World Energy Resources

Marine Energy | 2016

TABLE OF CONTENTS

Europe to contribute 5.6 million euros to Met-Certified marine energy project

World's largest tidal energy farm launches in Scotland

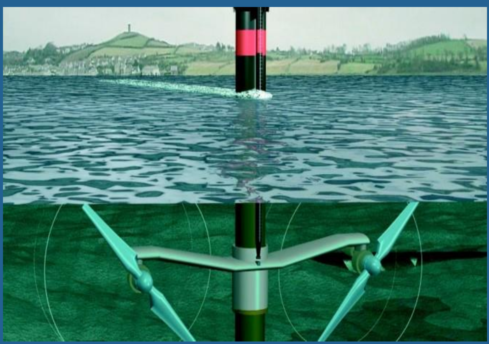
Tidal energy poised to turn commercial

China plans marine energy centre

New certification scheme helps 'de-risk' marine renewable energy technologies

Marine

Prime Ministers' support leads to joint UK & Canada marine energy project



Tidal power plan drifts into 2018 as Government support wavers

US invests $40m in wave centre

World's largest tidal turbine to be tested in Orkney

Ocean energy engineers discuss reliability in a sea of risk

KEY FINDINGS

1. Marine is more viable.
2. Tidal is the more developed, but strong degree of support for ocean technologies.
3. Resources potential is huge.
4. Hostile financial environment, costs are high.
5. There could be a 'high scenario' for wave and tidal energy deployment the global market.
6. 0.5 GW of commercial marine energy generation capacity is in operation and another 1.7 GW under construction, with 99% of this accounted for by tidal range.
7. Environmental impacts on marine animals, underwater noise and disruption of natural movement of water are still a challenge.
8. 'High scenario' for wave and tidal energy deployment the global market could be 'worth up to c.£460bn (cumulative, undiscounted) in the period 2010-2050, with the market reaching up to c.£40bn per annum by 2050
9. If ocean energy deployment was on track to reach 748 GW by 2050 this could create approximately 160,000 direct jobs by 2030
10. The total theoretical wave energy potential is said to be 32 PWh/y, but is heterogeneous and geographically distributed, technology costs for marine energy are still very high, hindering deployment

INTRODUCTION

The conversion of ocean energy resources to electricity could play an important role in meeting rising global energy demand, mitigating climate change, diversifying our energy supply and bolstering economic activity. However, at to date only a handful of commercial ocean energy projects have been delivered, reflecting the current immaturity and high costs of these technologies, as well as the challenging market environment in which they operate.

This chapter examines four key sub-categories of ocean energy technology: wave, tidal stream, tidal range and ocean thermal energy conversion (OTEC). Unfortunately, it is difficult to draw a meaningful comparison of the theoretical global energy resource for each of these technologies but we find that in general wave energy and OTEC have a more abundant and spatially distributed resource versus tidal stream and range. Taken together, ocean energy presents a huge untapped resource available to most coastal countries in one form or another.

Today 0.5 GW of commercial ocean energy generation capacity is in operation and another 1.7 GW under construction, with 99% of this accounted for by tidal range. While relatively few commercial scale wave, tidal stream or OTEC projects are operational we find three tidal stream commercial projects accounting for 17 MW of capacity (two in Scotland and one in France) and a 1 MW commercial wave energy array in Sweden are to be commissioned shortly. A host of OTEC projects are also gathering momentum, with two 10 MW schemes being developed, one by DCNS in Martinique and the other by Lockheed Martin in China. If all planned commercial projects reach fruition then an additional 15 GW of ocean energy capacity will come online over the coming years, however in reality a fraction of this is likely to be delivered. Whilst the traditional leaders of this sector, namely the UK and US, continue to develop flagship projects we find other countries such as South Korea, Ireland, the Netherlands and China are now challenging their dominance.

Despite these positive developments a large number of projects have been suspended largely as a result of public and private funds having been withdrawn due to slow economic growth, falling oil prices and a failure by marine energy technology developers to deliver on initial expectations about their technologies' potential cost-effectiveness. The wave energy sector has been hit particularly hard by leading companies such as Pelamis and Aquamarine falling into administration.

Looking forward we find that the respective costs of these different ocean energy technologies remain a significant barrier to deployment. Innovation will be key to reducing and efforts will need to focus on sub-component (e.g. power take off, prime mover, control systems), component integration and array optimisation RD&D. In addition, various socio-economic, infrastructural and environmental barriers also need to be addressed such as developing supportive energy market conditions, delivering facilitative infrastructure, providing grid connection, growing supply chains and mitigating against associated environmental impacts.

1. ENERGY RESOURCE POTENTIAL

DEFINITIONS AND RESOURCE POTENTIAL

In this section we provide an overview of the four types of ocean energy resources under consideration and the level of resource that could potentially be extracted.

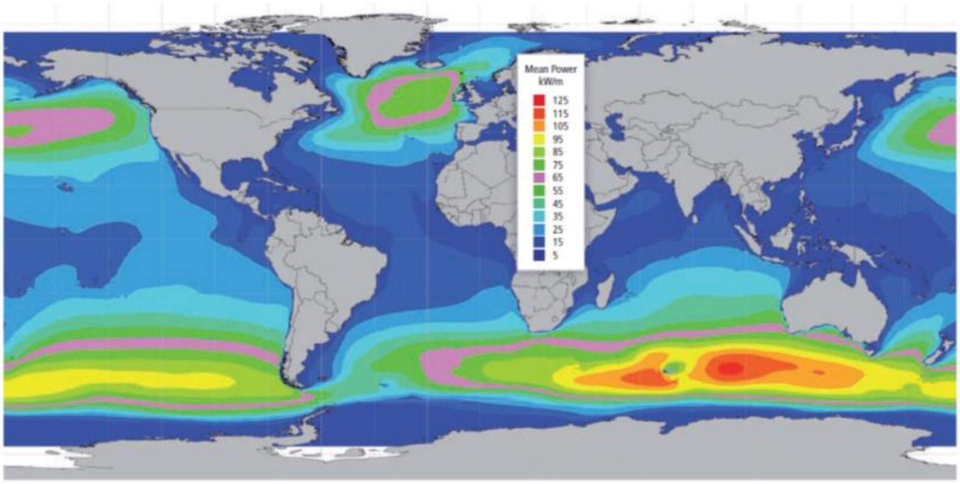
Wave energy

Waves are generated when the wind blows over the ocean's surface, which itself is a function of temperature and pressure differences across the globe caused by the distribution of solar energy[1]. Wave energy carries both kinetic and gravitational potential energy, the level of which is a function of both the height and period of the wave[2] . Harnessing this energy using a wave energy convertor (WEC) can in turn generate electricity.

Following a study conducted on behalf of the International Panel on Climate Change (IPCC)[3] we find that Mørk et al.(2010) estimate the total theoretical wave energy potential to be 32 PWh/yr, roughly twice the global electricity supply in 2008 17 PWh/yr. Figure 1 shows the regional distribution of the global annual wave energy potential, demonstrating how this resource is most abundant in the mid to high latitudes of both hemispheres.

[1] Barstow et al. (2007)
[2] Barstow et al. (2007)
[3] Lewis et al. (2011)

FIGURE 1: GLOBAL OFFSHORE ANNUAL WAVE POWER LEVEL DISTRIBUTION



Source: Cornett (2008)

In absolute terms Table 1 illustrates how Asia and Australasia receive the largest quantity of wave energy, with South and North America also receiving impressive amounts. Despite its rich resource on its western seaboard Western and Northern Europe performs moderately well given its relatively small size. Finally, Central America and the Mediterranean Sea and Atlantic Archipelagos perform poorly given their mid-latitude position.

TABLE 1: REGIONAL THEORETICAL POTENTIAL OF WAVE ENERGY

REGION	Wave Energy TWh/yr
Western and Northern Europe	2,800
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300
North America and Greenland	4,000
Central America	1,500
South America	4,600

Africa	3,500
Asia	6,200
Australia, New Zealand and Pacific Islands	5,600
TOTAL	**29,500**

Source: Mørk et al. (2010)
Note: The total resource potential is less than 32,000 TWh/yr quoted previously as the table accounts for only theoretical wave power P≥ 5 kW/m and latitude ≤66.5º

These estimates do not account for geographical, technical or economic constraints and the sum of energy that could be practically recovered will ultimately be an order of magnitude less. Various estimates about what can practically be recovered have been made with Pelc and Fujita (2002) estimating that 5.5 PWh/yr is realistic, while both Thorpe (1999) and Cornett (2008) are less optimistic estimating approximately 2 PWh/yr. Naturally these estimates are based on different underpinning assumptions and what is deemed 'economically viable' will undoubtedly change over time if existing technologies fall in cost or new technologies emerge.

Tidal stream

Oceanic tides are the function of the motion of the moon and sun relative to the earth. These gravitational forces in combination with the rotation of the earth on its axis cause periodic movements of the oceans and seas[4]. As explained by Mofor et al.(2014) 'the vertical rise and fall of water, known as tides…is accompanied by an incoming (flood) or outgoing (ebb) horizontal flow of water in bays, harbours, estuaries and straits' (p.4). It is this flow that is known as tidal current or tidal stream. Tidal stream devices working in a similar fashion to wind turbines using water currents instead of wind to convert kinetic energy into electricity.[5]

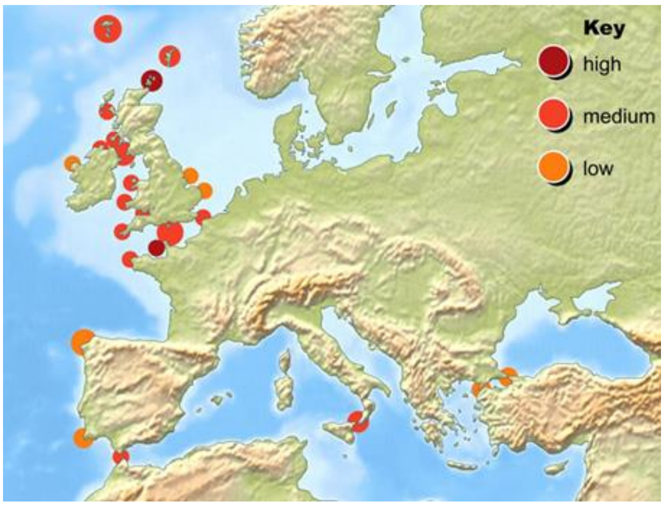
The energy potential of tidal currents is typically located in areas with the greatest tidal range. Consequently, Figure 2 is a good indicator of where the greatest tidal stream potential exists. However, this potential increases in areas where the flow of water is constrained or funnelled by local topography such as narrow straits and headlands, and where the water depth is relatively shallow[6]. 'In particular, large marine current flows exist

[4] SI Ocean (2012)
[5] Magagna & Uihlein (2015)
[6] Aqua-RET (2012); Mofor et al. (2014)

where there is a significant phase difference between the tides that flow on either side of large islands'[7].

It is difficult to identify reliable estimates for global tidal stream energy potential but Charlier & Justus (1993) estimate total tidal energy potential (i.e. tidal range and tidal stream) at 3 TW, with 1 TW located in relatively shallow waters. However, due to geographical, technical and environmental constraints only a fraction of this could be captured in practical terms. In practice, suitable locations need mean spring peak tidal currents that are faster than 2-2.5 m/s to offer an energy density that allows for an economically viable project,[8] accounting for the fact that as the tide changes there will be little or no horizontal flow of water.[9] Importantly, 'major tidal streams have been identified along the coastlines of every continent, making it a global, albeit site specific, resource'[10]. For example, at the European level 106 locations with a strong tidal stream potential were identified, together offering 48 TWh/yr (0.17 EJ/yr) of potential resource[11]. A similar study examined Europe's tidal stream potential identifying that it was predominantly concentrated around the British Isles and English Channel[12] (Figure 2).

FIGURE 2: EUROPEAN TIDAL STREAM RESOURCE DISTRIBUTION (AQUA-RET 2012)



Source: Aqua-RET (2012)

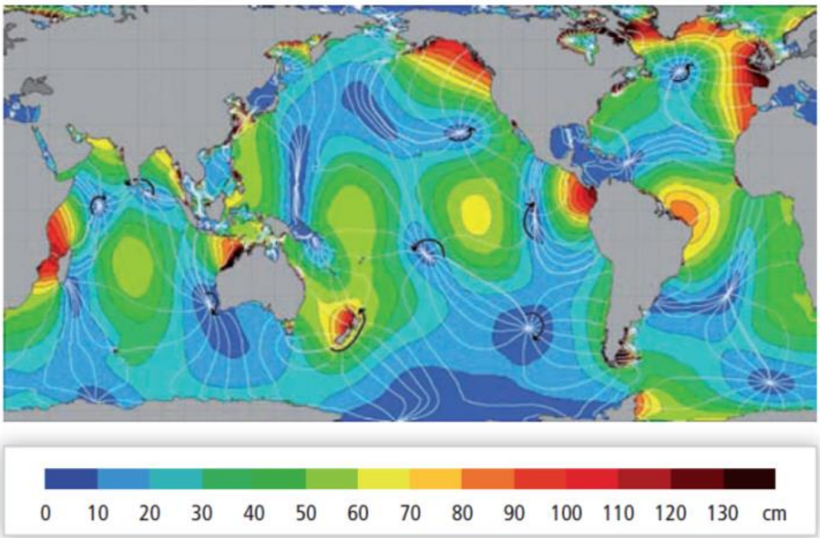
[7] Aqua-RET (2012)
[8] Aqua-RET (2012)
[9] Mofor et al. (2014)
[10] Mofor et al. (2014) p.4
[11] CEC (1996)
[12] Aqua-RET (2012)

Tidal range

The gravitational forces from the sun and moon generate oceanic tides and the difference in sea level between high and low tide is known as the tidal range. At most coastal sites high and low tides occur twice a day (semi-diurnal tides), however in some places just one high and low tide takes place per day (diurnal tides) whilst others experience a combination of diurnal and semi-diurnal oscillations (mixed tides) [13]. Even so these tides have been studied for centuries and can be easily forecast meaning that tidal range energy offers both a consistent and predictable form of energy.

Figure 3 demonstrates how the tidal range resource potential varies considerably across the globe and is ‘amplified by basin resonances and coastline bathymetry to create large surface elevation changes at specific geographic locations’.[14] Consequently, some areas exhibit huge tidal ranges, like the Bay of Fundy in Canada (17 m tidal range), Severn Estuary in the UK (15 m) and Baie du Mont Saint Michel in France (13.5 m).[15] In contrast other locations such the Mediterranean see a tidal range of less than 1 m.[16]

FIGURE 3: GLOBAL SEMIDIURNAL (M2) TIDAL AMPLITUDE



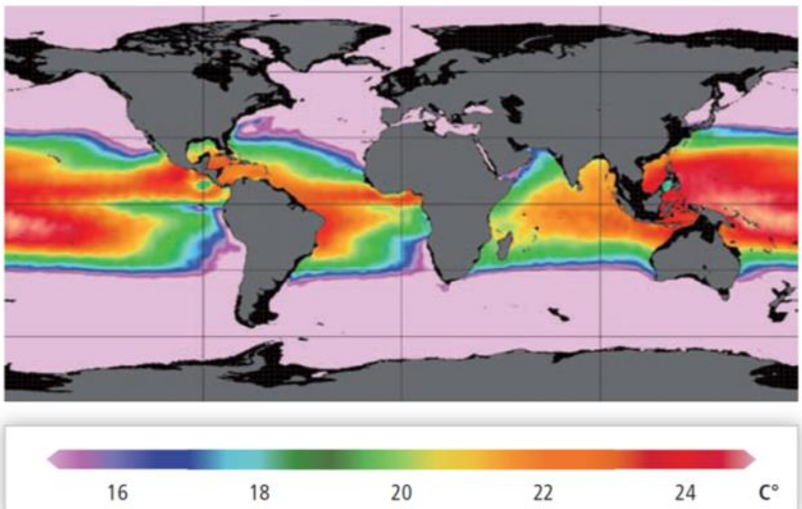
Source: NASA (2006)

[13] Mofor et al. (2014)
[14] Mofor et al. (2014 p.2).
[15] Kerr (2007)
[16] Usachev (2008)

OTEC

Approximately 15% of the total solar energy falling incident on the oceans is retained as thermal energy and stored as heat in the upper layers of the ocean.[17] This energy is concentrated in the top layers and falls exponentially with depth as the thermal conductivity of sea water is low[18]. As illustrated by Figure 4, the temperature differential in the tropics can exceed 25°C between 20 m and 1 km in depth[19]. The temperature gradient between the relatively warm sea surface water and the colder, deep seawater can be harnessed using different ocean thermal energy conversion (OTEC) (see Technologies section). OTEC typically requires a differential of about 20°C to work effectively meaning where cool water (~5°C) is drawn from depths of around 800–1000 m and surface water temperatures sit at a constant 25°C[20]. Consequently, its potential application is limited to between 35º latitude north and south of the equators. Whilst small seasonal variations do occur this energy potential is available all-year round, although its power density is considered relatively low.[21]

FIGURE 4: WORLDWIDE AVERAGE OCEAN TEMPERATURE DIFFERENCES (°C) BETWEEN 20 AND 1,000 M WATER DEPTH (NIHOUS 2010)



Source: Nihous (2010)

[17] Lewis et al. (2011)
[18] Lewis et al. (2011)
[19] Nihous (2010)
[20] NOAA (2014); Kempener & Neumann (2014a)
[21] Lewis et al. (2011); Mofor et al. (2014)

Estimates of the total potential global OTEC energy resource that could be extracted without having a major impact on the thermal characteristics of the world's oceans range between 30 and 90 PWh.[22] On this basis there is a much larger potential resource versus the other forms of ocean energy. However, the resource that could practically and economically be captured is significantly limited by economic and technical constraints.

[22] Pelc & Fujita (2002); Nihous (2010); Charlier & Justus (1993)

2. TECHNOLOGIES

In this section we provide an overview of the key characteristics of the four ocean energy technologies covered in this report. We begin by examining wave and tidal stream energy, before turning to tidal range and OTEC.

WAVE ENERGY

Six key dimensions make up a wave energy device, which together ultimately convert the movement or flow of the oceans into electricity[23]. These are equally applicable to tidal stream covered in the following sub-section:

1. **Structure and Prime Mover:** The physical structure of the device which captures energy and the main interface between the resource and the power take off equipment within the ocean energy converter. The predominant structural material is steel, although certain concepts are exploring alternatives. Prime movers such as turbine blades are made of composite materials.

2. **Foundations and Moorings:** The method used to secure the device to the sea bed. This includes permanent foundation constructions such as gravity bases or pile-pinned foundations, or could consist of moorings such as tight or slack moored systems.

3. **Power Take Off:** The means by which the mechanical energy extracted from the waves or tides is converted into electrical energy. Several types of Power Take Off (PTO) exist including mechanical, hydraulic, or electrical direct drive using permanent magnet generators.

4. **Control:** Systems and software to safeguard the device and optimise the performance under a range of operating conditions. Control systems may adjust certain parameters of the device autonomously in order to ensure favourable operation.

5. **Installation:** The method of placing the structure and device at its power generating location. This includes all vessels and ancillary equipment needed to fully deploy an ocean energy device.

6. **Connection:** The cables and electrical infrastructure for connecting the power output from the device to the electricity network. Alternatively, water is pumped ashore for conversion to electricity and/or desalinated water. Subsequently, power

[23] SI Ocean (2012)

conditioning systems and transformers are needed to provide a grid code compliant electrical output.

Wave energy devices are broadly located in three different ocean environments: onshore, nearshore and offshore. In the following we provide a description of these and their relative strengths and weaknesses:

- **Shoreline devices** - integrated into a natural rock face or man-made breakwater[24] having the advantage of being close to the utility network and relatively easy to maintain. Less likely to be damaged as energy is lost due to friction with the seabed, however this reduces the potential resource that could be captured.[25]

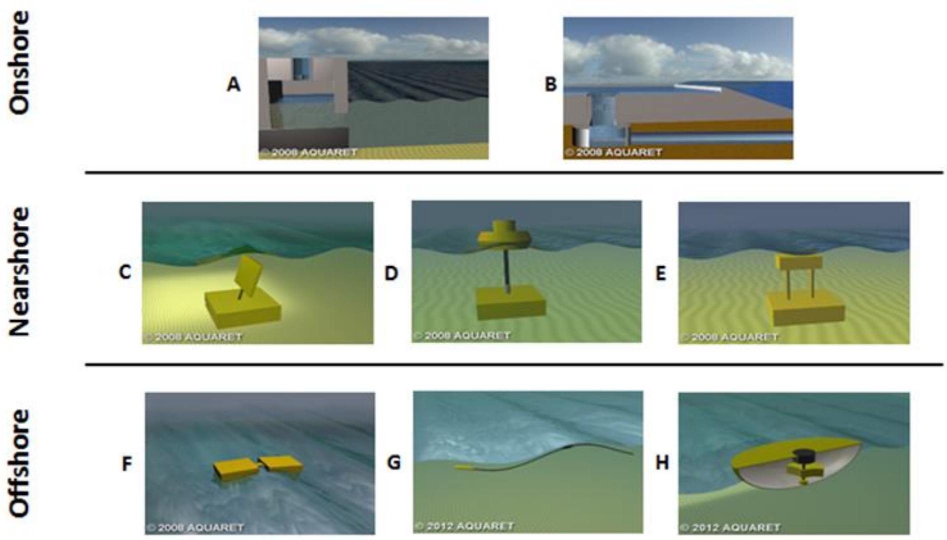
- **Near-shore devices** - located in water shallow enough to allow the device to be fixed to the seabed either via pinned pile foundations or gravity mass[26]. This is turn provides 'a suitable stationary base against which an oscillating body can work'[27]. Disadvantages are similar to shoreline devices.

- **Offshore devices** - located in water tens of metres deep and tethered to the sea bed using tight or slack moorings mass.[28] Much greater potential energy resource versus on - or nearshore but more difficult to construct, operate and maintain and must be designed to survive more extreme conditions.[29]

In each of these locations we typically find different types of devices as outlined in Figure 5, which are described in detail in Table 2.

[24] SI Ocean (2012)
[25] SI Ocean 2012; Drew et al. (2009)
[26] SI Ocean (2012)
[27] Drew et al. (2009 p.888)
[28] Drew et al. (2009; SI Ocean (2012)
[29] Drew et al. (2009)

FIGURE 5: SCHEMATIC OF TYPICAL WAVE ENERGY DEVICES[30]



Source: Aquaret (2012)

TABLE 2: TYPICAL WAVE ENERGY CONVERTORS

Location	Device type	Description
Onshore	Oscillating water columns (OWC)	Oscillating water columns (OWC) use the oscillatory motion of a mass of water induced by a wave in a chamber to compress air to drive an air turbine. The water column thus acts as a piston on the air volume, pushing it through the turbine as the waves increase the water level in the chamber, and drawing it as the water level decreases. OWCs are one of the first types of wave energy converters developed, and different operational ones are installed onshore in self-contained structures. Floating OWCs have been tested and are currently under development for offshore deployment.
	Overtopping devices or	Overtopping devices or terminator WECs convert wave energy into potential energy. This is stored in a reservoir and used to drive low-head turbines. The design of overtopping devices facilitates waves breaking on a ramp to be

[30] Note: A - Oscillating water columns (OWC); B - Overtopping devices or terminator WECs;
C - Oscillating wave surge converters; D - Point Absorber; E - Submerged Pressure Differential devices;
F – Attenuator, G - Bulge wave devices; H - Rotating mass converters

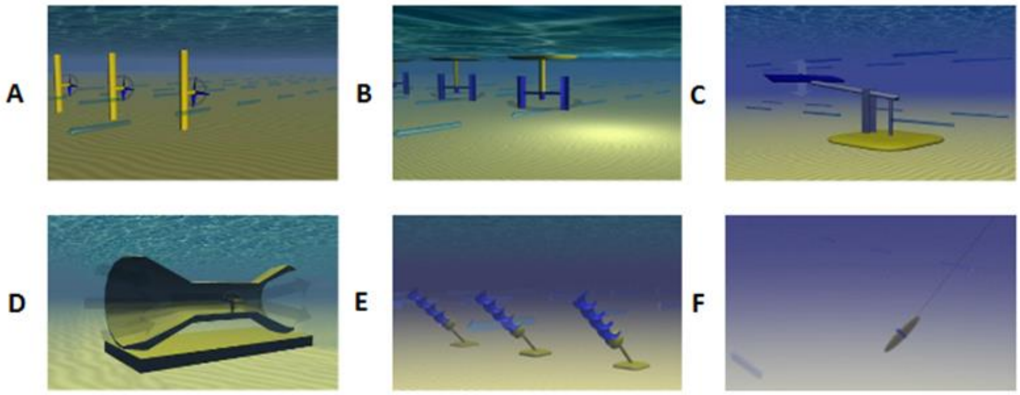
	terminator WECs	collected in a reservoir above the free water surface. Water contained in the reservoir can produce energy by flowing through a low-head hydraulic turbine. Overtopping devices have been proposed to be built for integration in breakwaters, for self-contained onshore operation and for offshore installation.
Nearshore	Oscillating wave surge converters	Oscillating wave surge converters exploit the surging motion of near-shore waves to induce the oscillatory motion of a flap in a horizontal direction. OWSCs are bottom-mounted devices, although prototypes of floating OWSC are already under development.
	Point Absorber	Point absorbers are normally heaving/pitching devices that exploit the relative motion between an oscillating body and a fixed structure or component, which can be either moored to the seabed or installed on the seabed through a large foundation mass. Point absorbers are normally smaller in dimension compared to other WECs. They are non- directional devices, as their performances are not affected by wave directionality.
	Submerged Pressure Differential devices	Submerged Pressure Differential devices are fully submerged devices, exploiting the hydro- dynamic pressure induced by waves to force an upward motion of the device, which then returns to its starting position once the pressure differential is reduced.
Offshore	Attenuator	Attenuators exploit the incoming wave power to generate an oscillatory motion between adjacent structural components. The resulting motion activates the power take-off (PTO), either by pumping high-pressure fluids through a hydraulic motor or by operating a direct- drive generator. Attenuators are designed to operate offshore, and are commonly surface floating, although fully submerged devices have been proposed.
	Bulge wave devices	Bulge wave devices use wave-induced pressure to generate a bulge wave within a flexible tube. As the bulge wave travels within the device it increases in size and speed. The kinetic energy of the bulge is used to drive a turbine at the end of the tube.
	Rotating mass converters	Rotating mass converters exploit the relative motion of waves to induce pitching and rolling in a floating body, thus forcing the rotation of an eccentric mass contained within the device. As the mass rotates it drives an electrical generator.
	Other	Novel wave energy devices currently under development that do not fit any of the above categories.

Source: Magagna & Uihlein (2015); EMEC (2016)

TIDAL STREAM

Tidal stream devices convert the kinetic energy of free flowing water into electricity. Numerous different types of devices exist and these typically fall into six categories as illustrated in Figure 6 and described in Table 3.

FIGURE 6: SCHEMATIC OF TYPICAL TIDAL STREAM ENERGY DEVICES[31]



Source: Aquaret (2012)

TABLE 3: TYPICAL TIDAL ENERGY CONVERTORS

Device type	Description
Horizontal-Axis Turbine	Similarly, to wind energy converters, this technology exploits the lift from the tidal flow to force the rotation of the turbine mounted on a horizontal axis. This operates a rotor, converting mechanical energy to electrical energy through use of a generator.
Vertical-Axis Turbine	The principle of operation of vertical axis turbines is similar to the horizontal devices, except the turbines are mounted on a vertical axis.
Oscillating Hydrofoil (Reciprocating Device)	Oscillating hydrofoils comprise a hydrofoil located at the end of a swing arm, which is allowed to oscillate in pitching mode by a control system. The motion is then used to pump hydraulic fluid through a motor. The rotational motion that results can be converted to electricity through a generator.

[31] Note: A - Horizontal-Axis Turbine; B - Vertical-Axis Turbine; C - Oscillating Hydrofoil (Reciprocating Device); D - Ducted Turbine or Enclosed Tips; E - Archimedes' Screw; F - Tidal Kite

Ducted Turbine or Enclosed Tips	Enclosed tips (ducted) turbines are essentially horizontal-axis turbines contained within a Venturi duct. This is designed to accelerate and concentrate the fluid flow. Ducted structures could also reduce turbulence around the turbines and facilitate the alignment of water flow towards the turbines.
Archimedes' Screw	These devices are a variation of the on vertical-axis turbines, drawing power from the tidal stream as the water flows up through the helix.
Tidal Kite	Tidal kite devices comprise a tethered kite with a small turbine. The kite effectively flies through the flow, increasing the relative flow velocity entering the turbine.
Other	Novel tidal concepts currently under development that do not fit any of the above categories.

Source: Magagna & Uihlein (2015); EMEC (2016)

To date tidal stream has exhibited a much stronger degree of technological convergence compared with wave energy, with approximately ¾ of all R&D investments focusing on horizontal axis turbines versus other designs[32]. A contributing factor may well be the dominance of horizontal axis turbines in the wind industry, which work on very similar engineering principles and the ability to draw upon expertise from this sector for technology development. Importantly tidal devices must be 'designed to suit the higher density and different characteristics of the surrounding environment'[33], as well as accounting for factors such as reversing flows, cavitation and harsh underwater marine conditions (e.g. corrosion, debris and fouling).[34]

TIDAL RANGE

Tidal range technology shares a range of similarities with hydropower, capitalising on the artificial height differential of two bodies of water created by a dam or barrier, and the gravitational potential energy this provides, to generate electricity via a low-head hydroelectric turbine.[35]

Tidal range plants normally take two forms: tidal barrage or tidal lagoon. Tidal barrages work on a very similar basis to a hydroelectric power plant by damming the flow of water either into or out of a tidal inlet (Figure 7). The gravitational potential difference between the two bodies of water either side of the barrage drives an electrical turbine, normally a bulb

[32] Corsatea & Magagna (2013)
[33] Mofor et al. (2014 p.4)
[34] Lewis et al. (2011)
[35] Mofor et al. (2014)

turbine commonly found in hydro plants as at the La Rance tidal range facility in France.[36] A tidal lagoon is different in the sense that it is an independent enclosure that is typically located away from estuarine areas.[37] These offer greater flexibility in terms of capacity, are considered less costly and offer little or no impact on delicate estuarine environments.[38]

FIGURE 7: LA RANCE TIDAL RANGE BARRAGE IN FRANCE

Source: Tethys (2012)

Traditional tidal range plants can also be single or multi-basin schemes. Single basin plants are the traditional model where a barrage or lagoon creates a single basin of water that drains or fills in sync with the tides, thus constraining the flexibility of its generating capacity. Multi-basin schemes on the other hand ‘are filled and emptied at different times with turbines located between the basins’ thus offering ‘more flexible power generation availability over normal schemes, such that it is possible to generate power almost continuously’.[39]

The main advantage of tidal range technology is that it is highly predictable and could therefore, offer an important source of baseline electricity generation at easily forecastable times of the day.[40] However, there are numerous concerns in relation to its impact on the

[36] Bosc (1997)
[37] Magagna & Uihlein (2015); Mofor et al. (2014)
[38] Lewis et al. (2011)
[39] Lewis et al. (2011 p.510)
[40] Magagna & Uihlein (2015)

local estuarine environment and socio-economic activities such as shipping, tourism etc. explored (see Economics and Markets section).

OTEC

OTEC takes advantage of the temperature differential between the relatively warm surface waters and the significantly cooler deep waters to drive an electrical turbine. Ocean thermal energy conversion (OTEC) plants fall into three conversion types: open, closed and hybrid.[41]

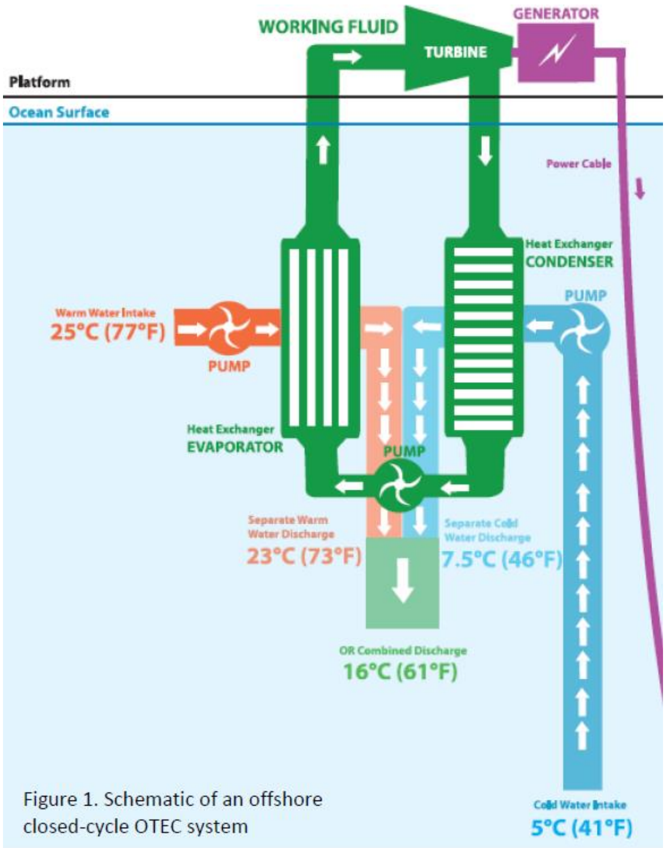
- **Open-cycle** - Warmer surface water is flash evaporated in a very low-pressure environment and the water vapour is then used to drive the electrical generator. The vapour is condensed using the cold sea water pumped up from below to complete the cycle[42]. This system has the advantage of generating desalinated water.[43]

- **Closed-cycle** - Warm water (25°C) is used to 'flash evaporate' a working fluid such as ammonia, propane or chlorofluorocarbon (CFC) with a much lower boiling point than water by passing it over a heat exchanger. The vaporised working fluid drives an electrical turbine before condensing as it comes into contact with a heat exchanger cooled with cool sea water (5°C), which is then pumped back to the evaporator to start the cycle once again.[44]Closed-cycle systems operate more efficiently than open-cycle but are often smaller in scale as the secondary working fluid operates at a higher pressure[45] (Figure 8).

- **Hybrid** - Firstly electricity is generated using the closed cycle system, however instead of discharging the warm seawater it is evaporated using the open-cycle OTEC system and then later condensed with cool water.[46] This has the advantage of harnessing the advantages of both closed- and open-loop systems.

[41] Charlier and Justus (1993)
[42] Kempener & Neumann (2014a)
[43] Magagna & Uihlein (2015)
[44] Magagna & Uihlein (2015)
[45] Charlier & Justus (1993); Lewis et al. (2011)
[46] Kempener & Neumann (2014a)

FIGURE 8: OFFSHORE CLOSED-CYCLE OTEC SYSTEM



Source: NOAA (2014)

OTEC plants can be located onshore or offshore. Onshore facilities have the advantage of being cheaper and easier to maintain, as well as providing the option for producing desalinated water, however they typically demand a very long cold water intake pipe that is costly and subject to heat gains from friction, air temperature etc.[47] They also tend to suffer from having access to a limited ocean thermal energy resource and posing negative impacts on tourism given their coastal location.[48] On the other hand, floating offshore plants have shorter inlet pipes and better thermal resource availability but are subject to higher construction and O&M costs given their remote location and exposure to harsh conditions.

[47] WEC (2010).
[48] Devis-Morales et al. (2014); Magagna & Uihlein (2015)

Furthermore, significant costs will be incurred by integrating the offshore facility to the grid.[49]

A key advantage of some OTEC plants is their ability to generate desalinated water that can be used for drinking water, irrigation etc. and provide cool water to be used for air-conditioning systems post-cycle.[50] This cool ocean water is also rich in nutrients like nitrogen and phosphates and can be used in aquaculture. Finally, OTEC is also a non-intermittent renewable energy technology with a very strong capacity factor (90-95%), however this is undermined to some extent by the very low efficiency of the Carnot cycle (maximum 7%) and the energy losses suffered as a result of pumping (approximately 20%-30%).[51]

[49] Magagna & Uihlein (2015); WEC (2010)
[50] Kempener & Neumann (2014a); Magagna & Uihlein (2015)
[51] Kempener & Neumann (2014a).

3. ECONOMICS & MARKETS

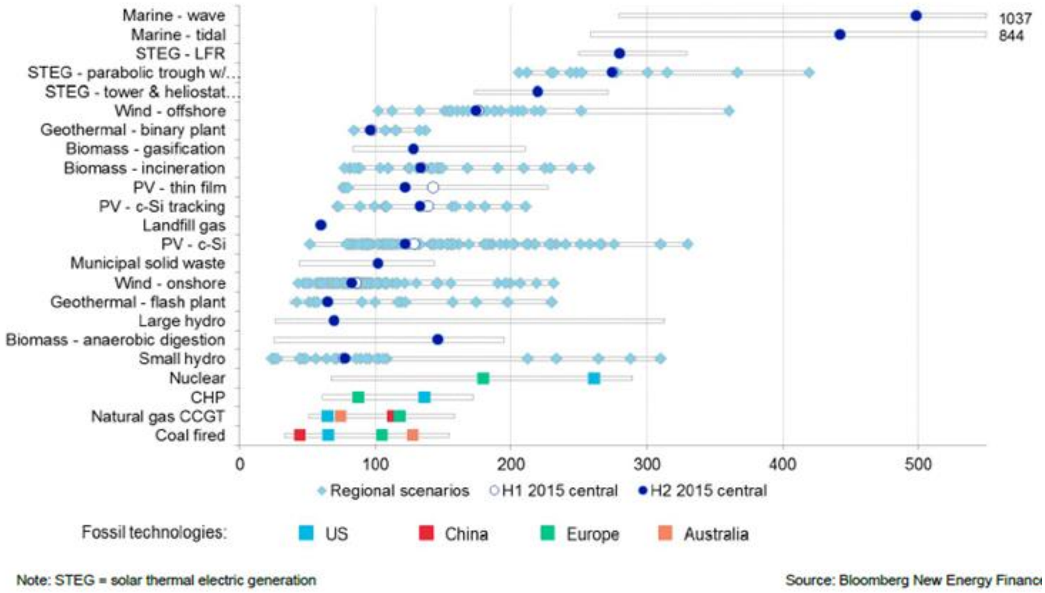
This section begins with an overview of the economic costs associated with these four technologies and is followed by a review of historical, recent and forthcoming developments relating to these technologies' development and deployment.

TECHNOLOGY COSTS

Bloomberg New Energy Finance's (BNEF) analysis of energy technologies levelised cost of electricity (LCOE) identifies the major disparity between the cost of ocean energy versus other forms of generation (Figure 9). The central scenario for 2015 (H2) estimates the LCOE of wave energy at approximately US$500/MWh whilst tidal sits at approximately US$440/MWh. It could be argued that there is a stronger degree of certainty over the costs of tidal versus wave energy given the stronger technological convergence and greater installed capacity. More broadly, Figure 9 illustrates the extremely high cost of ocean energy versus other renewables, for example offshore wind (US$174/MWh), crystalline silicon solar PV (US$122/MWh), onshore wind (US$83/MWh) and large hydro (US$70/MWh).[52]

[52] BNEF (2015b)

FIGURE 9: LEVELISED COST OF ELECTRICITY TECHNOLOGIES ($/MWH) FOR 2015



Source: BNEF (2015a)

BNEF's analysis does not cover OTEC and so in order to offer a more complete picture we consider a review conducted by Kempener & Neumann (2014a). They identified that the LCOE for small-scale OTEC plants (1-10MW) ranges somewhere between US$190/MWh and US$940/MWh, however if the facility were to be scaled up to between 50-400 MW the cost would fall dramatically and likely range between US$70/MWh and US$320/MWh.

These high costs illustrate the immaturity of these technologies and the relatively short gestation period that ocean energy technologies, with the exception of tidal range, have undergone. Consequently, many of the cost issues could be addressed through ongoing RD&D efforts examined in the next section. Tidal range is slightly different in the sense that the technology was first installed on a commercial basis in mid-20th century in countries like Canada, France and China. Consequently, the underpinning technological principles are well understood and many of the installations have operated without significant issues suggesting that further RD&D is unlikely to dramatically reduce its costs.[53] Even so, it is possible to improve the relatively poor load factor (25%) of tidal range technology due to

[53] Kempener & Neumann (2014b)

tidal cycles and turbine efficiency and in turn improve its LCOE by using multi-basin designs and/or turbines for ebb and flood generation.[54]

Whilst not always the case, energy technology costs typically fall as deployment increases due to a combination of learning by doing and learning by using, as well as other factors such as supply chain maturity and increased investor confidence. In this context Table 4 presents an assessment of ocean energy costs in relation to different stages of deployment. Here we find that ocean energy costs are expected to fall with increased deployment and that the LCOE of wave, tidal stream and OTEC could fall in line with today's cost of competing renewable and fossil fuel technologies.[55]

[54] Kempener & Neumann (2014b)
[55] BNEF (2015a)

TABLE 4: SUMMARY DATA AVERAGED FOR EACH STAGE OF DEPLOYMENT AND EACH TECHNOLOGY TYPE

Deployment stage	Variable	Wave		Tidal Stream		OTEC	
		Min	Max[56]	Min	Max	Min	Max
First pre-commercial array / First Project	Project Capacity (MW)	1	3	0.3	10	0.1	5
	CAPEX ($/kW)	4000	18100	5100	14600	25000	45000
	OPEX ($/kW per year)	140	1500	160	1160	800	1440
Second pre-commercial array/ Second Project	Project Capacity (MW)	1	10	0.5	28	10	20
	CAPEX ($/kW)	3600	15300	4300	8700	15000	30000
	OPEX ($/kW per year)	100	500	150	530	480	950
	Availability (%)	85%	98%	85%	98%	95%	95%
	Capacity Factor (%)	30%	35%	35%	42%	97%	97%
	LCOE ($/MWh)[57]	210	670	210	470	350	650
First Commercial-scale Project	Project Capacity (MW)	2	75	3	90	100	100
	CAPEX ($/kW)	2700	9100	3300	5600	7000	13000
	OPEX ($/kW per year)	70	380	90	400	340	620

[56] For wave, the maximum value in the table is either that from the responses of consulted developers or from any of the reference studies analysed, this is particularly relevant for OPEX, where developers are now presenting costs that are significantly more optimistic than past studies have suggested.
[57] This study has used the standard method for LCOE assessment proposed by the IEA.

	Availability (%)	95%	98%	92%	98%	95%	95%
	Capacity Factor (%)	35%	40%	35%	40%	97%	97%
	LCOE ($/MWh)	120	470	130	280	150	280

Source: OES - IEA (2015)

HISTORIC, RECENT AND FORTHCOMING MARKET DEVELOPMENTS

At present 0.5 GW of commercial ocean energy generation capacity is in operation with another 1.7 GW under construction. However, 99% of this is tidal range with only 11 MW of tidal stream, 2 MW of wave and no OTEC. Instead these technologies are typically deployed via pre-commercial demonstration schemes as outlined in the Country Notes. There is also 15 GW of ocean energy projects at various stages of the development pipeline with, the majority of these are tidal range (11.5 GW) followed by tidal stream (2.6 GW), wave (0.8 GW) and OTEC (0.04 GW). However, only 0.8 GW of these projects have received consent with the vast majority for tidal range. Below we consider historic, recent and forthcoming developments across these four technologies, examining both commercial and pre-commercial projects.

Wave energy

Historic developments

Wave energy can be traced back to 1799, when Pierre Girard and his son filed the first wave energy patent in France.[58] Following the pioneering post-war work of Yoshio Masuda in Japan and Walton Bott in Mauritius wave energy innovation really gathered pace following the work of Stephen Salter on his device ‘the Salter Duck’ in the UK during the 1970s.[59] Subsequently, the UK government moved to establish the world’s first major wave energy programme in 1976, but following slow progress in terms of cost reductions the programme was halted in 1982. While the UK stalled, other countries forged ahead like Norway who in 1985 launched the world’s first wave power station: two full-sized (350 and 500 kW rated power) shoreline OWC prototypes at a site near Bergen.[60] The UK eventually followed suit in 1991 by installing its own 75 kW prototype Limpet OWC on Islay, Scotland, officially the UK’s first commercial wave energy plant.[61]

[58] Ross (1996)
[59] Ross (1996)
[60] Ross (1996); Falcão (2010)
[61] Ross (1996); Cleveland (2014)

The 1990s was characterised by a move from European government to support wave energy innovation following its commitment of 2 million ECUs[62] to ocean energy under its Joule 2 programme leading to further demonstration projects include an OWC on Pico island in the Azores.[63] However, confidence in wave energy was soon shaken again following the high-profile sinking of a 2 MW OWC 'OSPREY' device on its UK launch in 1995 following damage from a storm while still undertaking installation.[64] Despite this setback the UK delivered the world's first commercial grid connected wave energy device when it commissioned its upgraded 500 kW Limpet device on Islay in 2001.[65] The 1990s also saw two key players enter the market, namely the US's Ocean Power Technologies and UK's Pelamis (formerly known as Ocean Power Delivery) who committed significant resources towards developing their respective devices during the 2000s in the context of growing concerns about climate change, energy security and increasing oil prices.

Major developments in the 2000s included the establishment of the European Marine Energy Centre (EMEC) Ltd in 2003, a centre offering 'at-sea' testing capabilities for both wave and tidal energy devices in both challenging and less challenging (nursery) conditions. This enabled Pelamis to become the first company in the world to generate electricity into a grid system from an offshore WEC in 2004 and the first to deliver a wave energy array, installing 3 Pelamis devices (2.25 MW total nominal rating) off the coast of Portugal at Aguacadora in 2008. Unfortunately, this was decommissioned shortly after due to technical faults.[66]

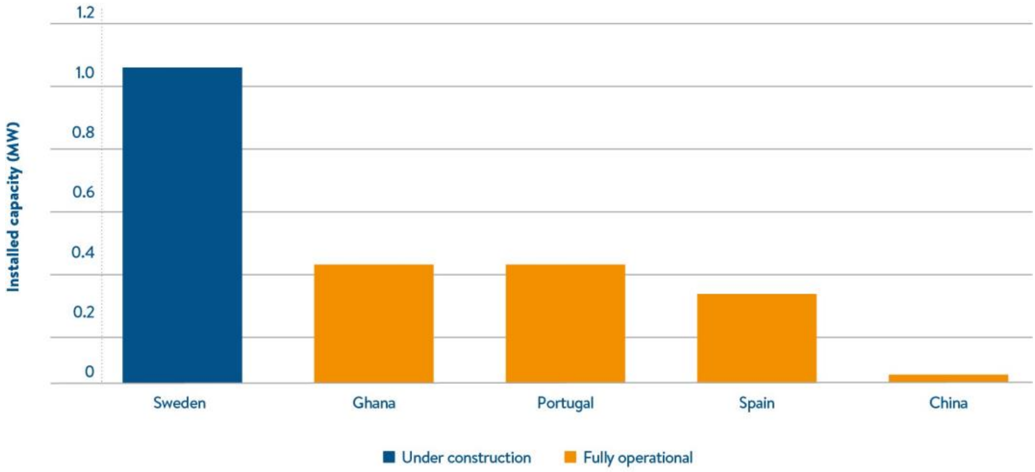
Following an increase in the number of successful demonstration projects during the mid to late 2000s the wave energy sector saw energy utilities like E. On and Scottish Power, Original Equipment Manufacturers (OEMs) like Voith Hydro in WaveGen and ABB in Aquamarine, as well as Venture Capitalists, enter the wave energy market. Subsequently, a worsening financial environment, falling oil prices and a failure to deliver on initial expectations about reductions in LCOE meant investors began to pullback from the wave energy sector, resulting in major job losses and large companies like Pelamis and Aquamarine falling into administration, with numerous planned demonstration projects cancelled.

Ongoing developments

While the UK has scaled back its commercial deployment activities, Sweden's Seabased has begun construction the world's largest commercial wave energy array at Sotenas. It will incorporate 42 devices and deliver 1.05 MW of capacity. They have also recently installed a second project in Ghana consisting of 6 devices, together providing 400 kW of capacity (Figure 10).

[62] European Currency Units
[63] Ross (1996).
[64] Ross (1996).
[65] Whittaker et al. (2004.
[66] Cleveland (2014)

FIGURE 10: WAVE ENERGY INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



Source: OES (2016a)

A host of pre-commercial demonstration projects are also underway and one of the highest profile has been in Australia where Carnegie has demonstrated 3 of its CETO 5 devices rated at 240 kW off Garden Island. Numerous other demonstration projects are taking place across the UK, Canada, Denmark, Korea, Spain and the United States among others.

Forthcoming developments

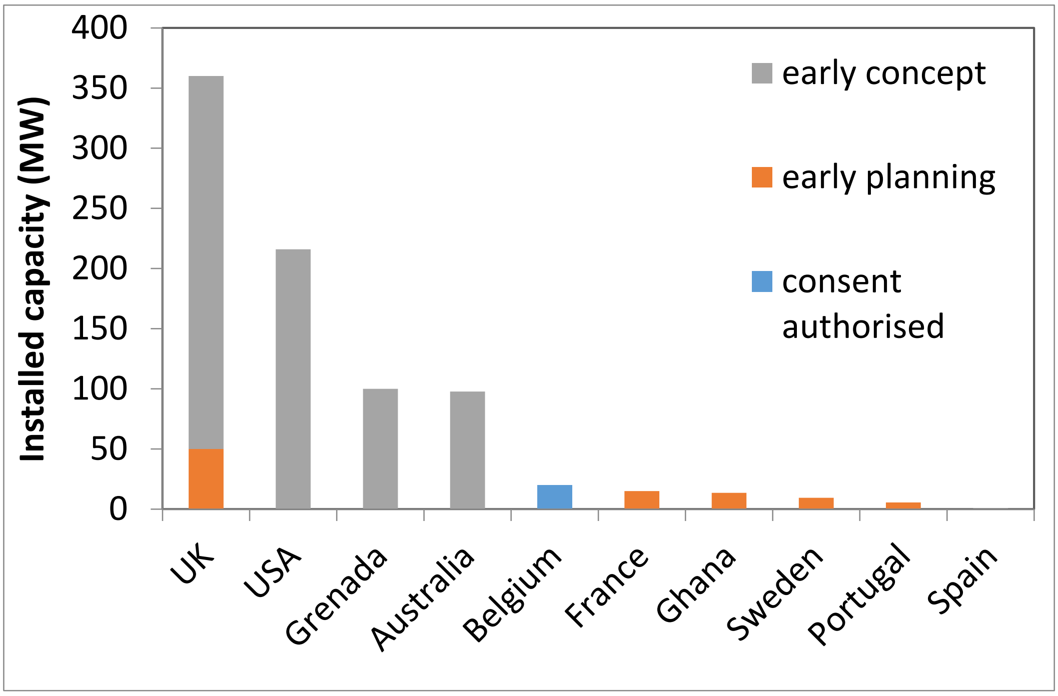
In total, 838 GW of wave energy projects are currently at different stages of development, however only 20 MW of this has received authorised consent relating to a project at Mermaid/Bligh Bank in Belgium (Figure 11). In addition, there is 94 MW at the early planning and 725 MW at the early concept stage. Importantly a second phase of both Seabased's projects in Sweden and Ghana are at an early planning stage and will be contingent of the performance of the first phase. The former delivering a further 378 devices and 9.5 MW of capacity, with the second delivering a further 560 devices and 14 MW of capacity. Portugal's 5.6 MW SWELL project north of Peniche Peninsula is also at the early planning stage and will consist of sixteen 350 kW oscillating Wave Surge Converters.[67]

At the early concept stage is Ocean Power Technologies' three major commercial projects in Australia equating to almost 100 MW, whilst AWS Ocean Energy have proposed a two phase project in the north of Scotland, the first phase would be for 4 devices (10 MW) and

[67] European Commission (2012); European Commission (2014)

the second for 76 devices (190 MW). However, given the early stage of these projects very little capacity is expected to come online in the near future.

FIGURE 11: WAVE ENERGY INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

At a pre-commercial stage, the UK is looking to take the lead once more with a number of major projects are in development at the UK's WaveHub including a 10-15 MW array of Carnegie CETO 6 devices, a 10 MW array of Fortum devices and a 10 MW array of Seabased devices.[68] Furthermore, after the loss of Pelamis and Aquamarine Power, the Scottish Government recently established Wave Energy Scotland that has a budget of £10m between 2014 and 2017. Unlike previous UK wave energy RD&D funding schemes, this offers 100% funding throughout procurement, negating the needs to rely on difficult to secure match funding from the private sector. It also incorporates a strong focus on developing commercial sub-components prior to commercial device, as well as a clear 'stage-gating' approach that demands concepts meet stringent criteria before being eligible for further funding and finally, a much stronger focus on collaboration via a requirement for consortia.

[68] Ocean Energy Systems (2016)

Outside the UK, Carnegie is planning to deploy its CETO 6 device at its Garden Island facility in Australia prior to UK deployment. Another major planned demonstration projects includes Ireland's 5 MW WestWave project located at Killard Point in County Clare and due for commissioning in 2018.

Tidal stream

Historic developments

One of the very first tidal stream prototypes can be traced back to the UK's Peter Fraenkel and his work in southern Sudan in the 1970s, where he used a catamaran raft and vertical axis rotor to generate 2–3 kWh in order to pump 50 m^3 of water a day for local communities.[69] Fraenkel's Marine Current Turbines subsequently developed a 15 kW prototype called SeaGen and tested this in Loch Linnhe in 1994 followed by a 300 kW pillar mounted prototype system called SeaFlow in the Bristol Channel.[70] This work ultimately led to the world's first large-scale, grid-connected commercial tidal stream generator, a 1.2 MW device in the Strangford Narrows between Strangford and Portaferry in Northern Ireland,[71] which is set to be decommissioned shortly.

Despite the UK's rich heritage, it has by no means been the only pioneer in this field. Other major developers that delivered successful demonstration projects in the 2000s included Italy's University of Naples Federico II (2000), Norway's Hammerfest Strom (now Andritz Hydro Hammerfest) (2003), Ireland's OpenHydro (2006), Australia's Atlantis Resources (2006), Netherlands' Tocardo (2008) and Korea's Korea East West Power Co (2009).

Despite these positive developments a large number of projects have been suspended largely as a result of public and private funds having been withdrawn due to slow economic growth, falling oil prices and a failure by marine energy technology developers to deliver on initial expectations about their technologies' potential cost-effectiveness. The wave energy sector has been hit particularly hard by leading companies such as Pelamis and Aquamarine falling into administration.

Looking forward, we find that the respective costs of these different ocean energy technologies remain a significant barrier to deployment. Innovation will be key to reducing and efforts will need to focus on sub-component (e.g. power take off, prime mover, control systems), component integration and array optimisation RD&D. In addition, various socio-economic, infrastructural and environmental barriers also need to be addressed such as developing supportive energy market conditions, delivering facilitative infrastructure, providing grid connection, growing supply chains and mitigating against associated environmental impacts.

[69] Whitaker (2011).
[70] WEC (2010); Cleveland (2014)
[71] Cleveland (2014)

Following a range of successful demonstration projects, the late 2000s saw a large number of Original Equipment Manufacturer (OEMs) move into the tidal stream market. For example, Rolls Royce acquired Tidal Generation Ltd (TGL) in 2009, Siemens AG acquired Marine Current Turbines (MCT) in 2012, Andritz Hydro acquired Hammerfest Strom in 2012 and DCNS acquired OpenHydro in 2013. However, following the financial crisis many of these large companies began to retrench in the early 2010s to focus on their core competencies, with Siemens and Rolls Royce both withdrawing. However, other OEMs moved in with Alstom acquiring TGL in 2013 and Atlantis acquiring MCT and SeaGen Ltd in 2015. Additionally, Lockheed Martin, one of the highest profile aerospace and defence OEMs, began to co-develop the AR1500 turbine with Atlantis in 2014 (Figure 12).

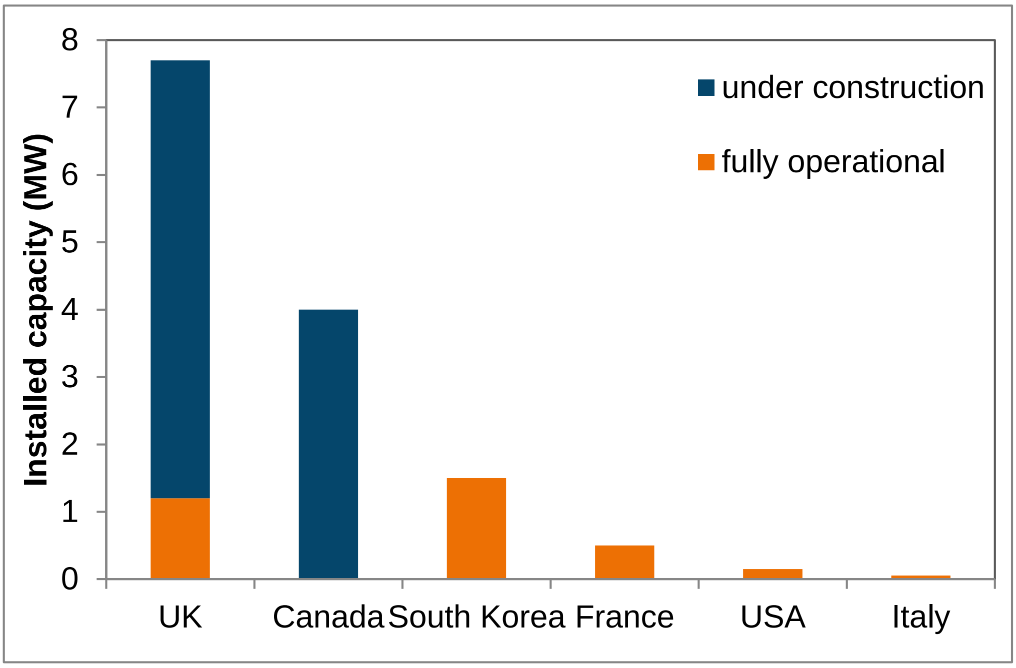
FIGURE 12: ATLANTIS AND LOCKHEED MARTIN'S CO-DEVELOPED AR1500

Source: Atlantis (2016)

Ongoing developments

Today there is almost 4.3 MW of commercial tidal stream installed capacity and the largest two plants are at the Uldolmok Tidal Power Station in South Korea and MCT's SeaGen installation in Strangford Lough, Northern Ireland. There is however a further 10.5 MW of commercial capacity under construction across three projects, all of which incorporate horizontal axis-turbines. The largest is the 6 MW MeyGen Phase1, the world's first commercial tidal stream array, located north of Caithness in Scotland. It will incorporate three Andritz Hydro Hammerfest HS1500 turbines and one Lockheed Martin-designed Atlantis AR1500 turbine due to be installed in summer 2016. The second is the 4 MW Cape Sharp project in the Bay of Fundy, Canada that will incorporate two 2 MW OpenHydro turbines. The third is the Shetland Tidal Array where Nova Innovation has recently commissioned the first of three 100 kW devices targeting a community ownership model, with a view to deploy two more. The third scheme is a single 0.5 MW device deployed by Sabella in Brittany, France (Figure 13).

FIGURE 13: TIDAL STREAM INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



Source: OES (2016a)

Numerous pre-commercial demonstration projects are also underway. One of the largest is DCNS/Open Hydro's project at Paimpol Bréhat in France incorporating two 0.5 MW ducted turbine devices, the first of which has now been deployed. This builds upon the extensive demonstration of a 250 kW device at EMEC during the preceding few years. The largest capacity tidal stream device developed to date has also recently been deployed at EMEC, namely ScotRenewables' 2 MW (twin turbine) SR2000 M1 full scale prototype. They have also recently won €10m via the EU development fund Horizon2020 to construct and deploy a second generation SR2000 device to be deployed in parallel to the first at EMEC over the next year. Other notable projects include Bluewater's pilot 200kW BlueTEC device in the Netherlands, as well as the numerous projects underway in both Canada (and specifically the FORCE test site) and South Korea.

Forthcoming developments

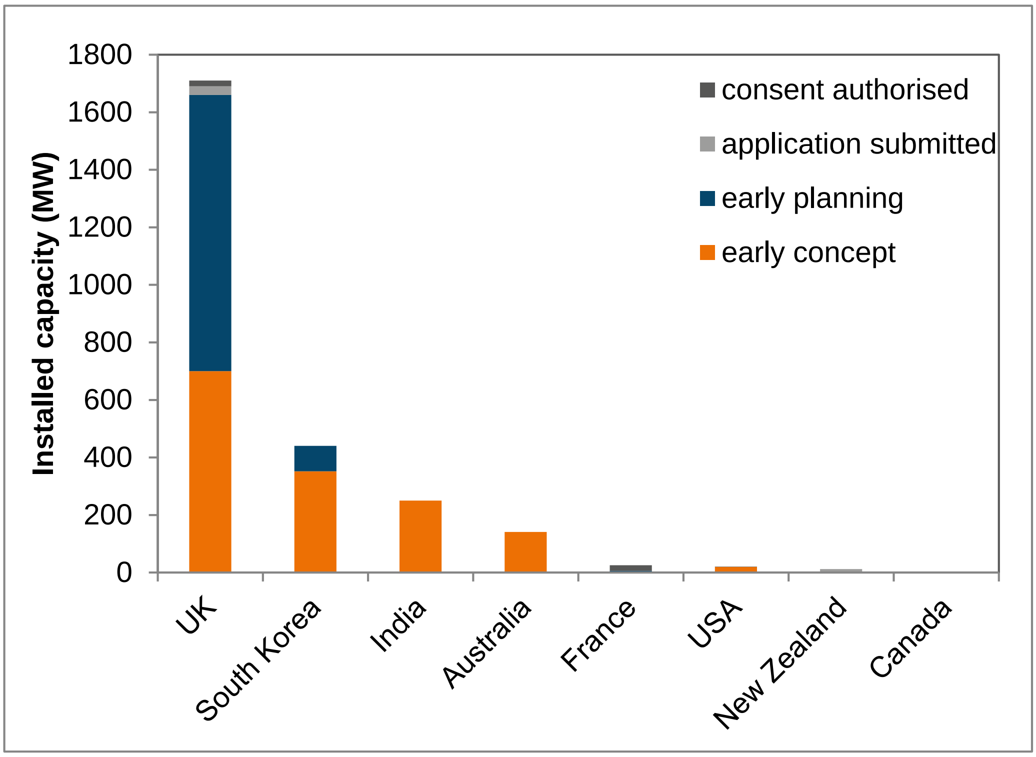
At present planning consent has been granted for 44 MW of installed capacity with consent having been applied for a further 42 MW of capacity. Whilst Atlantis MCT has shelved two major UK schemes including the 10 MW Anglesey Skerries array in Wales and the 8 MW

Kyle Rhea array in Scotland to focus on its MeyGen project.[72] Following the deployment of Phase 1A (4 turbines) it will look to deliver Phase 1B that will deliver a total of 86 MW installed peak capacity followed by Phase 2 will raise the total capacity to 398 MW.

Other large consented projects include the 10MW array of 9 devices (each holding three turbines) rated at 400 kW off St. Davids Head, Wales. Consent has been authorised and at the time of writing the first 400kW device had been installed off Ramsey Sound, Wales in 2015. Developers will wait to see how it performs before continuing with the installation of the remaining 8 devices.[73] Two other large projects are proposed both in northern France, are the Normandie Hydro project, a 5.6 MW 4 device scheme led by General Electric[74] (2017) and the Raz Blanchard project, a 7 device 14 MW scheme led by OpenHydro (2018). A 10 device 10MW scheme is also proposed by Andritz Hydro Hammerfest UK within the Sound of Islay, with a targets date of 2017. With regards to non-consented projects, 1 GW of projects is at the early planning stage and 1.5GW at the early concept stage Figure 14.

[72] Harris (2016)
[73] Ocean Energy Systems (2016)
[74] Formerly Alstom, which was acquired by General Electric in 2015

FIGURE 14: TIDAL STREAM INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

Tidal range

Historic developments

The first instance of capturing tidal range power dates back to 787 when the first tide mill was built at the Nendrum Monastery on Strangford Lough in Northern Ireland.[75]Instead of generating electricity these mills used a dam to contain the tide when it was high, the water then turning a water wheel once the tide fell to turn machinery such as a mill stone grind.[76] Subsequently, projects were developed to generate electricity using a very similar process. The world's first large-scale tidal range power plant was the la Rance Tidal Power Station (240 MW) that became operational in 1966 in Brittany, France and still operates today.[77] Other major projects were subsequently developed including the 20 MW Annapolis Royale plant in Canada installed in 1982 and the 254 MW Sihwa tidal plant in South Korea.[78] A smaller but important development was the upgrading of China's Jiangxia tidal power plant

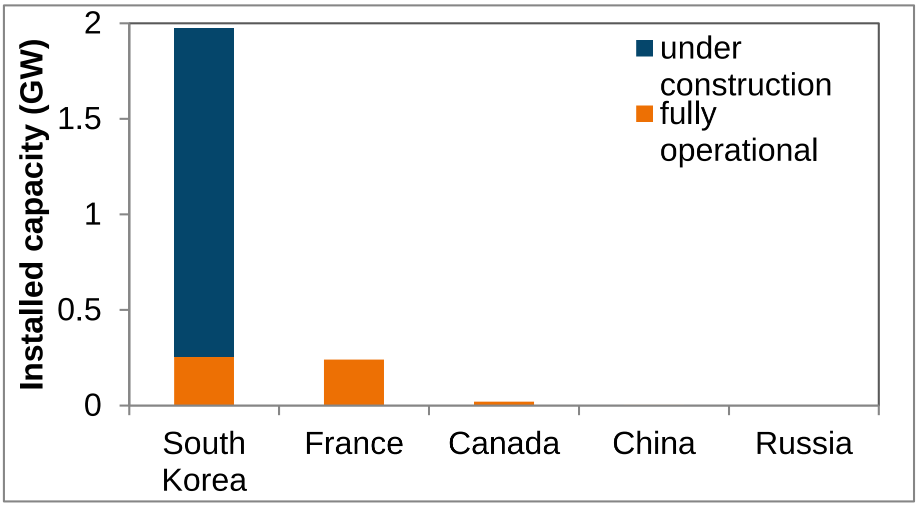
[75] Newman (2016)
[76] TidalPower (2013)
[77] Mofor et al. (2014)
[78] Mofor et al. (2014); TidalPower (2013); WEC (2010)

originally established in the 1980s from 3.9 MW to 4.1 MW following the upgrading of one of its turbines.

Ongoing developments

These developments along with a host of smaller scale projects have resulted in approximately 521 MW of tidal range capacity worldwide with another 1.7 GW under construction (Figure 15). At present there are two large tidal range projects under construction, both in the South Korean Yellow Sea: The Incheon Tidal Power Plant (1.3 GW) and Saemangeum Reclamation Project (0.4 GW). The former is set to go live in 2017 and together these projects will more than triple existing capacity.

FIGURE 15: TIDAL RANGE INSTALLED CAPACITY IN OPERATION OR UNDER CONSTRUCTION



Source: OES (2016a)

Forthcoming developments

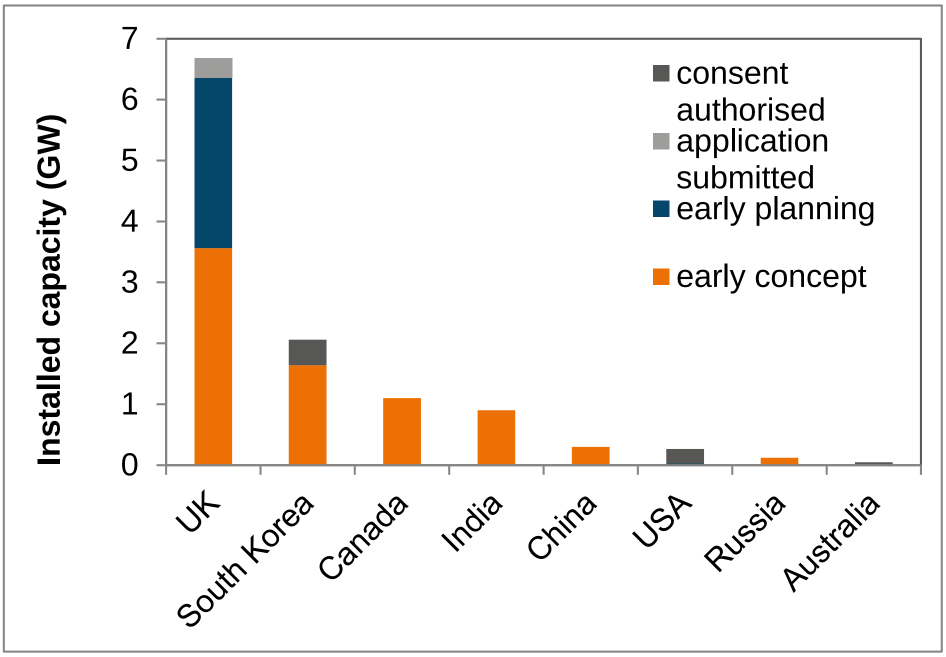
Over 13.7 GW of tidal range is currently planned for deployment, however only 0.7 GW of this has received consent. Major projects include the 0.42 GW Ganghwa Tidal plant consented in the East China Sea, South Korea and the 0.24GW Turnagain Arm Tidal Electric Generation Project in the Kenai Peninsula, US.

There is approximately 10.7GW of non-consented projects in the global pipeline with 0.32 GW under consideration for planning[79], with 2.8 GW at the early planning stage and over 7.6 GW at the early concept stage. With major tidal lagoons proposed at Swansea,

[79] This is solely for the Swansea tidal lagoon in the UK.

Newport, Bridgewater and Cardiff, the UK leads with over 6.7 GW of non-consented planned capacity, however these projects face a wide-range of issues and will have to overcome major political, socio-economic and environmental obstacles if they are to come to fruition. South Korea is also planning to bolster their already significant capacity with another 2 GW, with projects in both the East China and Yellow Seas, whilst Canada continues to develop its 1.1 GW Scots Bay project in the Bay of Fundy (Figure 16).

FIGURE 16: TIDAL RANGE INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

OTEC

Historic developments

The principles of OTEC were first described by Jacques D'Arsonval of France who explained how the difference between the warm surface sea water and cold deep ocean water could generate electricity.[80] The first OTEC facility was built in 1929 by Georges Claude of France in Matanzas Bay, Cuba; rated at 22 kW it required 80 kW to run[81]. It wasn't until 1979 that a net gain of electricity generation was achieved from an OTEC

[80] Cleveland (2014)
[81] Cleveland (2014)

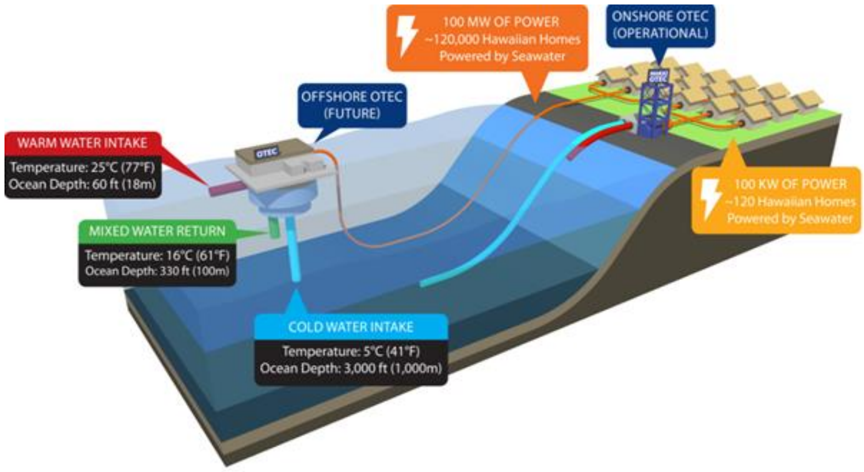
facility at the Natural Energy Laboratory of Hawaii via a via a 15 kW[82] closed-cycle ocean thermal energy conversion mounted on a converted U.S. Navy barge moored offshore[83]. This was quickly followed by a 32kW[84] Japanese system in the Pacific Ocean in 1981. The first open-cycle system was constructed in 1992 operating between 1993 and 1998, with peak production of 103 kW and 0.4 l/s of desalinated water[85]. The first major hybrid prototype (30kW) was constructed in Japan in 2006 by the Saga University.[86]

Ongoing developments

A host of pre-commercial demonstration projects are underway including the Goseong, Korea a 200 kW plant that was completed by the Korea Research Institute of Ships & Ocean Engineering (KRISO) in December 2014[87], while a 100 kW[88] closed-cycle OTEC plant was constructed by Makai Ocean Engineering in 2015 at the Natural Energy Laboratory of Hawaii Authority (NELHA) in Hawaii, with sufficient capacity to power 120 homes (Figure 17 17). The latter project is with a view to develop a much larger 100 MW offshore OTEC plant on the same site. Japan has also opened its own 100 kW pilot plant in 2013 on Kume Island near Okinawa drawing upon much of the expertise generated from NELHA and Makai from their work in the US. Even so some larger projects have failed to materialise such as a 10 MW scale plant planned by both Lockheed Martin and the US Naval Facility Engineering Command on Hawaii.[89]

[82] Net power generation. Rated capacity minus electricity required to run facility.
[83] Cleveland (2014)
[84] Net power generation. Rated capacity minus electricity required to run facility.
[85] Lewis et al. (2011)
[86] Lewis et al. (2011)
[87] Ocean Energy Systems (2016)
[88] Net power generation. Rated capacity minus electricity required to run facility.
[89] (Kempener & Neumann (2014a)

FIGURE 17: SCHEMATIC OF MAKAI OTEC PROJECT

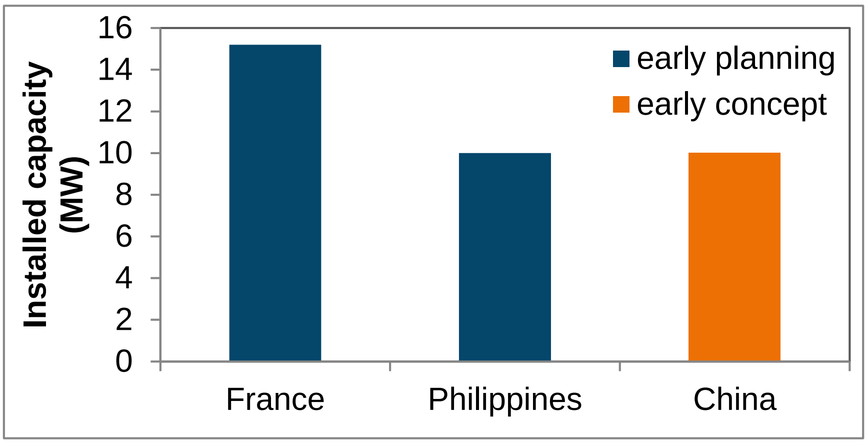


Source: Makai (2016)

Forthcoming developments

In comparison to the other ocean energy technologies there is very little planned deployment of OTEC projects. In total 25 MW of schemes are at the early planning stage (Figurer 18). Two French schemes on the Caribbean island of Martinique account for 15 MW with one of these led by the developer DCNS. A 10 MW is also planned by the Philippines in the South China Sea and a small 0.1 MW scheme by the Netherlands also in the Caribbean. In addition, China has a 10 MW scheme is at the early conceptual stage to be located off Hainan Island. However, given the very early stage of these development, very little OTEC capacity is expected to come online in the near future.

FIGURE 18: OTEC INSTALLED CAPACITY IN DEVELOPMENT



Source: OES (2016a)

Given its relatively early stage of development various pre-commercial demonstration projects are also planned, the largest being a 1 MW plant to be launched in mid- 2016 by KRISO. It will be deployed in the equatorial Pacific Ocean and completed by 2020.[90] The Netherlands' Bluerise will also soon deliver its 500 kW OTEC demonstration plant on the Caribbean Island of Curacao.[91]

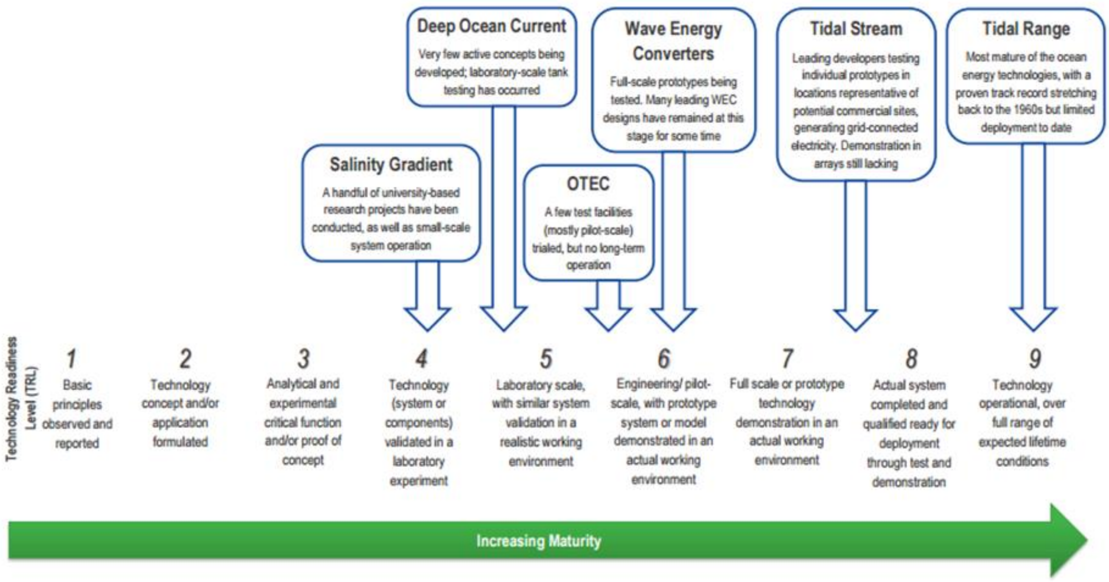
[90] Ocean Energy Systems (2016)
[91] Ocean Energy Systems (2016)

4. INNOVATION CHALLENGES

In comparison to more established technologies, ocean energy is less mature and needs to overcome a wide-range of engineering challenges before costs fall sufficiently for them to enjoy wide-scale deployment. Consequently, this section outlines the major innovation challenges facing ocean energy technologies.

Whilst some cross-cutting challenges face all four technologies we find that there is a different emphasis on innovation for each of these considering they are at different levels of development. Figure 19 illustrates how OTEC is considered the least mature, sitting somewhere between Technology Readiness Levels (TRLs) 5 and 6, with wave energy at a similar stage. Tidal stream is considered to be located somewhere between TRLs 7 and 8 and thus on the brink of commercialisation. Only tidal range is considered to have reached commercialisation. Even so, many of the barriers outlined in the previous sub-section facing these technologies can be addressed by further RD&D.

FIGURE 19: TECHNOLOGY READINESS LEVELS OF MAIN OCEAN ENERGY TECHNOLOGIES



Source: Mofor et al.(2014)

CROSS-CUTTING

There are some cross-cutting technology innovation challenges that face the majority of ocean energy technologies as a whole that include:

- **Advanced materials** – development and utilisation of materials other than steel for the structure and prime mover, such as Steel Reinforced Concrete, rubber or Fibre Reinforced Polymer to provide advantages such as weight savings.[92] Innovative device coatings will also help protect materials from corrosion, water absorption, cavitation etc. in the marine environment, such as Ceramax manufactured by Bosch Rexroth.[93]

- **Control systems** - control systems and software that increase yield by improving the way the device interacts with the sea, e.g. adjusting pitch, yaw, height etc. [94]

- **Electricity infrastructure** - Innovative solutions that reduce the costs of cable installation and operation, specifically solutions to increase the safe range of working conditions for cable installation and trenching, the durability of cables and capacity for dynamic cables to manage device movement.[95]

- **Environmental monitoring** – Remote sensory solutions to better assess the condition and performance of ocean energy devices as a result device-environment interaction, e.g. biofouling, mammal interactions, turbulence. [96]

- **Foundations and moorings** – Innovative methods like 'pin' pile foundations from remote-operated submarine vehicles to reduce array costs. Multiple rotors or devices per foundations or mooring will also help to reduce costs. [97]

- **Installation** - Innovative solutions to improve the speed of installation and reduce the costs of foundation installation such as fast-setting, non-spilling grout, pin piling techniques etc. Similarly solutions for retrieval and disconnection.[98]

- **Integrated array design** – Develop innovative design software tools and models to optimise array performance.[99]

- **Operation and Maintenance** – Reduce time and cost of retrieval of devices and infrastructure via solutions such as ROVs, and on site sensors (cameras,

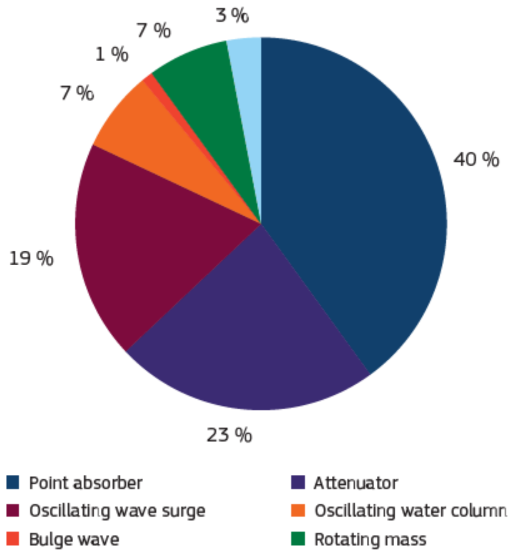
[92] SI Ocean (2013b)
[93] Drew et al. (2009); Lewis et al. (2011)
[94] SI Ocean (2013a)
[95] ORE Catapult (2016)
[96] LCICG (2012); ORE Catapult (2016)
[97] ORE Catapult (2016)
[98] ORE Catapult (2016)
[99] Hannon et al. (2013)

positioning sensors etc.). Reduce the need to maintain or retrieve array components via solutions such as optimised mooring or anchoring systems.[100]

- **Resource characterisation** – Solutions to offer a more detailed and accurate picture of existing and future the ocean energy resource conditions, such as wind speed, atmospheric temperature, wave height, tidal flow etc.[101]

The relative immaturity of wave energy technology can be illustrated by the lack of convergence around one single device design, with R&D funding split between several different device types (Figure 20).

FIGURE 20: DISTRIBUTION OF R&D EFFORTS ACCORDING TO WAVE ENERGY TECHNOLOGY TYPE



Source: Magagna & Uihlein (2015)

The key priority at present for wave energy innovation at present is to improve the performance and drive down the cost and weight of devices' power take off (PTO) systems. As explained in the previous sub-section a host of different PTOs exist for WECs but direct drive (linear) or rotary generators in particular could provide a route to reduced costs within future generations of WEC.[102] In addition, radical integrated PTO/structure technologies

[100] ORE Catapult (2016); Lewis et al. (2011)
[101] ORE Catapult (2016); Hannon et al. (2013)
[102] SI Ocean (2013b)

(such as dielectric membrane and bulge devices) could show promise for long term cost reduction. It is also essential that any improved PTO is scalable and applicable across a wide-range of devices.[103]This is evidenced by Wave Energy Scotland's focus on funding PTO development as a sub-system versus the development of a stand-alone device.

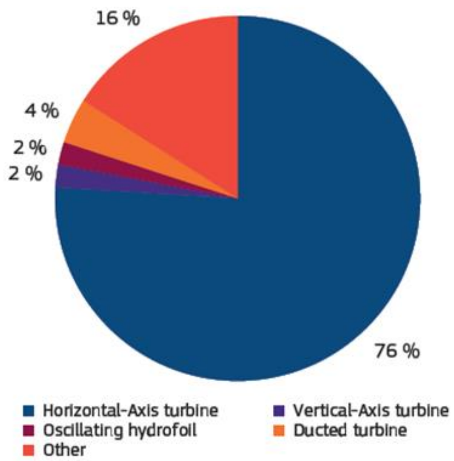
The other main focus is on the WEC's structure and prime mover. Besides the use of alternative materials highlighted previously, it is key that different structural configurations are devised that yield greater power outputs. These will look to ensure the structure's 'geometry and mass will be designed around the resonant frequencies that need to be achieved to maximise energy extraction at a given location'.[104]This approach should initially take precedent over simple scaling up of existing devices.[105]Furthermore, the structure's design would look to improve robustness and reliability in higher energy environments while crucially minimising material costs at scale through the use of distensible materials (e.g. polymer) or low cost materials (e.g. concrete).

TIDAL STREAM

Whilst other device types continue to be developed the main commercial scale application of tidal stream has been a strong convergence around the horizontal-axis turbine, with 76% of R&D funds committed to this one device (Figure 21).

[103] ORE Catapult (2016)
[104] SI Ocean (2013a p.13)
[105] SI Ocean (2013a)

FIGURE 21: DISTRIBUTION OF R&D EFFORTS ACCORDING TO TIDAL ENERGY TECHNOLOGY TYPE



Source: Magagna & Uihlein (2015)

Lewis et al. (2011) explain that horizontal axis turbines are likely to follow a similar development trajectory to wind turbines, where we will see increasingly larger capacity turbines be deployed. This will largely rely on an increase in advances in tidal stream blade design, for example where the blades will sweep a larger area in order to generate more power. Other necessary blade advances will include a reduction in blade erosion to improve durability, including the option of 'self-healing' to damaged blades.[106] Additionally improving blade manufacturing quality is essential to improve blade performance and durability, as well as improving blade design and testing.[107] There are also opportunities for PTO advances not least the use of permanent magnet generators that eliminate the need for gearboxes, thus reducing overall weight, performance losses and maintenance frequency.[108]

It is also expected that new generations of tidal stream device will come to the fore over the next few years. Whilst first-generation tidal stream devices consisted of bottom mounted designs, second-generation devices, such as floating TECs, may look to capitalise on lower installation costs and faster flowing water in the mid/high water column or fix multiple rotors on one foundation structure. Third-generation devices, such as the tidal kite or Archimedes'

[106] ORE Catapult (2016)
[107] ORE Catapult (2016)
[108] SI Ocean (2013a)

screw, which for example may look to move the PTO through the current rather than relying on an area swept by a static prime mover.[109]

TIDAL RANGE

In addition to efforts to progress tidal lagoon and multi-basic technology outlined in the previous section a key innovation focus is to improve the efficiency of the tidal range turbines, which typically have a load factor of 25%. One option could be to develop and implement reversible or bi-directional turbines that generation during both ebb and flood [110]The other major priority is the development of variable frequency generation by developing appropriate gearing system that deliver different rotation speeds.[111]This would offer greater control over tidal range output and means that supply could be better matched with demand. Finally, efforts are being made to develop dynamic tidal power (DTP) technology. This involves the construction of: "a 30-60 kilometre (km) long dam that runs perpendicular to the coast line. At the end of the dam, there is a barrier forming a large "T" shape. The dam interferes with the oscillating tidal waves on either side of the dam, and creates a height difference between the water levels. This height difference creates potential energy, which can be converted into electricity using the low-head turbines that are being used in tidal ranges".[112]

This approach has a number of advantages versus tidal barrage or lagoons. The first is that it doesn't require a very high natural tidal range (1-3m) to create sufficient discharge to deliver appropriate levels of electricity generation. The second is that if two dams are installed at the correct distance from one another (approx. 125 miles) they offer complementary generation profiles, i.e. one is at full output when the other is not generating.[113]

OTEC

The primary focus for OTEC developers is to reach commercialisation, which requires the plants to have a rated capacity of 100 MWe or more.[114] One of the biggest innovation challenges facing OTEC systems is the efficiency of heat exchangers used for evaporation and condensation, which account for between 20 to 40% of the total plant cost.[115]Given the need for long-term lifespans of OTEC plants and their operation in a hostile marine environment, these heat exchangers need to be highly durable. As such present R&D efforts are focused on 'substituting durable, but low-cost, aluminium alloys for durable, but more expensive, titanium ones'[116] that are more corrosion resistant. This would help to increase their load factor and operational lifetime, thus reducing the system's LCOE.

[109] SI Ocean (2012)
[110] Kempener & Neumann (2014b); Lewis et al. (2011)
[111] Lewis et al. (2011)
[112] Kempener & Neumann (2014b); Lewis et al. (2011). Kempener & Neumann (2014b p.17)
[113] Steijn (2015)
[114] Mofor et al. (2014)
[115] Lewis et al. (2011)
[116] Mofor et al. (2014 p.12)

Another pressing innovation challenge for OTEC is the width and length of the pipes that draw the seawater into the system. Huge volumes of water are required by the system, estimated at around 10-20 billion of gallons of water per day.[117] Such a volume of water demands pipes wide enough (~10m in diameter)[118] to deliver 750 tonnes of water per second through the OTEC system.[119]There are however opportunities to draw upon large-riser technology developed from the oil and gas industry.[120]Another major challenge is to install a cold water pipe at a depth of 1000 m that can withstand the harsh deep-water conditions (e.g. pressure, ocean currents, bio-fouling).[121]

[117] NOAA (2014)
[118] NOAA (2014); Kempener & Neumann (2014a)
[119] DOE (2012)
[120] Lewis et al. (2011)
[121] Kempener & Neumann (2014a)

5. SOCIO-ECONOMIC & ENVIRONMENTAL FACTORS

In this section we consider the socio-economic and environmental impacts of ocean energy, as well as the related factors that will serve to either support or constrain ocean energy deployment.

SOCIO-ECONOMIC

Economic growth

A common argument for developing a marine energy sector is the potential global market value it presents. Various estimates exist but one of the most comprehensive is from the Carbon Trust (2011), which suggest that in its ‘high scenario’ for wave and tidal energy deployment the global market could be ‘worth up to c.£460bn (cumulative, undiscounted) in the period 2010-2050, with the market reaching up to c.£40bn per annum by 2050’ (p.1). Whilst the Carbon Trust do not provide any figures for global job creation the IEA’s OES implementing agreement estimate that if ocean energy deployment was on track to reach 748 GW by 2050 this could create approximately 160,000 direct jobs by 2030.[122]

It is important to note that this economic value would be unequally distributed globally and countries with the greatest manufacturing capabilities for exports and deployed capacity are likely to enjoy the majority of the added value. For example, given the UK’s rich heritage in ocean energy the Carbon Trust estimate that ‘the UK could capture c.£76bn of the global marine market or around 22% of the accessible global market (cumulative, undiscounted to 2050 in our high scenario) between 2010 and 2050. This would suggest a gross contribution to UK GDP of c.£15bn over the forecasted period (c.£10bn for wave, and c.£5bn for tidal, and not accounting for any displacement effects)’ (p.1). One study estimated that this could create over 68,000 jobs in the UK from marine energy by 2050.[123] It is important however to consider what the counterfactual would be if public and private funds were redirected elsewhere such as other renewable or non-renewable energy technologies, or even outside the energy sector.

[122] Executive Committee of the OES (2011)
[123] The Carbon Trust (2011)

Energy security

Another important socio-economic consideration is ocean energy's impact on energy security considering the different intermittency and forecasting profiles of the four modes of generation under examination. Wave energy is considered to be a "stochastic" resource similar to wind energy and cannot be accurately predicted over a long time period[124], with accurate forecasts limited to around one week in advance.[125] Furthermore, the variability of wave energy is relatively low over a time period of a few hours but can vary greatly on a seasonal or annual basis.[126] Tidal stream and range energy generation is periodic meaning that highly accurate forecasts are possible over long time horizons.[127] While monthly or annual variations are relatively small, the nature of diurnal or semi-diurnal tides means that variability is very high on an hourly basis[128]. In contrast, OTEC represents a very low degree of variability when located in tropical climes as ocean surface temperatures exhibit little temporal change.

In the context of other forms of intermittent renewable electricity generation being added to the grid, such as wind or solar, ocean energy offers a complementary form of renewable energy that could 'flatten out' the load on the grid and thus improve the synchronicity of electricity supply and demand.[129]For example, wave energy is sometimes out-of-synch with wind energy because whilst waves are generated by winds it takes some time for waves generated by winds offshore to reach the shoreline[130]. Even so, it is perfectly possible for the variable peak of these different forms of ocean energy to coincide not just with one another but other forms of intermittent renewable energy (e.g. wind, solar). Under these conditions the grid can come under immense pressure due to the increased electricity load and raise issues with regards to the integrity of the grid[131]. Conversely, it is also possible that the lowest output from these forms of renewable energy generation could coincide presenting a real-danger of blackouts. Both situations pose problems for energy security and which would require energy storage to resolve.

Quantifying the economic benefits of incorporating marine energy, however one study by Redpoint (2009) that was included in the UK Department of Energy and Climate Change's Marine Energy Action Plan[132] identified that it could save ~£900m ($1.38bn)/year by reducing the need for more intermittent renewable generation capacity provided by the likes of wind and solar.

[124] Iyer et al. (2013)
[125] Executive Committee of the OES (2011)
[126] Lewis et al. (2011)
[127] Uihlein & Magagna (2015)
[128] Uihlein & Magagna (2015)
[129] Blue Energy (2014)
[130] Executive Committee of the OES (2011)
[131] Uihlein & Magagna (2015)
[132] DECC (2010)

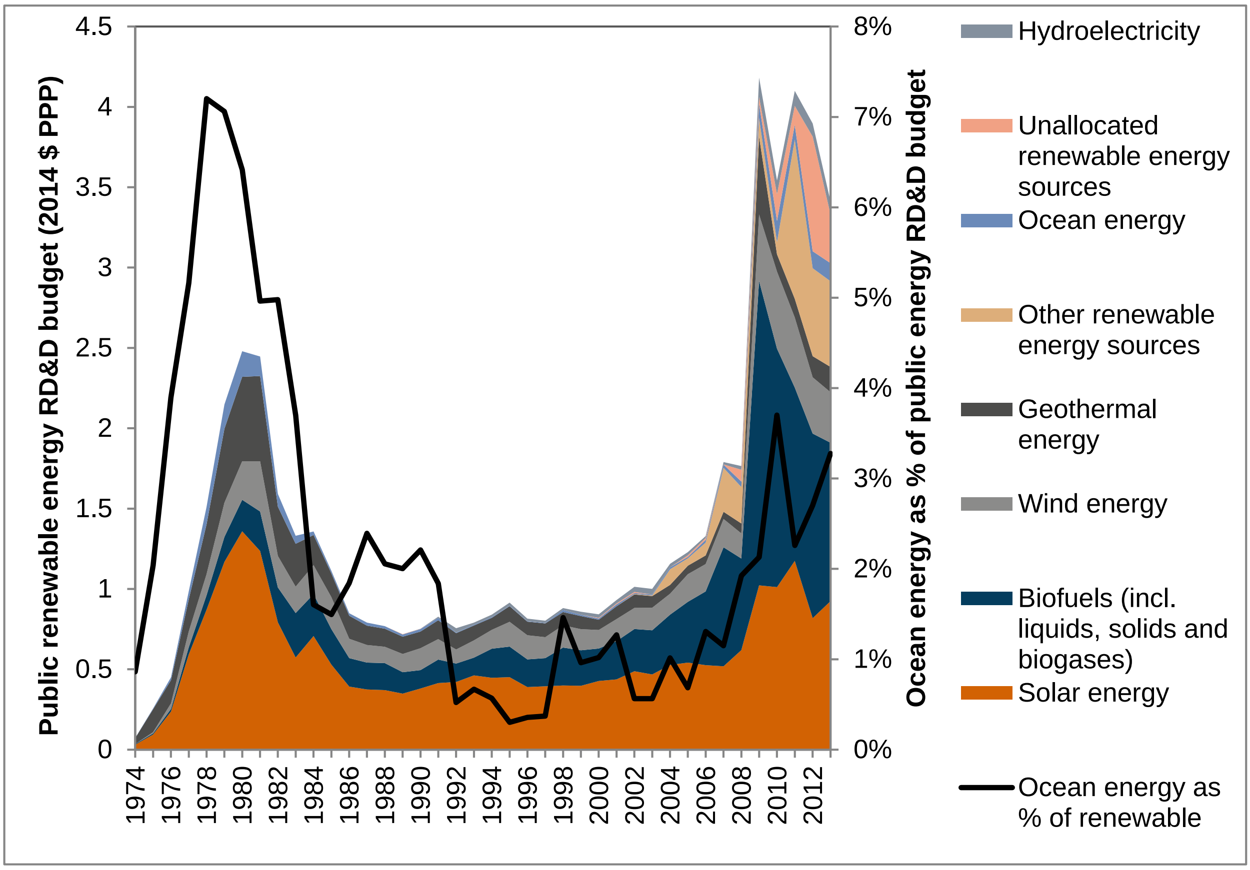
Government policy

Energy innovation policy

Given the relative immaturity of ocean energy technologies versus most other energy technologies much of the focus in terms of barriers to deployment has been on the level and type of energy innovation support for ocean energy. We find that between 1974 and 2013 the global public budget for ocean energy RD&D was $1.6bn.[133] This was however significantly less than for most other renewable energies including solar (US$23.3bn), biofuels (US$14.1bn), wind (US$6.8bn), geothermal (US$6.2bn) and other renewables (US$3bn), higher only than hydro (US$0.8bn). Figure 22 helps illustrate this showing how ocean energy's proportion of total public renewable energy RD&D fell from a high of 7% in the late 1970s to a low of 0.3% in the 1990s. While this did begin to increase once again in 2000s to reach 3.7% in 2010, we find that a much more RD&D support has been committed to other renewable technologies, potentially explaining their greater maturity.

[133] PPP (2014)

FIGURE 22: PUBLIC ENERGY RD&D BUDGETS FOR RENEWABLE ENERGY 1974-2013



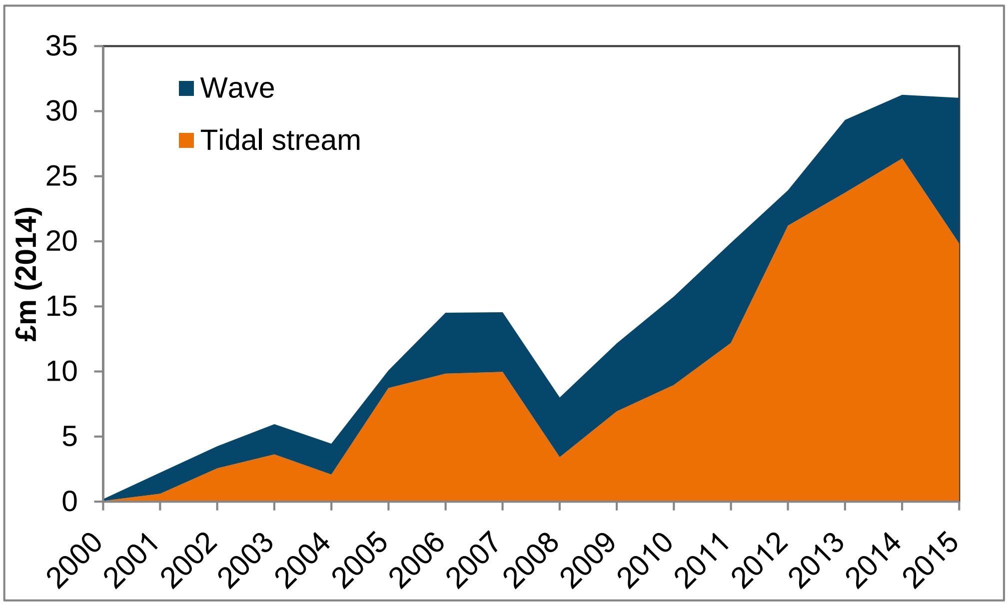
Source: IEA (2016)

Figure 22 illustrates the intermittent nature of ocean energy funding, which has led to a 'boom and bust' funding cycle that has significantly interrupted innovation progress.[134]Other issues include the unrealistic assumptions by funders and developers alike that marine energy could reach commercialisation in a relatively short timeframe versus other energy technologies, leading to an erosion in confidence in the technology from investors following developers' failure to deliver on their ambitious promises.[135]The premature focus on full-scale demonstration has also resulted in an emphasis on device-level versus sub-component innovation (e.g. power take off, prime mover, control system).[136] This has led to a wide-range of characteristically distinct wave energy devices (Figure 5) based on different

[134] Vantoch-Wood (2012)
[135] Jeffrey et al. (2013); Mclachlan (2010)
[136] Renewables Advisory Board (2008)

components, delaying the design consensus that is key to commercialisation.[137] Another issue has been public funders' requirement for developers to secure match-funding from the private sector for these high-risk activities before funds are released.[138] This has resulted in public funds for ocean energy often going unspent, such as the UK's £50m Marine Renewables Deployment Fund. Finally, the conceptual 'bundling' of different ocean energy technologies into the same RD&D programmes despite their different characteristics and maturity[139], leading to a bias towards certain technologies. For example, Figure 23 illustrates how tidal stream has enjoyed twice the public RD&D funding versus wave in the UK since 2000, potentially a function of its greater maturity versus wave.

FIGURE 23: COMPARISON OF WAVE AND TIDAL STREAM FUNDING OF UK RD&D PROJECTS 2000-2015



Note: Includes public funding for basic or applied research, experimental development, demonstration, training, knowledge transfer and networking for wave and tidal stream projects taking place in the UK.

Source: Hannon forthcoming

Public acceptability

Studies of the public acceptability of ocean energy reveal a strong degree of support for the technology. While no global surveys of ocean energy could be uncovered, a survey carried out in 25 EU member-states reveals that 60% of respondents favour ocean energy use,

[137] Magagna & Uihlein (2015)
[138] Winskel (2007)
[139] Mclachlan (2010); Vantoch-Wood (2012)

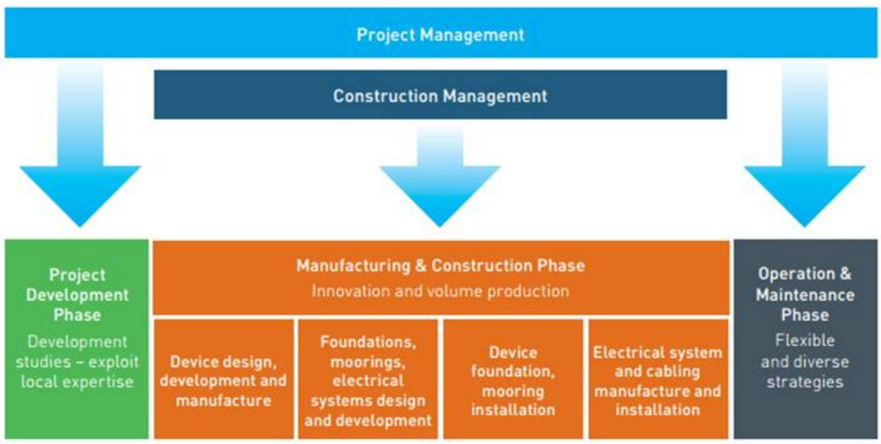
while 24% have a neutral attitude.[140] If we focus on the UK, an international leader of ocean energy development we find that a recent survey from the Department of Energy and Climate Change[141] identified that the level of support for wave and tidal energy sat at 73%, higher than biomass (65%) and on-shore wind (66%), identical to off-shore wind (73%) but lower than solar (80%). Compared to nascent fossil fuel generation such as shale gas (23%) it registers a much stronger degree of support. Similar levels of support for ocean energy were also identified in Portugal, the US and Canada.[142]

While public acceptability for ocean energy seems strong at present Mofor et al. (2014) warn that this is likely to be a function of its relatively low levels of deployment. As installed capacity increases, so too will the public's awareness of the technology, at which point we might see growing concerns about the ocean energy's economic and environmental impacts.[143]

Supply chain

The delivery of ocean energy arrays, as with other energy technologies, requires a large number of supporting companies offering different services (Figure 24).

FIGURE 24: OCEAN ENERGY SUPPLY CHAIN



[140] European Commission (2006)
[141] DECC (2015)
[142] Stefanovich & Chozas (2010)
[143] Uihlein & Magagna (2015)

Source: HIE & Scottish Enterprise (2015)

The Syndicat des Energies Renouvelables (ENR) estimate that approximately 170 companies make-up the ocean energy industry in France split across different sub-sectors including installation, mechanical engineering, electrical engineering, marine engineering, steel works etc.[144]A recent report by BVGA (2015) identify the following sub-components as critical to the ocean energy supply chain:

- Ocean energy devices and subsystem developers
- Wave / tidal farm design, development, ownership and asset management
- Foundations and mooring systems
- Subsea array and export cables
- Substation electrical systems
- Installation ports
- Foundation and device installation
- Subsea cable installation
- Specialist vessels to support O&M, installation, retrieval etc.
- Consultancy and R&D services to support development of test facilities

One of the major challenges facing ocean energy is the under-development of its supply chain and its lacks of capacity to scale up deployment to capture the economies of scale necessary to drive down LCOE. For example, many of the current companies involved in the 'fabrication, assembly and installation of prototypes will not always have the capabilities or resource to scale-up production and deliver the value engineering required for mass deployment'.[145] Proposed solutions involve the entry of Original Equipment Manufacturers (OEMs) who can bring the necessary expertise, finances and specialist facilities to accelerate technology development, as well as 'piggy-backing' on the closely related offshore oil, gas and wind industries that possess many of the required expertise (e.g. subsea array and export cables, support vessels etc.) but also sectors like aerospace and shipping with regards to large-scale device manufacture and survivability. Even so, each ocean energy technology presents specific supply-chain requirements making the

[144] ENR (2014)
[145] Mofor et al. (2014 p.45)

development of a satisfactory ocean energy supply chain more complex and multi-faceted.[146]

A related issue is the lack of the skills required for each of these supply chain components to function with a recent study by RenewableUK identifying that across the wind and marine energy sectors, employers reported difficulty in filling vacancies for 42% of listed jobs between 2011 and 2013.[147]

Infrastructure

While deployment of ocean energy is relatively low, infrastructural constraints do not pose a huge obstacle to market development at present as test centres (e.g. EMEC, WaveHub, FORCE etc.) offer the necessary infrastructure for developers to test their devices.[148] However, as deployment ramps up infrastructural capacity will pose a critical barrier. The first issue is the site infrastructure to harness ocean energy resources such as a subsea electrical system, submarine cable connection, foundations, moorings etc. The second is grid infrastructure, i.e. the necessary grid connection and capacity to transfer the generated electricity to its market. This is often an obstacle as good ocean energy resources are often located in remote and sparsely populated areas.[149] The third is port infrastructure to provide necessary offshore operations and maintenance services, such as ships, dry-dock facilities etc.[150]

This issue is not unique to ocean energy but also affects offshore wind. Consequently, co-locating these two forms of generation could offset some of the high infrastructure costs[151]. A similar co-location of other offshore activities (e.g. shipping, oil and gas, wind) made to discount the provision of the necessary port infrastructure.[152] This infrastructure could be coordinated internationally as demonstrated by the North Sea Countries Offshore Grid Initiative; a consortium of 10 countries around the North Seas designed ‘to maximize the efficient and economic use of the renewable energy resources as well as infrastructure investment’.[153]

ENVIRONMENTAL

Environmental impacts

Environmental impacts from ocean energy technology fall into three main categories.[154] The first relates to the interaction of marine animals with the device. There is a threat of animals colliding with the moving parts of an ocean energy device. For example, tidal stream turbine blades could strike animals or OTEC devices make ‘hoover’ up animals into the system

[146] Mofor et al. (2014).
[147] Renewables UK (2013)
[148] Mofor et al. (2014)
[149] Magagna et al. (2014)
[150] Vosough (2014)
[151] Executive Committee of the OES (2011)
[152] Vosough (2014)
[153] Benelux (2014)
[154] Copping et al. (2014)

given the enormous volume of water they take in. This interaction may be harmful to both animals and the device. Devices could also pose a barrier to animals' natural movements or migration.

The second relates to underwater noise disturbance generated from ocean energy devices such as wave energy and tidal stream devices, which could influence the behaviour of marine animals, not least some species of whales, dolphins, seals, sea turtles, migratory fish and invertebrates. This is because animals tend to use underwater sound rather than light to communicate, navigate etc. and so any ambient noise can affect their ability to perform these functions.[155] Given the low levels of deployment thus far there is a distinct lack of empirical information about how these devices impact upon marine animals.

The final category relates to the potential effects that the installation of ocean energy devices could have on the movement of water by tides, waves, ocean currents and density in reaction to the removal of energy from the marine environment or disruptions to the natural flow of water. However, as Copping et al. (2014) explain it is likely that any major changes will only really be perceptible once large arrays of marine energy devices are in place, unless of course these are simulated via mathematical models like ETI's SmartTide project.[156]

Of all the four technologies under examination it is tidal barrage technology that is generally considered to have the greatest potential environmental impact. Tidal barrages can slow down the flow of water and in turn the amount of suspended sediment, resulting in loss of intertidal habitat. There are conflicting studies on whether it poses a positive and negative effect on the concentration of metals, nutrients, and pathogens within estuarine environment. Similarly, it is unclear whether it is an overall increase in biodiversity, but that there is likely to be a change in the species that make-up the local habitat. Finally, it is expected that even with specially designed turbines to reduce fish strikes, some degree of fish mortality is inevitable. Furthermore, a barrage may increase levels of fish mortality due to predation, disease, habitat loss and disruption to movement. [157]

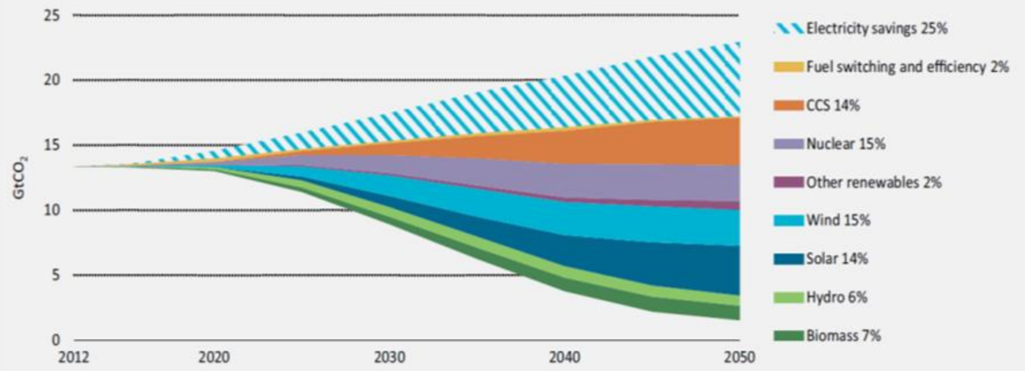
In contrast, some scholars emphasis the environmental benefits that ocean energy technologies could pose. For example Kempener & Neumann (2014b) explain that some tidal range installations, such as the Sihwa barrage in South Korea or potentially the Grevelingen lake in the Netherlands, has improved environmental and ecological water quality. Other environmental benefits relate to renewable energies more broadly such as a reduction in air and water pollution. Finally, ocean energy devices could attract marine animals by providing an artificial habitat or reef that acts as a fish aggregating device and safe haven from fishing.[158]

[155] Clark et al. (2009)
[156] http://www.eti.co.uk/project/smarttide/
[157] Wentworth (2013)
[158] Copping et al. (2014)

Climate change

Renewable energy technology using ocean energy offers an important route for climate change mitigation. Naturally the absolute level of carbon abatement will be in line with the level of future deployment, average load factor, LCOE etc. Unfortunately, no breakdown of the exact level of carbon savings ($GTCO_2$) is offered by the IEA as part of either its GEO or ETP publications (see Market Outlook section). Even so Figure 25 indicates that ocean energy, alongside geothermal and 'other' renewable technologies, could deliver 2% (0.68 $GTCO_2$) of the GHG emissions reduction necessary to limit global temperature rise to 2ºC versus 6ºC by 2050, the latter broadly considered the outcome of business as usual.

FIGURE 25: KEY TECHNOLOGIES TO REDUCE POWER SECTOR CO2 EMISSIONS BETWEEN 6DS AND 2DS

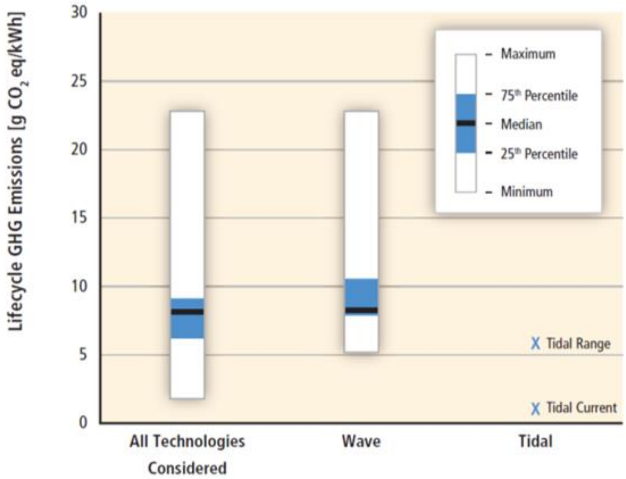


Note: Percentage numbers refer to the contribution of the technology area to the cumulative CO_2 reduction between the 6DS and 2DS over the period 2012-50.

Source: IEA (2015a)

In the context of the perceived GHG emissions savings some studies have undertaken a life cycle analysis (LCA) of ocean energy technologies to offer a more complete picture of their associated emissions. Lewis et al. (2011) present a comprehensive review of LCA studies published since 1980 and find that 'lifecycle GHG emissions from wave and tidal energy systems are less than 23 g CO2eq/kWh, with a median estimate of lifecycle GHG emissions of around 8 g CO2eq/kWh for wave energy' (p.517-8) as demonstrated in Figure 26. They note that the distributions shown represent an assessment of likelihood and that their figure reports the distribution of currently published literature estimates that passed their own quality and relevance controls. Whilst they call for further LCA studies to more accurately uncover the net emissions of ocean energy devices they do conclude that in comparison to fossil energy generation technologies, ocean energy device lifecycle emissions appear low.

FIGURE 26: ESTIMATES OF LIFE-CYCLE GHG EMISSIONS OF WAVE AND TIDAL RANGE TECHNOLOGIES



	All Technologies Considered	Wave	Tidal
Estimates:	10	8	2
References:	5	3	2

Source: Lewis et al. (2011)

6. MARKET OUTLOOK

This section considers the long-term outlook for it ocean energy by examining two long-term global energy scenarios from the International Energy Agency (IEA). The first of these is the World Energy Outlook (WEO) 2015, which offers a vision of what the world's energy sector could look up to 2040 under three scenarios:

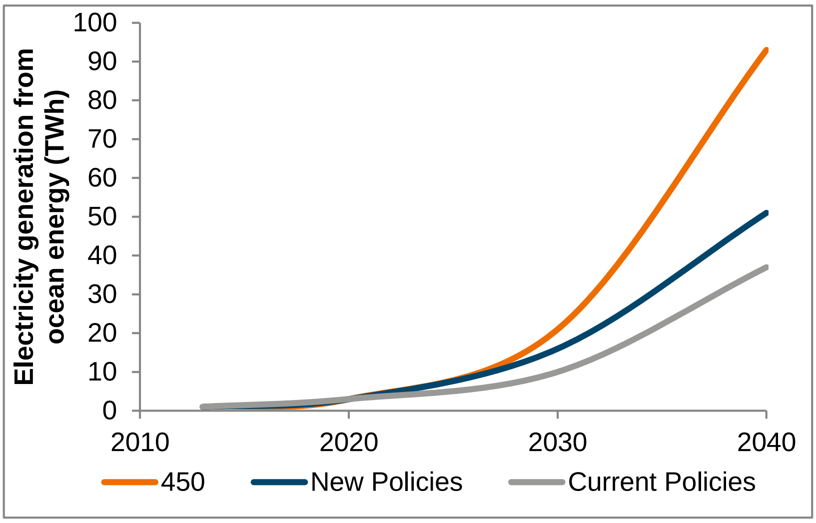
- **New Policies scenario** - takes into account the policies and implementing measures affecting energy markets adopted as of mid-2015 (including energy-related components of climate pledges submitted prior to COP21), together with relevant declared policy intentions.

- **Current Policies scenario** - takes into account only policies enacted as of mid-2015.

- **450 scenarios** - depicts a pathway to the 2 °C climate goal that can be achieved by fostering technologies close to commercialisation.

As is evident from Figure 27 the share of renewable electricity is expected to increase across all three scenarios but is most pronounced in the 450 Scenario with 53% of electricity generation from renewables by 2040 with marine energy contributing 93 TWh per annum under this scenario with 36 GW of installed capacity. Compared to the 1 TWh generated in 2013 this would constitute a huge leap in terms of deployment. However, given the advantage other types of renewables enjoy in terms of cost, supply chain maturity etc. marine energy is still expected to play a relatively minor role under this scenario, accounting for only 0.5% of total renewable electricity generation by 2040. Furthermore, it contributes significantly less under the other two scenarios (Figure 27 and Table 5).

FIGURE 27: ELECTRICITY GENERATION FROM OCEAN ENERGY BETWEEN 2013 AND 2040



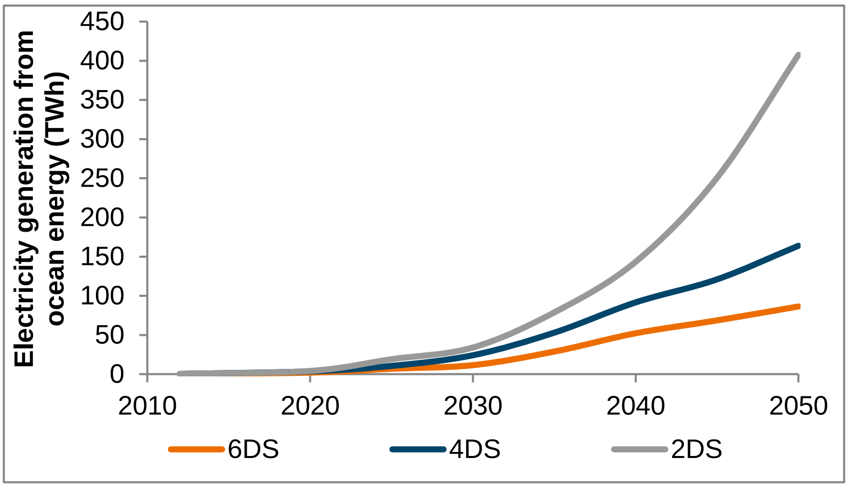
Source: IEA (2015b)

IEA also produces scenarios as part of its annual Energy Technology Perspectives (ETP). The ETP scenarios run to 2050 and explicitly relate to average global rise in degrees centigrade (DS) associated with anthropogenic climate change:

- **2 DS** - this provides at least a 50% chance to limit a mean temperature increase below 2°C.
- **4 DS** - takes into account climate and energy policies being planned or under discussion with a less dramatic temperature increase of 3.7°C.
- **6 DS** - assumes no GHG mitigation efforts beyond policy measures already implemented, which could lead to a 60% increase in annual energy and process-related CO_2 emissions, leading to a temperature increase of 5.5°C.

Figure 28 and Table 5 illustrate the envisaged level of generation from ocean energy under these three scenarios. Overall, the outlook is more positive for ocean energy with 52 TWh generated under 6DS, 92 TWh under 4DS and 144 TWh under 6DS. This is a result of total installed ocean energy capacity increasing from approximately 1 GW in 2013 to 37 GW under 6DS, 71 GW under 4DS and 178 GW under 6DS by 2050. Even so, under all three scenarios ocean energy accounts for under 1% of total renewable electricity generation.

FIGURE 28: ELECTRICITY GENERATION FROM OCEAN ENERGY BETWEEN 2012 AND 2050



Source: IEA (2015a)

Taken together we find that by 2040 the range of electricity generation from ocean energy sits between 51 and 144 TWh and installed capacity between 14 and 62 GW. We also find that ocean energy contributes between 0.3% and 0.7% of renewable electricity generation and 0.1% and 0.4% of total electricity generation.

TABLE 5: OCEAN ENERGY ELECTRICITY GENERATION SCENARIOS BY 2040 FOR IEA'S GEO AND ETP SCENARIOS

	2013 (GEO)	GEO (2040)			ETP (2040)		
		Current Policies	New Policies	450 Scenario	6DS	4DS	2DS
Total electricity (TWh)	23318	43120	39444	33910	41515	40045	35887
Renewable electricity generation (TWh)	5105	11487	13429	17816	11104	13726	19434
Bioenergy	464	1258	1454	2077	1445	1767	2474

Hydropower	3789	5902	6180	6836	5531	5891	6454
Wind	635	2778	3568	5101	2696	3703	5650
Geothermal	72	299	392	541	285	402	595
Solar PV	139	1066	1521	2232	910	1480	2261
Concentrating solar power	5	147	262	937	185	391	1856
Ocean	1	37	51	93	52	92	144
Renewables as % of total electricity generation	22%	27%	34%	53%	27%	34%	54%
Ocean as % of total renewable electricity generation	0.02%	0.32%	0.38%	0.52%	0.47%	0.67%	0.74%
Ocean as % of total electricity generation	0.00%	0.09%	0.13%	0.27%	0.13%	0.23%	0.40%
Ocean installed capacity (GW)	1	14	20	36	22	40	62

Source:IEA (2015b; 2015a)

GLOBAL TABLES

INSTALLED COMMERCIAL CAPACITY

WAVE ENERGY

Status	Country:	Name:	Region:	Number of devices	Estimated date of commissioning	Converter manufacturer:	Converter type:	Converter working principle:	Converter capacity [MW]:	Capacity [MW]:
Fully Operational	China	Wave Pendulum	Daguan island, Shandong Province	1	1999	-	-	Oscillating wave surge converter	-	0.03
Fully Operational	Ghana	Ada Foah	near Ada Foah	1	2015	Seabased	Seabased WEC	Point Absorber	-	0.4
Fully Operational	Portugal	Pico Wave Power Plant	near Cachorro, Pico Island, Azores	1	1999	-	-	Oscillating Water Column	-	0.4

Fully Operational	Spain	Mutriku Wave Energy Plant	off Mutriku	16 (air chambers)	2011	Voith Hydro Wavegen	Wells turbine	Oscillating Water Column	0.25	0.3
Under construction	Sweden	Sotenas Project (1)	northwest of Kungshamn / Smogen	42	2016	Seabased	Seabased WEC	Point Absorber	0.025	1.05
										Operational: 1.1MW **Under construction: 1.1MW**

Source: OES (2016b)

TIDAL STREAM

Status	Country:	Name:	Region:	Number of devices	Estimated Date of commissioning:	Converter manufacturer:	Converter type:	Converter working principle:	Converter capacity [MW]:	Capacity [MW]:
Fully Operational	France	Sabella D10	off the island of Ouessant, Brittany	1	2015	Sabella	Sabella D10	Horizontal Axis Turbine	0.5	0.5
Fully Operational	Italy	Kobold I	Strait of Messina	1	2006	Ponte di Archimede	Kobold I	Vertical Axis Turbine	0.05	0.055
Fully Operational	South Korea	Uldolmok Tidal Power Station (1)	Jindo Island	-	2009	-	Vertical helical blade turbine	Vertical Axis Turbine	-	1
Fully Operational	South Korea	Uldolmok Tidal Power Station (2)	Jindo Island	-	2011	-	Vertical helical blade turbine	Horizontal Axis Turbine	-	0.5

Fully Operational	United Kingdom	SeaGen	near Portaferry, Northern Ireland	1	2008	Marine Current Turbines (MCT)	SeaGen S Mk 1	Horizontal Axis Turbine	1.2	1.2
Fully Operational	USA	Cobscook Bay 1	Maine	1	2012	Ocean Renewable Power Company	TidGen	Horizontal Axis Turbine	0.15	0.15
Under construction	Canada	Cape Sharp (1)	Nova Scotia	2	N/A	OpenHydro Group Ltd.	Open-Centre Turbine	Horizontal Axis Turbine	-	4
Under construction	UK	Shetland Tidal Array	Bluemull Sound, Shetlands	5	N/A	Nova Innovation	Nova 100	Horizontal Axis Turbine	0.1	0.5
Under construction	UK	Inner Sound (1A)	north of Caithness, Scotland	4	2016	Atlantis Resources Corporation, ANDRITZ HYDRO Hammerfest	AR1500, HS1500	Horizontal Axis Turbine	1.5, 1.5	6
									Operational:	

									4.3MW **Under construction: 10.5MW**

Source: OES (2016b)

TIDAL RANGE

Status	Country:	Name:	Region:	Number of devices	Date of commissioning	Converter manufacturer:	Converter type:	Converter working principle:	Converter capacity [MW]:	Capacity [MW]:
Fully Operational	Canada	Annapolis Royal Generating Station	Maine	1	1984	-	-	-	-	20
Fully Operational	China	Haishan Tidal		-	1972	-	-	-	-	0.25
Fully Operational	China	BaiShakou Tidal Power Station		-	1978	-	-	-	-	0.96

Fully Operational	China	JiangXia	Zhejiang Province	6	1980	-	-	-	-	4.1
Fully Operational	China	Haishan Tidal		-	1972	-	-	-	-	0.25
Fully Operational	France	Usine maremotrice de la Rance	Rance	24	1967	Alstom Power	Bulb hydro turbine	Other tidal energy conversion	10	240
Fully Operational	Russia	Kislaya Guba Tidal Power Station (1)	in proximity to Ura Guba, Kola Peninsula, Murmansk	1	2004	-	-	-	-	0.2
Fully Operational	Russia	Kislaya Guba Tidal Power Station (2)	in proximity to Ura Guba, Kola Peninsula, Murmansk	1	2007	-	-	-	-	1.5
Fully Operational	South Korea	Sihwa-Lake Tidal Power Plant	Ansan, near Incheon	10	2011	Daewoo Engineering & Construction	Kaplan turbine	Other tidal energy conversion	25.4	254

Under construction	South Korea	Incheon Tidal Power Plant	Gyeonggi Bay	44	2017	-	-	-	-	1320
Under construction	South Korea	Saemangeum Reclamation Project	Saemangeum	44	N/A	-	-	-	-	400
									Operational: 0.5GW **Under construction: 1.7GW**	

Source: OES (2016b)

LIST OF TABLES AND FIGURES

FIGURES

TABLES

REFERENCES

Aquaret (2012), Download Images and Illustrations. Available at: www.aquaret.com/indexea3d.html?option=com_content&view=article&id=203&Itemid=344&lang=en#Animations [Accessed April 14, 2016].

Aqua-RET (2012), Tidal Stream - European Resource Map. Available at: www.aquaret.com/indexcd1b.html?option=com_content&view=article&id=112&Itemid=255&lang=en.

Atlantis (2016) AR1500. Available at: http://atlantisresourcesltd.com/turbines/ar-series/ar1500series.html [Accessed May 25, 2016].

Barstow S, Mollison D, & Cruz J (2007) The Wave Energy Resource. In J. Cruz, ed. *Ocean Wave Energy: Current Status and Future Perspectives*. pp. 93–132.

Benelux (2014), North Seas Countries' Offshore Grid Initiative. Available at: www.benelux.int/nl/kernthemas/energie/nscogi-2012-report/ [Accessed March 15, 2016].

Blue Energy (2014), *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyon*, Available at: http://ec.europa.eu/maritimeaffairs/policy/ocean_energy/documents/com_2014_8_en.pdf.

BNEF (2015a), *Levelised Cost of Electricity Update for the second half of 2015*,

BNEF (2015b), WIND AND SOLAR BOOST COST-COMPETITIVENESS VERSUS FOSSIL FUELS. Available at: http://about.bnef.com/press-releases/wind-solar-boost-cost-competitiveness-versus-fossil-fuels/ [Accessed May 23, 2016].

Bosc J (1997), The Rance bulb turbines after 30 years' service: feedback of experience. In *Congrès Colloque du 30e anniversaire de l'Usine Marémotrice de la Rance*. Société Hydrotechnique de France, Paris, France, pp. 18–24.

BVGA (2015), Wave and Tidal Supply Chain Development Plan : Supply chain capability and enabling action recommendations, (February).

CEC (1996), *Wave Energy Project Results: The Exploitation of Tidal Marine Currents. - DGXII - Report EUR16683EN, Commission of the European Communities*, Brussels, Belgium.

Charlier RH, & Justus JR (1993), *Ocean Energies: Environmental, Economic and Technological Aspects of Alternative Power Sources.*, Amsterdam, The Netherlands: Elsevier.

Clark CW et al (2009), Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series*, 395, pp.201–222.

Cleveland CJ, (2014), Handbook of Energy. In C. J. Cleveland & C. Morris, eds. *Handbook of Energy*. MA, USA: Elsevier Science, pp. 323–332. Available at: www.sciencedirect.com/science/article/pii/B9780124170131000182.

Copping A et al (2014) An international assessment of the environmental effects of marine energy development. *Ocean and Coastal Management*, 99(C), pp.3–13. Available at: http://dx.doi.org/10.1016/j.ocecoaman.2014.04.002.

Cornett AM (2008) A Global Wave Energy Resource Assessment. *Proceedings of ISOPE*, 8(March), p.9.

Corsatea TD, & Magagna D (2013) *Overview of European innovation activities in marine energy technology*, Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC86301/ldna26342enn.pdf.

DECC (2015) *DECC Public Attitudes Tracker – Wave 15*, Available at: www.gov.uk/government/uploads/system/uploads/attachment_data/file/254725/summary_wave_7_findings_decc_public_attitudes_tracker.pdf.

DECC (2010), *Marine Energy Action Plan 2010. Executive Summary & Recommendations*, London. Available at: www.decc.gov.uk/assets/decc/What we do/UK energy supply/Energy mix/Renewable energy/explained/wave_tidal/1_20100317102353_e_@@_MarineActionPlan.pdf.

Devis-Morales A et al (2014) Ocean Thermal Energy Resources in Colombia. *Renewable Energy*, 66, pp.759–769.

DOE, (2012), *Modelling the Physical and Biochemical Influence of Ocean Thermal Energy Conversion Plant Discharges into their Adjacent Waters*, Available at: www.osti.gov/scitech/.

Drew B, Plummer AR & Sahinkaya MN (2009), A review of wave energy converter technology. *Journal of Power and Energy*, 223, pp.887–902. Available at: http://pia.sagepub.com/content/223/8/887.short?rss=1&ssource=mfr.

EMEC (2016), Tidal devices. Available at: http://www.emec.org.uk/marine-energy/tidal-devices/ [Accessed April 14, 2016].

ENR (2014), *Syndicat des Énergies Renouvelables: Annuaire de la filière française des énergies marines renouvelables*, Available at: www.enr.fr/rechercheadherents.

European Commission (2006), *Energy Technologies: Knowledge-Perception Measures*, Available at: http://ec.europa.eu/research/.

European Commission (2012), Questions and Answers on the outcome of the first call for proposals under the NER300 programme. Available at: http://europa.eu/rapid/press-release_MEMO-12-999_en.htm [Accessed December 18, 2015].

European Commission (2014), Questions and Answers on the outcome of the second call for proposals under the NER 300 programme. Available at: http://europa.eu/rapid/press-release_MEMO-14-465_en.htm [Accessed December 18, 2015].

Executive Committee of the OES (2011), *An international vision for ocean energy*, Available at: www.ocean-energy-systems.org/library/oes-strategic-plans/document/oes-vision-for-international-deployment-of-ocean-energy/.

Falcão AF de O (2010), Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3), pp.899–918. Available at: www.sciencedirect.com/science/article/pii/S1364032109002652.

Hannon M, Skea J & Rhodes A (2013), *ENERGY RESEARCH AND TRAINING PROSPECTUS: Wind , Wave and Tidal Energy*, London. Available at: https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final Reports/RCUK ESF prospectus - WWT.pdf.

Harris M (2016), Atlantis surrenders Crown Estate leases for two tidal energy sites. *HydroWorld*. Available at: www.hydroworld.com/articles/2016/03/atlantis-surrenders-crown-estate-leases-for-two-tidal-energy-sites.html.

HIE & Scottish Enterprise (2015), Marine Energy : Seizing the supply chain opportunity. , (March).

IEA (2015a), *Energy Technology Perspectives 2015. Mobilising Innovation to Accelerate Climate Action*, Paris.

IEA (2016), *IEA Energy RD&D Data*, Paris. Available at: http://wds.iea.org/WDS/Common/Login/login.aspx.

IEA (2015b), *World Energy Outlook*,

Iyer AS et al (2013), Variability and phasing of tidal current energy around the United Kingdom. *Renewable Energy*, 51, pp.343–57. Available at: http://dx.doi.org/10.1016/j.renene.2012.09.017.

Jeffrey H, Jay B, & Winskel M (2013), Accelerating the development of marine energy: Exploring the prospects, benefits and challenges. *Technological Forecasting and Social Change*, 80(7), pp.1306–1316. Available at: http://dx.doi.org/10.1016/j.techfore.2012.03.004.

Kempener R & Neumann F (2014a) *Ocean thermal energy conversion*, Available at: www.irena.org/DocumentDownloads/Publications/Ocean_Thermal_Energy_V4_web.pdf.

Kempener R, & Neumann F (2014b), *TIDAL ENERGY TECHNOLOGY BRIEF*, Available at: www.irena.org/documentdownloads/publications/tidal_energy_v4_web.pdf.

Kerr D (2007), Marine Energy. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 365(1853, Energy for the Future), pp.pp. 971–992. Available at: http://libproxy.uta.edu:2055/stable/25190483.

LCICG (2012), Carbon Innovation Coordination Group Technology Innovation Needs Assessment (TINA) Marine Energy Summary Report. *Energy*, (August 2012). Available at: www.lowcarboninnovation.co.uk/document.php?o=7.

Lee KS (2015), Outlook for Ocean Energy Development in Korea. In *THE EAST ASIAN SEAS CONGRESS 2015*. Available at: http://eascongress.pemsea.org/sites/default/files/file_attach/PPT-S3W3-10-Lee.pdf.

Lewis A et al (2011), Ocean Energy. In O. Edenhofer et al., eds. *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom: Cambridge University Press, pp. 497–533. Available at: http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch06.pdf.

Magagna D et al (2014), *Wave and Tidal Energy Strategic Technology Agenda*, Available at: www.oceanenergy-europe.eu/images/OEF/140215_SI_Ocean_-_Srategic_Technology_Agenda.pdf.

Magagna D, & Uihlein A (2015), *2014 JRC Ocean Energy Status Report: Technology, market and economic aspects of ocean energy in Europe*, Petten, Netherlands.

Makai (2016), Offshore OTEC Diagram. Available at: www.makai.com/images/Offshore_OTEC_Diagram_9495x5161.png [Accessed May 25, 2016].

Mclachlan C (2010), Tidal stream energy in the UK : Stakeholder perceptions study A research report by The Tyndall Centre University of Manchester. , (May).

MeyGen (2014), £51 million MeyGen Financial Close Completed. Available at: www.meygen.com/the-project/meygen-news/.

Mofor L, Goldsmith J, & Jones F (2014), *OCEAN ENERGY: Technology Readiness, Patents, Deployment Status and Outlook*, Paris.

Mørk G et al (2010), Assessing the global wave energy potential. In *Proceedings of OMAE2010 (ASME), 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering*. Shanghai, China.

NASA (2006), *TOPEX/Poseidon: Revealing Hidden Tidal Energy*, Greenbelt, Maryland. Available at: svs.gsfc.nasa.gov/stories/topex/.

Newman S (2016), Technology in the Middle Ages. Available at: www.thefinertimes.com/Middle-Ages/technology-in-the-middle-ages.html [Accessed April 6, 2016].

Nihous GC (2010), Mapping available Ocean Thermal Energy Conversion resources around the main Hawaiian Islands with state-of-the-art tools. *Journal of Renewable and Sustainable Energy*, 2(4).

NOAA (2014), *Ocean Thermal Energy Conversion (OTEC) Technology*, Available at: http://coastalmanagement.noaa.gov/programs/otec.html.

Ocean Energy Systems (2016), *Annual Report Ocean Energy Systems 2015*, Available at: https://report2015.ocean-energy-systems.org/documents/OES-Annual-Report-2015/.

OES (2016a), Ocean Energy in the World: GIS Map Page. Available at: www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/ [Accessed February 25, 2016].

OES (2016b), Offshore installations worldwide - GIS map. Available at: www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/ [Accessed April 1, 2016].

OES - IEA (2015), International Levelised Cost Of Energy for Ocean Energy Technologies. , (May), p.35. Available at: www.ocean-energy-systems.org/library/oes-technical-reports/market-overview/document/international-levelised-cost-of-energy-for-ocean-energy-technologies-2015-/.

ORE Catapult (2016), Wave & tidal innovation challenges. Available at: https://ore.catapult.org.uk/wave-tidal-innovation-challenges [Accessed March 17, 2016].

Pelc R, & Fujita RM (2002), Renewable energy from the ocean. *Marine Policy*, 26, pp.471–479.

Renewables Advisory Board (2008), Marine renewables: current status and implications for R&D funding and the Marine Renewables Deployment Fund. , (January). Available at: www.oceanrenewable.com/wp-content/uploads/2008/02/uk-govt-progress-assess-02-08-2007.pdf.

Renewables UK (2013), Working for a Green Britain & Northern Ireland. , (September).

Repoint Energy Limited (2009), *The benefits of marine technologies within a diversified renewables mix*,

Ross D (1996), *Power from the Waves*, Oxford: Oxford Univeristy Press.

SI Ocean (2013a), *Ocean Energy: Cost of Energy and Cost Reduction Opportunities*, Available at: http://si-ocean.eu/en/upload/docs/WP3/CoE report 3_2 final.pdf.

SI Ocean (2012), Ocean Energy: State of the Art. *EU project Report*, p.79. Available at: http://si-ocean.eu/en/upload/docs/WP3/Technology Status Report_FV.pdf.

SI Ocean (2013b), *Ocean Energy: State of the Art*, Strategic Initiative for Ocean Energy. Available at: http://si-ocean.eu/en/upload/docs/WP3/Technology Status Report_FV.pdf.

Stefanovich MA, & Chozas JF, (2010), Toward Best Practices for Public Acceptability in Wave Energy: Issues Developers Need to Address. , pp.1–9.

Steijn R (2015), Dynamic Tidal Power Technology Advances. *RenewableEnergyWorld.com*. Available at: www.renewableenergyworld.com/articles/2015/01/dynamic-tidal-power-technology-advances.html.

Tethys (2012), La Rance Tidal Barrage. Available at: https://tethys.pnnl.gov/annex-iv-sites/la-rance-tidal-barrage [Accessed May 25, 2016].

The Carbon Trust (2011), Marine Renewables Green Growth Paper. Available at: www.carbontrust.com/media/597981/marine-green-growth-carbon-trust.pdf.

Thorpe T (1999) *A Brief Review of Wave Energy*,

TidalPower (2013), History of Tidal Power. Available at: http://tidalpower.co.uk/history-of-tidal-power [Accessed April 6, 2016].

Uihlein A, & Magagna D (2015), A review of the current state of research in the area of ocean energy. *Renewable & Sustainable Energy Reviews*, Submitted (MAY).

Usachev IN (2008), The outlook for world tidal power development. *International Journal on Hydropower and Dams*, 15(5), pp.100–105.

Vantoch-Wood AR, (2012) *Quantifying Methods for an Innovation Systems Analysis of the UK Wave Energy Sector*. University of Exeter. Available at: https://ore.exeter.ac.uk/repository/bitstream/handle/10871/11122/Vantoch-WoodA.pdf?sequence=1.

Vosough A (2014), *Wave Energy: Technology Brief*, Available at: www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf.

WEC (2010), *Tidal Energy: 2010 Survey of Energy Resources*,

Wentworth J (2013), *POSTNOTE: Environmental Impact of Tidal Energy Barrages*, Available at: www.parliament.uk/briefing-papers/POST-PN-435.pdf.

Whitaker D, (2011), *Sea Turbines : Turning the Tide in Energy Production*, Available at: www.energy.siemens.com/hq/pool/hq/energy-topics/publications/living-energy/pdf/issue-04/Living-Energy4-Marine-Turbines-Tidal-Power.pdf.

Whittaker TJT et al (2004) The Limpet Wave Power Project – The First Years Of Operation. *Scottish Hydraulics Study Group - Seminar on the Hydraulic Aspects of Renewable Energy*, (1997), pp.1–8.

Winskel M (2007), Policymaking for the niche: successes and failures in recent UK marine energy policy. In *International Summer Academy of Technology Studies - Transforming the Energy System*. Available at: www.sts.aau.at/eng/content/download/5044/45551.

ACKNOWLEDGEMENTS

The project team would like to thank the individuals who informed the project's approach, supplied information, provided ideas, and reviewed drafts. Their support and insights have made a major contribution to the development of the report.

WORLD ENERGY COUNCIL

Executive Chair

Hans-Wilhelm Schiffer	RWE	Germany

Deputy Director Scenarios & Resources

Zulandi Van der Westhuizen	World Energy Council	UK

Project Management

Elisa Notarianni	World Energy Council	UK

Lead Author

Matthew Hannon	University of Strathclyde	UK
John Griffiths	European Marine Energy Centre	UK
Angus Vantoch-Wood	Carbon Trust	UK
Max Carcas	Caelulum Ltd	UK
Stuart Bradley	Energy Technologies Institute	UK
Richard Boud	Black & Veatch	UK
Stphen Wyatt	Offshore Renewable Energy Catapult	UK