. Cold water from the deep ocean, typically 1000 m below the surface, and at least 20°C cooler than the surface water is brought to the surface to re-condense the gas through another heat exchanger, and the process starts again. In a closed cycle system, the fluid used is ammonia, or another liquid with a low boiling point. In the open cycle system, it is the warm seawater that is flash vaporised in a vacuum chamber. The open-cycle system has the benefit of producing desalinated water as a by-product, which could be used by local communities. A hybrid cycle system begins the process like an open cycle system, but uses the steam generated from the sea water to vaporise the heat exchange fluid (e.g. ammonia), the cold deep sea water is then used to condense both the vaporised heat exchange fluid and the seawater.

OTEC installations can be offshore or onshore, offshore installations will be on a floating platform tethered to the seabed in excess of 1,000 m water depth. Onshore will require four large diameter pipelines two each for the warm water and cold water, to bring in and expel the water from the sea to the site.

Table 8: Diagrams of OTEC system configurations. Source: various

<table>
<tr><td>Closed Cycle OTEC system
Picture source: DForceSolar</td><td>
</td></tr>
<tr><td>Open Cycle OTEC system
Picture source: University of Alaska-Fairbanks</td><td>
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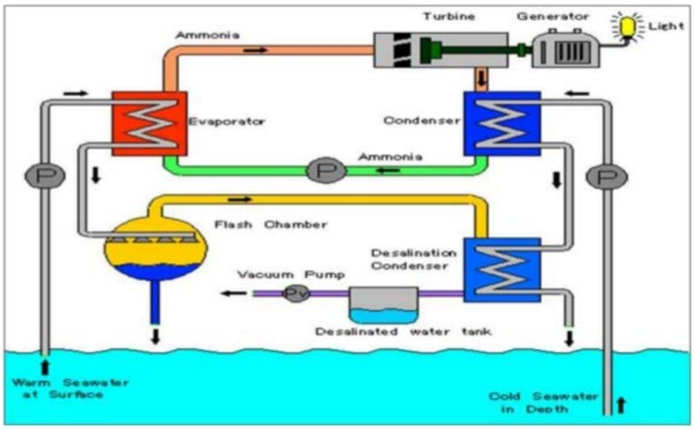
<tr><td>Combined or Hybrid Cycle OTEC system
Picture source: Zoombd24</td><td>
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Cost estimates are still vague due to the small number of deployments and the early stage of the technology, however, the Asian Development Bank, estimates a capital cost of $750 million (£640 m) for a 100 MW OTEC project.[25] The additional benefits including desalinated water and air conditioning are difficult to quantify at this stage, but should be included in any cost benefit analysis of technologies. The benefit of OTEC, as well as other MRE generators, is that they are often deployable in situations, such as small island communities, where the competing power source is imported diesel for generators, therefore the cost of energy does not necessarily have to compete with e.g. a western

[25] Asian Development Bank, Wave energy conversion and ocean thermal energy conversion potential in developing member countries, 2014

European grid price.

2.5.2. Resource

OTEC is a vast resource with the potential to contribute to baseload power, complementing more intermittent forms of renewable energy, as well as providing desalination, cooling and potentially aquaculture opportunities. OTEC however is a very low-density energy, although the efficiency of the system can be improved where the temperature gradient is maximised.

The OTEC zone is between 30°N and 30°S, covering approximately one-third of the ocean and can be seen in Figure 9.[6] There are a number of estimates of potential resource ranging from 30,000 to 90,000 TWh/yr, with estimates that 88,000 TWh/yr could be generated without causing an impact on the ocean's thermal structure.[17] Other estimates suggest 1 – 3 TW of theoretical potential, or as much as 7 TW when desalination is also included.[25,26] Greater understanding of the resource will come with further deployment of the technology. Although the 'OTEC zone' is limited to the equatorial regions, it does not limit countries outwith this area engaging in the supply chain, particularly where subsea experience and technology are not the strength of the area where the OTEC systems will be deployed.

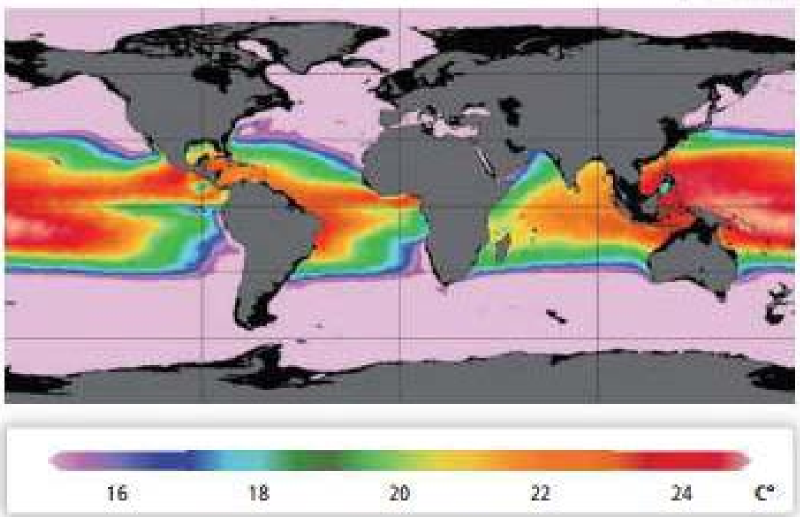

Figure 9: Worldwide temperature difference between 20 m and 1000 m water depth. Source IPCC

2.5.3. Global OTEC projects

There have been a handful of small demonstrations of OTEC since the first project in 1929, listed below in Table 9. In recent years there has been an increased interest in building demonstration projects, but these are yet to fully come to fruition.

Previous global OTEC installations[1]:

- Natural Energy Laboratory, Hawaii – 15kW closed cycle, mounted on a US Navy barge 1979
- A 32 kW project in Japan built in 1981
- First open cycle system ran from 1993 to 1998 it peaked at 103 kW and 0.4 l/s of desalinated water
- A hybrid prototype with a capacity of 30 kW was built by Saga University, Japan.

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[26] Gonçalves Neto, A., Hiron, L., Mendonça Pimenta, F. and Rodrigues Rodrigues, R., Northeast Brazil potential for land-based OTEC implementation, Ecological Vehicles and Renewable Energies (EVER), IEEE, 2014

Table 9: Current or proposed OTEC projects globally. Source: World Energy Council

Location	Capacity	Developer	Year / Status
Goseong, Korea	200 kW	Korea Research Institute of Ships and Ocean Engineering (KRISO)	2014
Natural Energy Laboratory Hawaii Authority (NELHA)	100 kW	Makai Ocean Engineering	2015
NELHA	100 MW		Proposed
Kume Island, Okinawa	100 kW		2013
Hawaii	10 MW	Lockheed Martin and US Naval Facility Command	Proposed
Martinique	Two projects totalling 15 MW	DCNS (one project)	Proposed
Philippines	10 MW		Proposed
Dutch Caribbean	100 kW		Proposed
Hainan Island, China	10 MW		Proposed
Pacific Ocean	1 MW	KRISO	Planned for 2020
Curacao	500 kW	Bluerise	Planned

2.6. Salinity Gradients

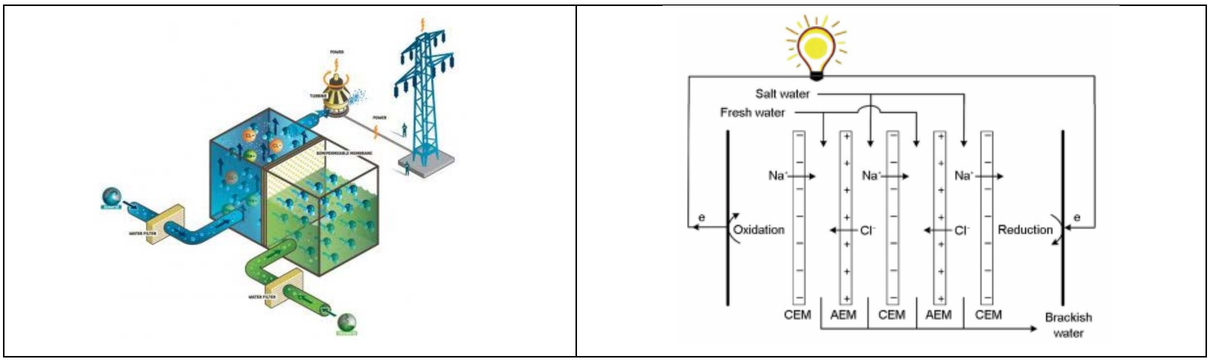
2.6.1. Technology

Salinity gradient, also known as osmotic power or blue energy, uses the potential energy created when freshwater from rivers meets the salt water of the oceans at river mouths and estuaries. There are currently two different methods being explored to generating electricity from the salinity gradient, described in Table 10. The general principle is that the osmotic pressure, either through the movement of water or the generation of electrical potential across a membrane as the two liquids naturally try to reach an equilibrium, is exploited to generate renewable energy.

Table 10: Methods for generating electricity from salinity gradients. Source: various

Pressure Retarded Osmosis (PRO)[27,28]	Reverse Electrodialysis (RED)[27]
PRO uses semi permeable membranes which only allow water molecules to pass through to separate the fresh and sea water. There is therefore movement from the dilute side (the fresh water) to the concentrated solution (the sea water) to form an equilibrium. The movement of the water, which depending on the difference in the salinities can be equivalent to 120 – 240 m of head for a hydroelectric turbine, can be used to drive turbines, and subsequently generate electricity.	RED uses ion-exchange membranes, which depending on the type (anionic or cationic) let either negatively or positively charged ions through, respectively. By allowing the ions to pass through the membranes an electrochemical potential is formed. By using alternating stacks of these membranes, a sufficient electrochemical charge can be accumulated to drive the generation of electricity. Electricity is generated by redox reactions at the electrodes.
PRO has been trialled by the Norwegians in a 4 kW plant. Due to difficulties with fouling of the membranes, development has been put on hold.	RED has been developed in a prototype by the Dutch research institute Wetsus, and a pilot project being run by spin-out REDSTACK, at the Afsluitdijk dike. It is aiming to reach a capacity of 50 kW.

[27] Salinity Gradient Energy: Current State and New Trends, *Engineering*, **1(2)** 2015: 164–166 DOI 10.15302/J-ENG-2015046
[28] Climate Tech Wiki, Ocean Energy: Salinity gradient for electricity generation, 2011



An early study by the International Renewable Energy Agency (IRENA), suggests that future costs for salinity gradient technologies could be in the region of $65-125/MW for PRO and $90/MW for RED by 2020 with levelized costs of energy in the region of $0.15-0.30/kWh for PRO and $0.11-0.20/kWh for RED. These cost estimates however, given the early stage of the sector, are not yet founded on experience and further development of the technologies will allow more accurate estimates to be made. The major factor on the capital cost for both technologies is the availability of large amounts of the required membranes.[29]

The subsea crossover with salinity gradient technology will largely be concerned with the pipework to bring the salt water to shore as well as materials, corrosion protection and monitoring for the equipment that is in regular contact with sea water, even based on land.

2.6.2. Resource

Salinity Gradient energy could provide a baseload type of power as the generation is continuous, and not dependent on e.g. the weather. There are various estimates for the theoretical resource available globally ranging from 647 GW (IRENA)[29] to 1183 GW (Alvarez-Silva et al.). There are slight seasonal variations in the sea's salinity and surface temperature which can also have an impact on the systems. The map in Figure 10 shows where the highest salinity is found in seawater globally. The extractable resource will be less once suitable locations, and any local or environmental concerns are factored in. The potential however, is significant, estimated to be approximately three per cent of global electricity demand.[30]

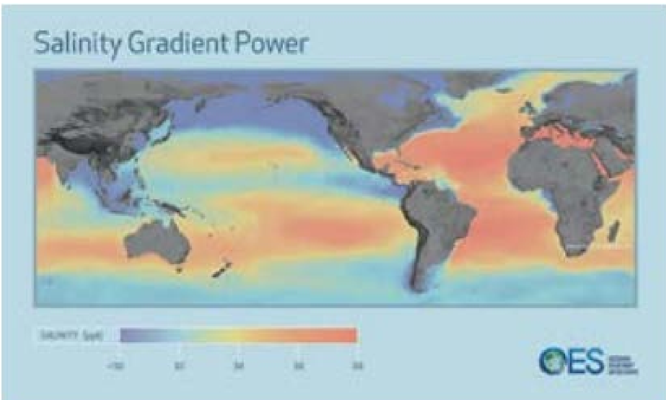


Figure 10: Map showing global sea water salinity. Source IRENA

[29] International Renewable Energy Agency, Salinity Gradient Energy, IRENA Ocean Energy Technology Brief 2, 2014

[30] Alvarez-Silva, O. A., Osorio, A. F. and Winter, C., Practical global salinity gradient energy potential, Renewable and Sustainable Energy Reviews 60 (2016) 1387–1395

3. Subsea Engineering Needs

Marine renewable energy is at an early stage in its development, unlike offshore wind where there has been consolidation in the market around a three-bladed horizontal axis turbine, the same is not true in terms of WECs and TECs. This is an innovation opportunity for the subsea oil and gas supply chain in order to work with technology companies at an early stage of development and embed themselves in the sector. It also means that for project developers there is an added stage in terms of choosing the technology, which will be highly site specific based on the characteristics of the resource and the local environment. At present, it is often the case that technology developers are also the project developers at this stage. In the longer term, this is less likely to be the case, but is currently a product of the stage in the development of the sector.

Below in Figure 11 is a generalised diagram, developed by the European Marine Energy Centre (EMEC) explaining the steps to developing an MRE power project. Within this flow diagram there are various entry point for the subsea oil and gas supply chain, including – but not limited to - health and safety, site screening, project development, outline design, environmental impact assessments (EIA), project fabrication, installation, operations and maintenance (O&M) and decommissioning.

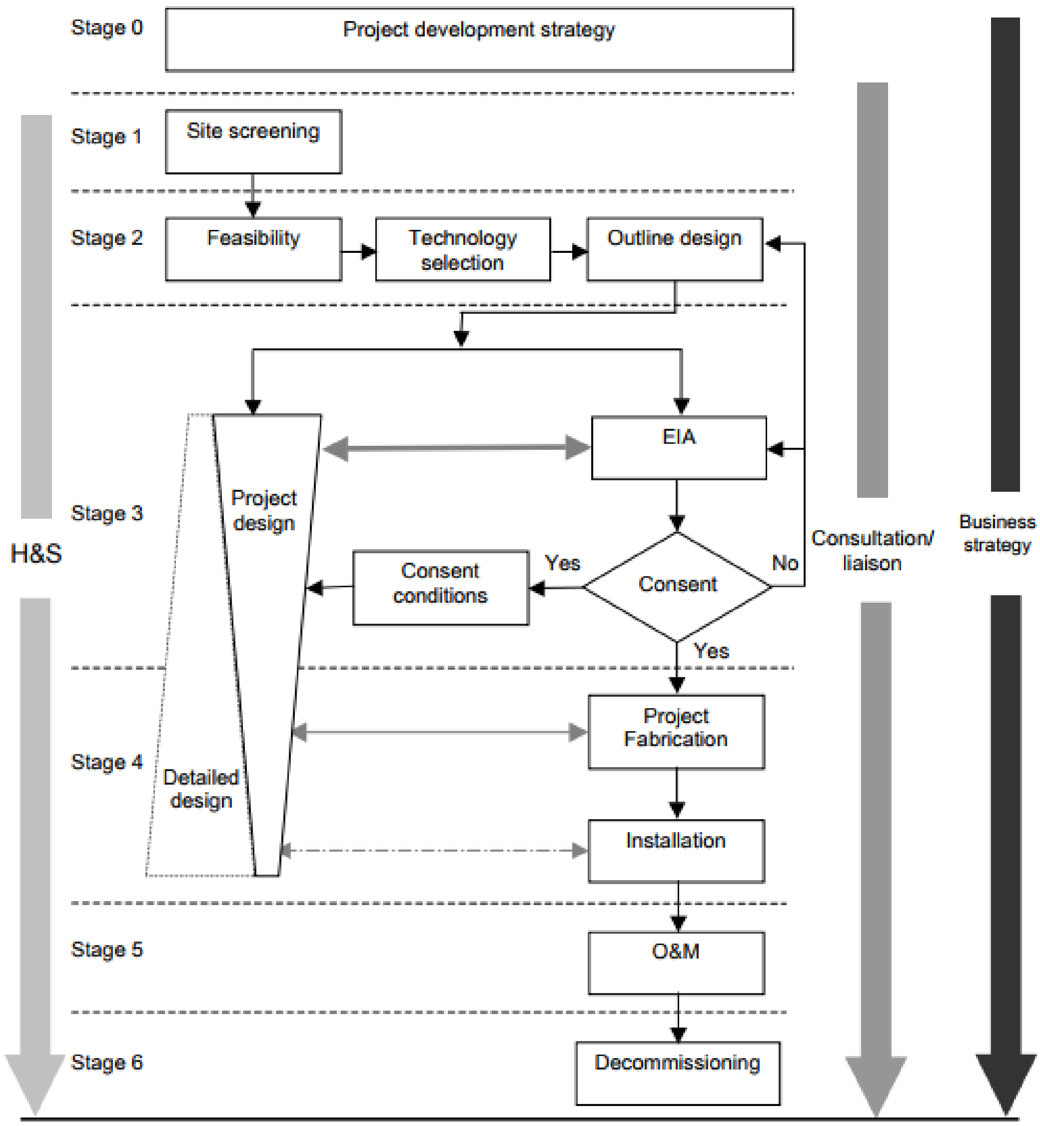


Figure 11: Flow chart of MRE project development. Source: EMEC

The sections below describe the project development stages in more detail, highlighting the particular areas where there are synergies with the subsea oil and gas sector[31].

3.1. Site selection and characterisation

Site selection occurs through large scale surveys of potential areas of resource, a consideration of other users of the area, availability of grid connections, and if relevant, leasing rounds of seabed areas or zones.

There is limited crossover with the O&G subsea sector at this point as this begins as a desk-based exercise, using available metocean data, national marine spatial plans (where available) or other national guidance on MRE development including Strategic Environmental Assessments (SEA). As more detailed site selection process develops there will be a requirement for meteorological, bathymetric, geotechnical and environmental surveys to be carried out. This will include onshore (at least shoreline) and offshore depending on the technology (e.g. shoreline applications such as OWC, salinity gradient or onshore OTEC) as well as suitable routes for onshore substations and grid export routes. Information will be obtained from, depending on the resource in question, e.g. buoys (for waves), ADCP (for tides), etc., satellite data and vessel surveys. There is requirement therefore, not just for the surveys themselves, but also the data analysis and modelling that will inform the decision making.

Seabed surveys, such as geophysical and geotechnical surveys will also be required as part of the final site selection. This is covered in section 3.3.

Many countries have a requirement for an EIA (or equivalent) to be carried out which will necessitate the collection of data on relevant species and habitats over a period of time. For MRE these can include fish, bird and marine mammal surveys, as well as benthic environment. The level of data and specific requirements will be determined by the response to the environmental statement (ES) or similar.

- Typical synergies at this stage include:
  - Analysis of metocean data
  - Environmental Impact Assessment (EIA)
  - Surveys: bathymetry, geotechnical, geophysical, etc.

3.2. Technology selection

As described in Section 2 there are a number of technologies available in each sector, and a decision about which technology or technologies must be made early in the process to be able to define the project. In some cases for consenting an ‘envelope’ approach can be used where the most extreme dimensions are used in order to obtain consent before final decisions are made, this is likely to be around, e.g. hub height or size of rotor for tidal turbines, etc.

At this stage understanding the resource enough to select an appropriate technology and undertaking due diligence on the preferred technology is required. The technology chosen should best match the resource and conditions available as well as any dual purposes, e.g. OWC wave technology as part of an active breakwater; open cycle vs closed cycle for OTEC to obtain freshwater for use, etc.

[31] Subsea UK, Subsea Technology and Engineering, 2014

3.3. Surveys and consenting

Further surveys will be required as part of the detailed design and consenting process. This will include more detailed resource assessments e.g. the use of wave buoys, ADCPs, temperature and/or salinity profiles, etc. The collection of geophysical, geotechnical and bathymetric data to understand the sea floor conditions and profile in terms of choosing and securing foundations and moorings.

There is also a requirement for environmental surveys which will be defined as part of the EIA, including fish, bird and marine mammal surveys and water quality including salinity, temperature, etc.

- Typical synergies at this stage include:
  - Analysis of data
  - Survey vessels and equipment
  - Surveys: bathymetry, geotechnical, geophysical, etc.

3.4. Project design and management

Project design starts at the earliest stage of the project and includes the management of health and safety; personnel; and decision-making strategies. Experience from the subsea oil and gas supply chain in terms of management of offshore projects can be put to use here. Synergies include:

- Project management; health and safety e.g. risk assessments and training; human resources
- Front End Engineering Design (FEED)
- Project Execution Plan
- Detailed design including: micro-siting of piles, anchors, cables.

3.5. Construction and commissioning

Construction techniques will be highly technology dependent with, for example, TECs being fabricated on shore and then deployed, but technology such as OWC or tidal barrages requiring to be built in-situ. Crossover therefore comes from the design of the offshore structures e.g. foundations for tidal turbines, moorings for floating OTECs; the materials that are used in an offshore environment e.g. Fibreglass reinforced plastic (FRP) for OTEC pipework; and offshore construction techniques, such as concrete structures.

- Construction and commissioning synergies therefore include, but are not necessarily limited to:
  - Seabed mounted structures – design and manufacture of foundations e.g. gravity bases, suction buckets.
  - Floating structures – mooring chains, cables and ropes; anchors and tethers; mid water arches.
  - Cables – export and inter-array cables; seafloor and floating cables; riser management; seabed preparation; and cable protection.
  - Vessel – MRE suitable vessels and station keeping in high tidal flows
  - Materials – steel; concrete; FRP; high density plastics
  - Pipelines – large diameter, low pressure pipes

3.6. Installation

Installation techniques and requirements will be technology dependent, but the general categories include:

- Floating devices: such as wave attenuators, floating tidal turbines, floating OTEC, ocean current turbines
- Seabed mounted devices e.g. seabed mounted TECs and WECs
- Coastal mounted devices e.g. OWC, barrages

Crossover with the subsea oil and gas industry is high with infrastructure, e.g. jack up barges, cranes, and remotely operated vehicles (ROVs) as well as the benefit of experience from installing offshore. As the MRE industry is still in its early stages there has not been much if any standardisation of procedures for installation but this is something that could help reduce cost within the industry. There is a drive with the MRE sector to minimise the use of large vessels, as part of cost reduction and therefore making modular or towable devices that are lighter and smaller to manoeuvre.

Even with smaller vessels port and harbour logistics as well as vessel management are a further area of crossover.

Seabed preparation will be required for cables as well as devices, with boulder removal and trenching being a direct synergy.

Use of ROVs for the installation, both work class and inspection will be required, for e.g. providing visuals underwater without the use of divers during an installation; tooling for the installation; and connecting cables to devices.

Lastly, some technologies, such as those that pump water to shore, or for cable export routes, may require directional drilling.

3.7. Operations, monitoring and maintenance

During the O&M phase, there is a requirement for ongoing planned maintenance as well as unscheduled maintenance. Some technologies, such as those that float, may be returned to shore for both types of maintenance, whereas bottom fixed and shoreline will be done in situ. In these circumstances, there will be a requirement for the use of ROVs, autonomous underwater vehicles (AUVs) or divers, and their tooling. Inspection, repair and maintenance (IRM) is a significant section of the subsea supply chain and there is direct crossover to MRE from O&G for this. This includes the use of sensors to monitor for e.g. corrosion and fatigue within MRE systems, as well as inspections by ROVs and AUVs with video and lights. Coupled to the collection of data on IRM is the management and processing of this data, including the use of data analysis to predict issues to be able to carry out preventative maintenance.

There is also a requirement to continually collect metocean data, to understand how the systems are working, and potentially a requirement for continued environmental monitoring depending on consent conditions, including sound. Metocean data analysis could also be linked to developing maintenance schedules inline with favourable metocean conditions.[32]

3.8. Decommissioning or repowering

At the end of the lifetime of a project, this is often 25 years, depending on the consenting conditions and length of the seabed lease, a project is required to be decommissioned. There may be options for repowering, i.e. replacing a turbine with a newer (potentially more efficient or greater capacity) turbine. A decision to repower will be done on a project by project basis, and would require surveys

[32] SI Ocean, Market Deployment Strategy, 2014

to ensure the integrity of any foundation or mooring, etc. as well as appropriate leases or consents.

If a project is to be decommissioned, a decommissioning plan must be in place. The process will require project management with offshore experiences, the use of ROVs, AUVs, and possible divers, vessels and seabed clearance including anchors, foundations and cables in line with local regulations and the agreed decommissioning plan.

4. Global Markets

The marine renewable energy industry is forecast to be worth up to £76 billion globally by 2050, with many synergies with the subsea oil and gas industry as previously discussed. This presents an interesting opportunity for diversification of the Scottish supply chain. Estimates are that £450 million has been spent in the UK alone, and €1 billion in Europe already in this industry. In the coming five years a further €1 billion of research and development spending is anticipated along with €3-4 billion of expenditure on technology deployment.[33,34]

The following sections, coupled with the information in Table 1, outline the global activity and ambition for MRE. Tidal range, tidal stream and wave energy are the most developed elements of this sector and therefore have the most information available. OTEC, salinity gradient and ocean currents are less well understood, where there is known resource this has been highlighted, but there it is likely, particularly for the latter trio of technologies that there is further resource available globally, that will be understood over time.

4.1. Europe, Middle East and Africa

Europe is the home of MRE with almost half of all wave and tidal companies based within the EU, as well as the majority of technology deployment.[8] It is predicted that 10% of Europe's electricity requirements could be met from MRE sources by 2050.[34]

DENMARK's resource area for MRE includes the Faroe Islands and Greenland, the main resource available is wave energy, with an estimated 3.4 GW or 30 TWh/yr.[35] Denmark has strong renewable energy ambitions and is a key player in the global wind industry. Support is available for MRE, but is largely in line with wind support, and therefore not necessarily high enough to stimulate the industry. Support is also available through two Danish test centres, managed by the Danish Wave Energy Centre (DanWEC), as well as an active network the *Danish Partnership on Wave Energy* which promotes the development of the wave energy sector through industrial partnerships. The Danish Partnership on Wave Energy states that the vision is to see 1500 GWh/yr generated from wave energy at a price DKK 0.10/kWh lower than offshore wind.[36]

FRANCE's Atlantic coastline, as well as the coastlines and locations of many of it's offshore territories (2nd largest global Exclusive Economic Zone (EEZ)), provides a sizeable wave energy opportunity. Wave resource in France ranges from 10-15 GW, or 40 TWh/yr. Tidal resources are in the region 3-5 GW or 5-14 TWh/yr and are centred around five areas along the Atlantic coast, Raz Blanchard, Raz de Barfleur, Passage du Fromveur, Chaussée de Sein and Héaux de Bréhat.[35,37,38]

France's *Plan de programmation pluriannuelle de l'Energie*, published in 2016, states a range of MRE (which in this case includes floating offshore wind) of between 100 MW and 2,000 MW by 2023.[39] It is worth noting however, that MRE activity in France appears to be currently mostly focused on tidal

[33] Lammey, M., Marine power windfall of £76bn up for grabs for supply chain, ONE says, Energy Voice, 2017
[34] Ocean Energy Forum, Ocean Energy Strategic Roadmap 2016, building ocean energy for Europe, 2016.
[35] Aquatera and Caelulum, International Emerging and Niche Market Research for the Marine Energy Sector, Volume 2, Country Profiles, 2016
[36] Danish Partnership on Wave Energy, Vision, Website, accessed March 2018.
[37] Gunn, K. and Stock-Williams, C., Quantifying the global wave power resource, *Renewable Energy,* **44** (2012) 296-304
[38] Cliquet, V., Wave and tidal energies in France, Innosea, All-Energy 2016, 2016.
[39] Renewables Now, France locks renewables target for 70 -76 GW by 2023, 2016

energy technology.

MRE has financial support in France, with a 20-year electricity tariff valued at €150/MWh as well as the potential for government grants in government tenders.[35] There is also France Energies Marines (FEM) which was established in 2012 in order to manage five MRE test sites. FEM is a public-private partnership and started with a 10-year operational budget of €130m.[40] France also has an active marine research institute, Ifremer, *Institut français de recherche pour l'exploitation de la mer*, which has an interest in MRE.

Energy policy decision making is with the regions in France, there is an interest in a number of regions to have their own homegrown energy, rather than relying on other regions. The north and western coastal regions: Brittany, Normandy, Aquitaine, Pays de la Loire, etc. are all active in promoting the regional strengths and opportunities in MRE. Opportunities being considered in La Reunion for wave energy

IRELAND has a developed interest in wave energy, with it's Atlantic facing western coast and an EEZ five times that of it's land mass. Gunn and Stock-Williams estimate a resource of 29 GW[37], The Sustainable Energy Authority of Ireland (SEAI) estimate the theoretical resource as 525 TWh, or 21TWh within 100km of the shoreline.[35]

There are strong ambitions for developing MRE in Ireland with Ireland's National Renewable Energy Action Plan (NREAP) 2007-2020, setting out plans for 500 MW of MRE by 2020.[41] The Offshore Renewable Energy Development Plan (OREDP), a framework for Ireland's development of its offshore energy resources, published in 2014, acknowledges that the 2020 targets will not be met due to the current status of the technology. OREDP however, does say that the ambition continues and the 2020 and they are valid to 2030 and beyond. The figures considered are 500 MW of wave energy and 200 MW of tidal stream, combined they could provide Ireland with a net present value (NPV) of €5.5-€12.75 billion (£4.8-£11.1 billion) by 2030.[42]

A further action of OREDP is the introduction of the 'Initial Market Support Tariff for Ocean Energy', which is anticipated to be worth €260/MWh (£227/MWh), and will be limited to the first 30 MW of deployed wave and tidal stream energy thereby focussing it on pre-commercial projects. This is on top of €26.3 million (£22.9 m) of support for research, development and demonstration, including support to the Irish test sites, porotype development fund and Integrated Maritime Energy Resource Cluster (IMERC) research centre.[42]

The NETHERLANDS are active in marine renewables with resource mainly centred around tidal stream, 50 – 100 MW and tidal range 60 – 100 MW, they also have a salinity gradient demonstrator by REDStack and OTEC demonstrators in their island territories. There is no specific MRE support, although renewables are supported in terms of a national target of 16% renewables by 2023 and the Demonstration of Energy Innovation support.[43] The Netherlands have an additional driver for the promotion of tidal energy as many of the delta inlets that were protected by storm surge barriers, now are required to be opened, in part, to the sea, to manage water quality. The opening of these barriers allows the adoption of tidal energies as well as re-oxygenating the inlets that have been

[40] France Energies Marine, Who We Are, website accessed December 2017

[41] Department of Communications, Climate Change and Environment, National Renewable Energy Action Plan, 2010.

[42] Department of Communications, Energy and Natural Resources, Offshore Renewable Energy Development Plan, 2014.

[43] Ocean Energy Systems, Country Profiles 2016, the Netherlands.

closed off since the Delta Works of the 1970s.[44]

PORTUGAL whose coastlines include the Azores and Madeira, has an estimated 15 GW potential wave resource and has been active in wave energy for a significant time including hosting the world's first wave farm consisting of three Pelamis WECs.[35,37]

Although Portugal is, in theory, supportive of wave power and has a significant resource, austerity measures put in place in 2012 meant that no new consenting of renewable energy projects would occur, coupled with the removal of wave energy from the Feed-in Tariff (FiT) scheme. In 2016 the inter ministerial commission for maritime affairs' working group presented the report *Energy at Sea - Roadmap to an Industrial Strategy for Oceanic Renewable Energies*, which has a series of recommendations for attracting investment in MRE into Portugal.[45]

Funding for MRE in Portugal is through the Foundation for Science and Technology (FCT) and there is an active association (industrial and public), the Wave Energy Centre (WavEC); as well as test centres including pico plant, an OWC which can be used for testing in the Azores; as well as zones for the demonstration of technology, including both Aguçadoura and Ocean Plug Pilot Zone (320 km^2).
SPAIN's vast wave energy resource of 20 GW, also includes the Canary Islands.[37] In mainland Spain, the most significant potential is along the Atlantic coastline namely off Galicia and Cantabria. The resource is also highlighted, along with the support for MRE in the 2011-2020 Renewable Energy National Plan. The plan includes an ambition for 100 MW of wave power by 2020, assuming 10 MW by 2016. Although the 2020 target is unlikely to be achieved there is still activity ongoing. Installed projects include the Mutriku OWC plant, as well as the Biscay Marine Energy Platform (BiMEP) and PLOCAN's offshore test facility in Gran Canaria.[46]

Spain does not have a coordinated policy for the consenting of MRE (although there is now a standardised requirement for an EIA), or specific support. However, regional governments have the ability to set regional targets. In 2016 the Basque Government published its Energy Strategy to 2030 which includes 60 MW of wave power by 2030. The region is very supportive of MRE including the active Basque Energy Agency (EVE).[46]

The **UNITED KINGDOM** is at the forefront of the global MRE industry as well as boasting a significant wave (43 GW)[37], tidal stream (32 GW)[47] and tidal range (25-30 GW)[48] resource. The UK is also home to test centres including the world renowned European Marine Energy Centre (EMEC) in Scotland, WaveHub in Cornwall and two demonstrator sites in Wales. In 2017 Scotland accounted for 90 percent of installed MRE capacity globally.[49]

Revenue support for MRE started in Scotland with a Marine Supply Obligation, and was then superseded by the introduction of the banded renewable energy obligation in 2009 which made available the equivalent of three renewable obligation certificates (ROCs) for tidal and five ROCs for wave, where one ROC was approximately £40/MWh. Following the implementation of the Electricity Market Reform programme and the introduction of Contracts for Difference (CfD), MRE was supported by a £300/MWh for tidal and £310/MWh for wave. However, although a significant support level, MRE projects were in direct competition for a pot of money with projects including

[44] BT Projects, Brouwersdam Tidal Quintet, accessed March 2018.
[45] Ocean Energy Systems, Country Profile 2016, Portugal
[46] Ocean Energy Systems, Country Profiles 2016, Spain
[47] The Crown Estate, 2012
[48] Department for Business, Energy & Industrial Strategy, Wave and tidal energy: part of the UK's energy mix, 2013
[49] ReNews, Challenges emerge to Scotland's crown, Global Marine Special Report 2017

offshore wind. There is no longer any ring fenced MRE support in the UK.[50]

Offshore planning in the UK varies across the countries with consenting done by the Marine Management Organisation in England and Northern Ireland, Natural Resources Wales and Marine Scotland. Leases for the seabed are issued from the Crown Estate (or the Crown Estate Scotland) and are most often done through competitive leasing rounds.

GHANA is leading the push for MRE in West Africa, with a recently installed six-device 400kW array, of Swedish company Seabased's WEC. There plans to install a second, 14 MW, phase of the project[1] and a contract was signed in March 2018 for a 100 MW contract.[51]

4.2. Americas

Over half of the population of the **USA** lives within 50 miles of coast, coupled with significant offshore renewable energy resource, MRE is a big opportunity to be harnessed. The USA's technical resource for MRE (or Marine and Hydrokinetic (MHK) as it is known in the USA) was estimated as 1,250 to 1,850 TWh/yr and 223 GW (roughly 1,950 TWh/yr) by Gunn and Stock-Williams.[37,52]

The USA has a draft national strategy for MRE, released in late 2016 by the Water Power Technologies Office[53], which includes a vision "*A U.S. Marine and Hydrokinetic industry that expands and diversifies the nation's renewable energy portfolio by responsibly delivering energy from ocean and river resources*" and a mission to "*Support the development of safe, reliable, and cost-competitive MHK technologies and reduce deployment barriers*". The draft strategy's specific goals are to:

- *Reduce the levelized cost of energy (LCOE) by 80% compared to the 2015 baseline LCOE values for wave (0.84 $/kW-h) and current (0.58 $/kW) technologies by 2030*
- *Enable the industry to rapidly increase MHK technology deployments by supporting research and stakeholder outreach activities to reduce deployment barriers and to accelerate project permitting processes*

The Department of Energy (DoE) is supporting the development of MRE with US$59 million budget for MRE, of which $30 million is for the Pacific Marine Energy Center South Energy Test Site (PMEC- SETS) off Oregon, which was recently permitted. There is also $4m for the support of collaborations between universities, national laboratories and marine renewable energy centres and a continuation of the coordination with the US Navy on MRE technology demonstration.[54]

The wave resource in **CANADA** is predominately on the west coast where the coastline is exposed to the large fetch of the Pacific Ocean. Opportunities for wave energy conversion can also be found in the provinces of Nova Scotia and Newfoundland. The technically viable wave resource is estimated by Marine Renewables Canada to be 27.5 GW and a tidal stream resource of 6.3 GW.[55] Canada's significant tidal resource is found at the Bay of Fundy (between the provinces of New Brunswick and

[50] RegenSW, Contracts for Difference Announcements, 2016.
[51] Seabased and TC Energy Joint Press Release, Seabased signs 100 MW Wave Power Plant Contract with Ghana, 2018
[52] Ocean Energy Systems, Country Profiles: United States of America, 2016.
[53] US Department of Energy, WPTO Releases Updated Draft MHK Strategy, 2016
[54] MarineEnergy.biz, US could allot almost $60M for MHK research, 2017
[55] Marine Renewables Canada, Charting the Course Canada's Marine Renewable Energy Technology Roadmap, 2011

Nova Scotia) as well as the provinces of British Columbia and Quebec.

In 2011 the MRE association Marine Renewables Canada published their 'Marine Renewable Energy Technology Roadmap'. The roadmap includes a vision to generate 2,000 MW by 2030 which would bring with it CAN$2 bn (£1.15bn) in annual economic value. Although behind on their initial step of 75 MW by 2016, there is still ambition within the country to pursue a significant MRE industry. The vision also lays out ambitions to be a global leader in MRE by providing technical solutions and services to 50 per cent of global projects by 2030. Although there is obviously a strong push for export as well as the homegrown industry they also comment on a willingness to collaborate. Scotland's first mover advantage in the MRE industry and global subsea reputation may provide a collaboration incentive for the Canadian MRE sector. In addition to national targets Nova Scotia Province has outlined its MRE ambition with 10MW demonstration project launching in 2018, and an ambition of 50 MW of tidal capacity to be installed in the next five years.[56]

The Bay of Fundy is home to the Fundy Ocean Research Centre for Energy (FORCE) grid connected tidal demonstration centre. Projects at FORCE include:

- Cape Sharp Tidal, a 4 MW grid connected two-turbine tidal array using the OpenHydro 2 MW open centre turbine. The first turbine was installed and commissioned in 2016

More than CAN$30m (£17.2m) has been invested by FORCE in onshore and offshore electrical infrastructure to allow demonstration turbines to connect to the power grid. The FORCE supply chain consists of approximately 125 companies and organisations. It has berths that are sized for grid connected demonstrations up to 5 MW.

Five developers have received approval to receive subsidies under the Development Tidal FIT programme. The projects total a capacity of 22 MW and include:

- Minas Energy, 4.0 MW
- Black Rock Tidal Power, 5.0 MW
- Atlantis Operations Canada, 4.5 MW
- Cape Sharp Tidal Venture, 4.0 MW
- DP Marine Energy, 4.5 MW

The FIT is administered by the Utility and Review Board, who have set rates for tidal stream demonstration projects:

- The Developmental rate is for 15 years and is CAN$530(£304)/MWh for ≤16,640 MWh/yr or CAN$420(£241)/MWh for >16,640 MWh/yr
- The testing rate has two paths
  - Path I - for 3 years: CAN$575(£330)/MWh for projects ≤3,300 MWh or CAN$455(£261)/MWh for projects >3,300 MWh
  - Path II – for 15 years (following Path I): CAN$495(£284)/MWh for projects ≤16,640 MWh or CAN$385(£221)/MWh for projects >16,640 MWh

In South America, CHILE has a significant wave and tidal resource along it's 4,000 km coastline, with an estimated wave resource of 164 – 240 GW and a tidal resource of 3 GW. Approximately two-thirds of the tidal stream resource is located in the Magellan Strait, with other significant resource in the Chacao Channel.[57,58]

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[56] ReNews, Nova Scotia demo tender a taste of things to come, Global Marine Special Report 2017
[57] IMMR
[58] Norton Rose Fulbright, Renewable energy in Latin America, 2017

In 2016 the Chilean Marine Energy Research and Innovation Center (MERIC) was opened as a focal point for MRE research in Chile as well as, from 2019, the demonstration of MRE technology.[59] Chile already has a relationship with Scotland, including a visit from their Energy Minister to EMEC in 2011, and Scottish consultancy Aquatera drafting the Recommendations for Chile´s Marine Energy Strategy – a roadmap for development in 2014.[60,61]

ARGENTINA, **BRAZIL** and **PERU** all also have an interest in developing MRE projects.

4.3. Asia and Pacific

From the 2012 resource study by Gunn and Stock-Williams, **AUSTRALIA** has the largest wave resource globally at 280 GW.[37] It also has a tidal stream resource, which is currently being assessed by a AUS$6 million project led by the Australian Maritime College at the University of Tasmania.[62] In addition there are also opportunities for ocean current technology in the East Australia Current which flows at speeds greater than 2 m/s; OTEC in the North Eastern tropical waters; and salinity gradient in the northern regions. However, as earlier stage technologies specific resource calculations have not been conducted.[63]

Australia has also hosted demonstration projects, notably the 240 kW three-WEC array of CETO 5 off Garden Island, with the developer Carnegie Wave Energy planning further demonstrations including a 1.5 MW CETO 6 device to be deployed in Albany in 2020.[1,64]

CHINA has MRE resources across wave, tidal range and stream, OTEC and salinity gradient totalling 64 GW. The largest resources available in China are 25.7 GW of OTEC and 22.3 GW of tidal range, across an estimated 242 locations and 1.66 – 3.5 GW of tidal current. There is an appetite for MRE in China, even for the sectors with more limited resources such as wave, where in excess of 1500 patents have been filed in respect of WECs. China also has two planned test centres for MRE the 'National Wave Energy Test Station' (NWETS) which will be built off the coast of Zhuhai, Guangdong province and the Northern National Ocean Energy Test Station (NNOETS) off the coast of Weihai. China's National Development and Reform Commission's (NDRC's) *Medium and Long-Term Development Plan for Renewable Energy in China* has a target for 100 MW of tidal capacity by 2020, with a proposed 10 MW demonstration plant being commissioned.[35,65,66]

INDONESIA has significant marine resources, and a National Energy Policy target of 3.1 GW by 2025. The archipelago has a theoretical tidal resource of 18 GW largely (approx. 70 percent of the resource) in the Riau islands and the Alas Strait. Resource studies for MRE are ongoing, so this figure may increase over time. Indonesia also possesses OTEC resource, estimated at 43 GW, and some wave

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[59] MarineEnergy.biz, Chile inaugurates marine energy R&D centre MERIC, 2016
[60] HIEnergy, Chilean Energy Minister visits Highlands and Islands, 2011
[61] Aquatera, Recommendations for Chile´s Marine Energy Strategy – a roadmap for development, 2014
[62] Australian Tidal Energy, Tidal Energy in Australia, accessed March 2018
[63] Manasseh, R., McInnes, K. L. and Hemer, M. A., Pioneering developments of marine renewable energy in Australia, *Journal of Ocean and Climate: Science, Technology and Impacts* (**8**) 2017
[64] ReNews, Western Australia grant changes wave direction, Global Marine Special Report, 2017.
[65] Shujie Wang, Peng Yuan, Dong Li and Yuhe Jiao, An overview of ocean renewable energy in China, *Renewable and Sustainable Energy Reviews*, **15**, 2011 pp91-111
[66] Ni Chenhua, Development of Ocean Energy Test Field in China, National Ocean Technology Center, Tianjin, China

resource, with estimates of a practical potential of 1.2 GW.[35,67,68]

Indonesia is also home to the South East Asian Marine Energy Centre (SEAMEC) which is a focal point for MRE research and activity in Indonesia.[69] There is already activity from UK MRE companies working in Indonesia on tidal projects, Atlantis with a 150 MW tidal project and DCNS who have signed a contract to explore tidal opportunities, both working with local companies.[70]

JAPAN has a large MRE resource from the waves, tides, ocean currents and OTEC, coupled with a drive to exploit these resources, including a 1.5 GW of MRE target for 2030. For ocean current the extractable energy is not quoted, but the Kuroshio Current that runs along the East and Southern coasts of Japan has a flow rate of 1 - 1.5 m/s.[71] Japanese wave resource is estimated at 31-36 GW.[35]

Japan's work in MRE included the New Energy and Industrial Technology Development Organization (NEDO) is inviting companies to engage in long term research and development on MRE.[72] As well as a tidal test side at the Goto Islands, Nagasaki. There is already a relationship between Scotland and Japan through O&G development with the Nippon Foundation, but also for example through MRE technology with a Japanese delegation visiting EMEC in 2015.[73]

The **PHILIPPINES** has a vast MRE resource, with estimates of 40-60 GW of technically feasible tidal resource, alongside wave resources and 265 MW of OTEC, MRE resources total 170 GW.[35] The global MRE industry has been attracted to the Philippines in particular due to announcements about a specific MRE feed in tariff (FiT).[74] However, the latest FiT order does not include ocean energy, this may still change in the future though. [75] The Philippines has a target of 100 per cent renewable electricity by 2030, and already has 12 GW installed, MRE is anticipated to have a capacity of 71 MW by 2030. MRE is listed in the Philippine Council for Industry, Energy and Emerging Technology Research and Development (PCIEERD) Energy roadmap, with specific actions on resource assessment and technology demonstration.[76]

TAIWAN has modest wave resource, with the Industrial Technology Research Institute (ITRI) estimating a potential resource greater than 2 GW in sites of 20-50 m water depth.[77] The biggest MRE resource in Taiwan is the access to the Kuroshio Current that runs along the east side of Taiwan.[35,78]

Activities in Taiwanese waters include the CSBC Corporation collaboration with the ITRI to designed

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[67] IRENA, Renewable Energy Prospects: Indonesia, 2017

[68] Sugianto, D., N., Kunarso, Helmi, M., Alifdini, I., Maslukah, L., Saputro, S., Yusuf, M. and Endrawati, H., Wave energy reviews in Indonesia, International Journal of Mechanical Engineering and Technology, (10) 2017 448-459

[69] Davies, G., SEAMEC, A gateway to the Indonesian MRE Market, All-Energy Presentation, 2016.

[70] Hydro World, Two UK companies will develop marine energy in Indonesia, 2017

[71] Shirasawa, K., et al, Development of an ocean-current turbine for the Kuroshio current, 6th International Symposium on Energy Challenges & Mechanics, 2016.

[72] MarineEnergy.biz, Japan plans ocean energy R&D demo project, 2018

[73] MarineEnergy.biz, EMEC assists in progressing Japan's marine energy, 2015

[74] MarineEnergy.biz, Philippines' ocean energy sector draws overseas attention, 2016

[75] Republic of the Philippines, Energy Regulatory Commission, Approval of Feed-in Tariff for calendar year 2017, 2017

[76] PCIEERD, Energy road map, accessed March 2018.

[77] Industrial Technology Research Institute, Wave Energy Conversion System Technology, accessed December 2017

[78] National Energy Program Phase II, Offshore wind power and marine energy focus centre, accessed December 2017.

and build the first Taiwanese 20 kW WEC. The point absorber WEC underwent sea trials in 2013.[79] Aquanet are trialling a 1 MW single unit WEC of their aquaWAVE OWC technology in Taiwanese waters. A successful demonstration is intended to be followed up by a small array in the next two years.[80] Taipei will host the Asian Wave and Tidal Energy Conference in 2018.[81]

[79] CSBC Corporation Taiwan, Wave Power http://www.csbcnet.com.tw/English/ServiceEng/EnergyZoneEng/WaveEnergyEng.htm, accessed January 2018
[80] Aquanet Power, Unique Full Scale PTO System Bi-Direction Wind Tunnel Test Facility, accessed January 2018
[81] 4th Asian Wave and Tidal Energy Conference, https://www.awtec2018.com/

Appendix: List of Acronyms

ADCP	Acoustic Doppler Current Profiler
AUV	Autonomous Underwater Vehicle
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EMEC	European Marine Energy Centre
EVE	Ente Vasco de la Energia / Basque Energy Agency (Spain)
FiT	Feed-in Tariff
FRP	Fibreglass Reinforced Plastic
GW	Gigawatt
IEA-OES / OES	International Energy Agency – Ocean Energy Systems Technology Collaboration Programme
IRENA	International Renewable Energy Agency
IRM	Inspection, Repair and Maintenance
ITRI	Industrial Technology Research Institute (Taiwan)
KRISO	Korea Research Institute of Ships and Ocean Engineering
kW	kilowatt
kWh	kilowatt hours
l/s	Litres per second
m/s	Metres per second
MHK	Marine and Hydrokinetic (US terminology for MRE)
MRE	Marine Renewable Energy
MW	Megawatt
NELHA	Natural Energy Laboratory Hawaii Authority
O&M	Operations and Maintenance
OREDP	Offshore Renewable Energy Development Plan (Ireland)
OTEC	Ocean Thermal Energy Conversion
OWC	Oscillating Water Column
PRO	Pressure Retarded Osmosis
RED	Reversed Electrodialysis
ROV	Remotely Operated Vehicle
TEC	Tidal Energy Converter (Tidal stream)
TRL	Technology Readiness Level
TW	Terrawatt
WEC	Wave Energy Converter