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The Tidal and Wave Energy Outlook

Opportunities and Challenges




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London Research International Ltd.
Elizabeth House, 39 York Road, London, SE1 7NQ, United Kingdom
Tel: +44 (0)20 7378 7300 Fax: +44 (0)20 7183 1899
E-mail: info@LondonResearchInternational.com
http://www.LondonResearchInternational.com
http://www.GreenTechEurope.com

Company Registration: 5004849 (England & Wales) Registered at the company address.
VAT Registration: 839 504 312

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EXECUTIVE SUMMARY

This report explores the progress of the wave and tidal energy industries.

There are a number of tidal energy technology companies, mainly operating in the UK, with devices capable of producing 1-2.5 MW. These devices are expected to be deployed in arrays in the next 2-3 years. Tidal arrays are unlikely to experience major delays because of their similarity with offshore wind arrays which already exist. The savings to be incurred through the economies of scale achieved by mass production are expected to bring the generation cost into close competition with that of offshore wind.

The number of wave energy technology companies at an advanced development stage is smaller than that of tidal ones. Devices have undergone full-scale sea trials and some are capable of reliably providing 0.75-2 MW to the grid. The deployment of these devices in arrays is expected to take place within 5 years. This will be a slower process than that of tidal array deployment since the interactions between devices is not well understood. A number of cost reduction techniques have been proposed and industry leaders are confident that they will be able to produce electricity at a competitive cost with offshore wind by 2020.

The global potential of marine energy is substantial. Tidal energy potential is estimated at 1 TW globally and approximately 20.6 GW in the UK alone. Wave energy potential is even higher; 2.13 TW and 80 GW for the world and the UK, respectively. The marine energy industry therefore has the potential to be a multi-billion dollar industry for developers.

Some of the current challenges are: the difficulty of building devices that can withstand the harsh underwater environment for many years, the complications involved in deploying large scale arrays, the costs incurred in installing and mooring the devices and the uncertainty of funding for the future of the industry. There are a number of support organisations such as the European Marine Energy Centre in Orkney that are helping to overcome these difficulties. Government support is essential for the development of this industry and the varying levels of support are summarized in this report.

Taking all these factors into account, and utilising projections from industry leaders, this report forecasts the industry size up to the year 2030. The installed capacity in the UK is predicted to be 2.1 GW by 2030, the largest portion of a 10.2 GW global capacity. This projection is conservative in comparison with other forecasts reviewed and discussed.

The report also gives detailed information about some of the leading technologies: Oyster and Pelamis in the wave sector and SeaGen, Flumill, Tocardo, DeltaStream and the SR-2000 for the tidal sector. The technological advantages of each and the difficulties facing them and the industry as a whole are discussed. Business and financial strategies are included as well as detailed information on capital costs and projected costs of each device.

Report Structure

Chapter 1 of this report gives an introduction to the topic and the report. Chapter 2 gives an overview of the tidal and wave energy industries. Examples of the different technology types are given in this section along with details of specific case studies conducted for this report. Chapter 3 discusses the current issues in the wave and tidal industries including challenges, niche markets and systems for support. Chapter 4 looks at the prospects of the sector. This involves mapping the potential of the resource and estimating how much of this potential can realistically be realized. Chapter 4 then gives an overview of the procedures necessary for commercial deployment, relevant government policy, the projected size of the industry up until 2030 and the outlook for potential investors. Chapter 5 details the specific case studies conducted for this report and Chapter 6 gives a general conclusion.

List of Abbreviations

Abbreviation	Explanation
CfD	Contracts for Difference
DECC	Department of Energy and Climate Change
EMEC	European Marine Energy Centre
ETI	Energy Technology Institute
FIT	Feed-in Tariff
IES	Institute for Energy Systems
LCF	Levy Control Framework
LCOE	Levelised Cost of Electricity
LRI	London Research International
MEP	Marine Energy Park
O&M	Operations and Maintenance
PPA	Power Purchase Agreements
R&D	Research and development
ROC	Renewables Obligation Certificates
TCE	The Crown Estate
TSG	Tidal Stream Generator
WEC	Wave Energy Converter

CHAPTER 1: INTRODUCTION

The global renewable power sector has achieved significant progress in technological development to harness renewable energy for power generation. As more offshore wind farm projects are implemented, attention is shifting to the final major renewable source of power: the ocean. Many governments have prepared the largest incentives for the operation of tidal and wave power projects, and hundreds of companies are involved in the development of tidal and wave power generation devices in the world. Skills and knowledge accumulated in the offshore wind power sector can be conveniently utilized for this final frontier of renewable power technology development.

Tidal and wave power generation is more predictable than wind or solar power with practically an unlimited number of available suitable sites. As unpredictable wind power represents larger shares in the power generation mix in many countries, more reliable tidal and wave power will be increasingly welcome, which is heightened by the anticipation that tidal and wave generation will be cost-competitive with offshore wind power.

Despite government support for R&D in the development of tidal and wave power, technological developments have been slow. Only a small number of technology developers can advise when their commercial prototype units will be ready, and virtually no developers can categorically advise when their technology will be deployed at a commercial scale. It is apparent that many developers are struggling to source sufficient funding for their development. According to Professor Peter Fraenkel, co-founder of Marine Current Turbines, £10-20 million is required to develop a commercial prototype of a tidal power device, and £50 million to reach a commercial deployment stage.[1] The cost can be lower for wave power technology but this is often accompanied by an increased investment risk.

Some tidal power developers are backed by large manufacturers such as Siemens and ABB. However, even for those companies, some technical issues remain and further tests are required. These technical concerns stem chiefly from the harsh environment in which these devices must survive. Wave devices especially have to withstand enormous forces for a lifetime of about 20 years. Technical issues can be categorized into two types: those related to the reliability or availability of an installation, and maintenance requirements against a decrease in power generation. Technology developers will be judged to have succeeded when a drastic cost reduction is achieved at a commercial production stage. It appears that few developers have reached a stage where such a vision becomes clear in the near future. A significant number of developers, if not all, currently experience both types of technical issues.

Despite the various obstacles technology developers face, power from tidal and wave energy remains important for the future low carbon society. There are opportunities to work in concord with other renewable technologies and expectations that marine energy could be cheaper to produce than offshore wind power. In comparison with other renewable power technologies, tidal and wave power has a wide variety of device concepts. This fact can be interpreted as a greater flexibility in terms of capacity size and location suitability.

This report will explain the current status of the development of tidal and wave power devices, including the challenges faced by current developers as well as significant future opportunities for

[1] Presentation, All Energy 2013, Aberdeen.

the sector. It is hoped that through the exposure of risks and opportunities in the sector, further support and investment will be mobilised to developers for successful commercial deployment.

CHAPTER 2: OVERVIEW OF THE TIDAL & WAVE ENERGY INDUSTRIES

Estimates suggest that the marine energy industry has the potential to undergo drastic expansion and evolution in the coming decades. The global value of the industry could reach £6 billion by 2035 and £76 billion by 2050.

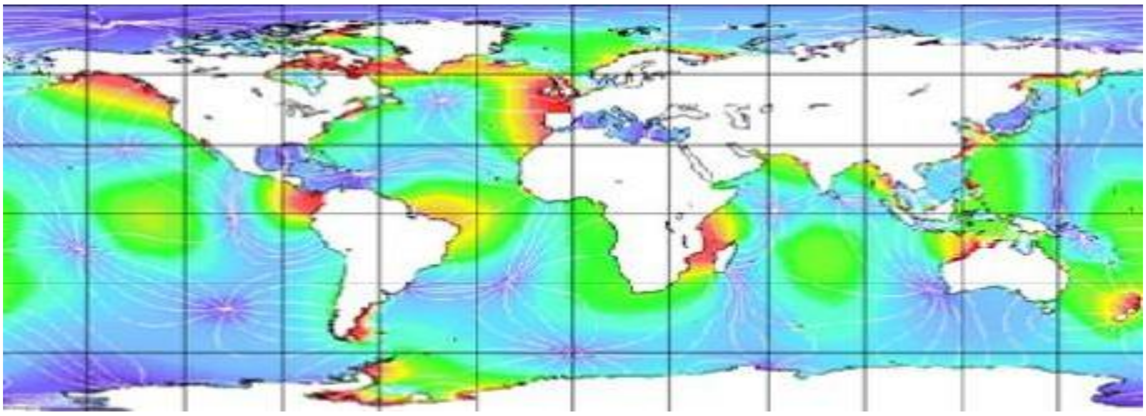
2.1 Tidal Energy

Tidal energy utilises the ebb and flow of coastal tides generated by the gravitational attraction of the moon and sun, as well as the centrifugal forces of the moon orbiting the earth. These forces generate tidal kinetic energy, and it is this energy that marine companies seek to harness. The technologies used are usually turbine based which capture the energy of continuous streams and the currents that flow within rivers and oceans. Gulfs, straits, inlets and other topological features all accentuate already fast streams, creating quicker flows that can be utilised to generate higher powers.

Offshore wind turbines require tall masts which are secured to the seabed. The tall masts offer considerable opportunities to attach offshore wind and tidal turbines to the same mast. The technological input required to install a tidal turbine to the mast beneath the sea surface is not significantly greater than the technology required for a standalone offshore wind turbine project. This hybrid arrangement would also benefit from reduced O&M costs, and would have less of an impact on the local ecosystems than two separate installation sites.

The International Energy Agency (IEA) estimates the total global accessible tidal energy resources to be approximately 17,000 TWh per year. Figure 2.1, generated by Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), displays the resources that are available around the planet. Darker colours represent sites of higher potential power density.

Figure 2.1: Global tidal resource



Source: LEGOS

The waters surrounding the UK clearly exhibit substantial opportunities for this technology. It is estimated that the UK possesses approximately 50% of Europe's tidal resources. Studies have concluded that the UK could have total tidal current resources of up to 16-18 TWh per annum, 40% of which can be attributed to the north of Scotland, where the European Marine Energy Centre (EMEC) facility is based.[2] The industry could create 16,000 jobs and power for 15 million homes in UK while saving 70 million tonnes of carbon emissions annually.[3] The UK is one of the most important countries for the development of the industry. The UK government is offering 5 Renewables Obligation Certificates (ROCs) for tidal and wave projects that will be operational by 2017. Table 2.1 summarises the locations of some of the most active waters in the UK.

Table 2.1: Active tidal sites in UK waters.

Site Name	Location	Water Depth (m)	% of UK resources
Pentland Skerries	Scotland	59	18
Stroma Pentland Firth	Scotland	71	13
Duncansby Head	Scotland	65	9
Casquets	Channel Islands	115	8
South Ronaldsay Pentland Firth	Scotland	58	7
Hoy, Pentland Firth	Scotland	76	6
Race of Alderney	Channel Islands	33	6
South Ronaldsay/Pentland Skerries	Scotland	63	5
Rathlin Island	Northern Island	80	4
Mull of Galloway	Scotland	80	4

Source: Mark Brewster, *Informational and Analysis of Wave and Tidal market in Scotland*, Pure Marine (2011) p7.[4]

2.1.1 Summary of Technologies

Tidal energy technologies can be categorised into three main types: tidal stream generators, tidal barrages and dynamic tidal power. Each of these exploits tidal flow in a different way. This report is primarily concerned with the first category, tidal stream generators. Dynamic tidal power has not yet been tested, so is not a feasible option.

2.1.1.1 Tidal Stream Generators (TSGs)

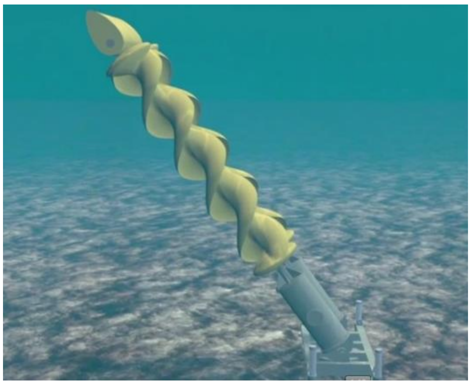
TSGs harness the kinetic energy of the tidal flow directly to drive a turbine. Turbines consist of blades attached to a hub, which together are called the rotor. The flow of the tide past the turbine gives rise to a hydrodynamic effect that causes the rotor to rotate about its axis. This rotor is attached to a gearbox which is further attached to a generator. Electricity generated is transmitted to the shore via subsea cables.

In terms of TSG designs, horizontal and vertical axis turbines are the most popular TSG devices. Alternative TSG designs include the Archimedes screw, which is a revolving helix, or a kite which consists of a tether to the seabed attached to a wing that carries a turbine. Figure 2.2 shows examples of two different turbine designs.

[2] Atlantis Resources Corporation
[3] Marine Current Turbines, *Tidal Energy:* http://www.marineturbines.com/Tidal-Energy
[4] http://www.investni.com/information_and_analysis_of_wave_and_tidal_market_in_scotland_march-2011_tds.pdf

Figure 2.2: Example of Tidal Devices

Source: Tocardo



Source: Flumill

The turbines are usually attached to the riverbed or seabed, the underside of floating platforms or to a tether which is fixed to the ground. They are best installed in areas of high velocity tidal flow or further out, where a constant ocean current is present. These turbine-based technologies are easily scalable and are based on the already well-established principles of wind turbine operation. Water has a density 832 times that of air, therefore in comparison to wind turbines, energy can be extracted using smaller-scale rotors and/or at tidal speeds far slower than winds speeds. The higher level of energy which can be harnessed from the tides comes at the expense of requiring materials with a stronger resistance to erosion. In spite of this general comparison, TSGs should not be compared with wind power in detail. As the design concepts are so different, and the operational environments are so different, it is too difficult to assess whether one is outperforming the other.

Within the industry there are a number of configurations of tidal turbines. Some developers choose to make single turbine units whereas others may have more than one hosted on a particular platform. Table 2.3 gives details on tidal power turbine developers studied in Chapter 5 of this report and their respective tidal turbine designs.

2.1.1.2 Tidal Barrage

Tidal barrages consist of a dam which allows water to flow into a river or bay at high tide, and out again at a low tide. The principal method of electricity generation here is to trap the water in the dam basin at high tide, and release it through sluices as the tide lowers, thereby converting the gravitational potential energy of the water into kinetic energy of the turbines. These turbines then use a gearing system to drive a generator to produce the electricity. Tidal barrages clearly need to be assessed for their impact on the local ecosystem and they have high construction costs.

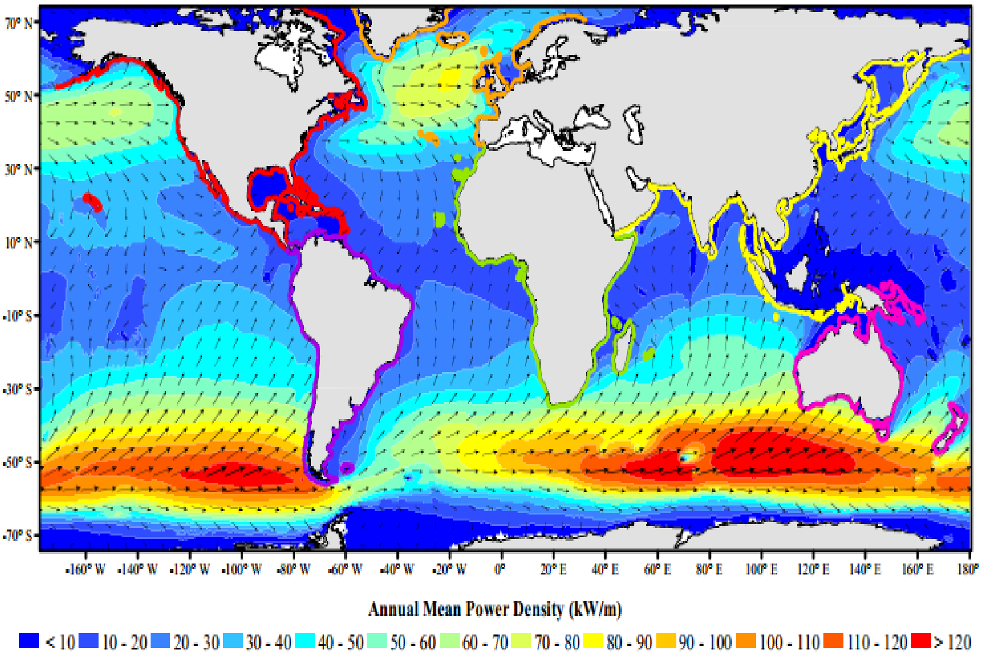
Table 2.2: Specific tidal power case studies included in Chapter 5 of this report

Project	Developer	Type	Capacity (MW)	Development stage	Location	Potential	Advantages
SeaGen	Marine Current Turbines	Dual turbines mounted onto a crossbar which is attached to a mast	2	Commercial unit has been operational for 4 years	Strangford Lough, Northern Ireland	Dependent on array size	Easy turbine access for maintenance. 4 years of successful testing. Demonstrated to have a minimal impact to local ecosystem.
Flumill	Energy Project Management	TSG, Archimedes Screw	2.2	Demonstration. Commercial, 2.2 MW unit to be completed in 2014.	Commercial development, Rystraumen near Tromsø, Norway	Dependent on array size	Design minimises turbulence and prevents vapour cavitation.
SR-2000	Scotrenewable Tidal Energy Ltd	Floating 2 turbine unit	2 MW at 3m/s flow	250kW prototype deployed	EMEC, Orkney, Scotland, UK	Dependent on array size	Streamline device for storm condition survivability.
Tocardo Turbines	Tocardo Tidal Turbines	TSG, Singular turbine units	0.1 – 0.2	0.1 MW available for deployment. 0.2 MW to be completed in 2014	Den Oever, Netherlands	Dependent on array size	Direct drive system (no gearbox).
Delta Stream	Tidal Energy Ltd	TSG, 3 turbines per unit, arranged onto a triangular base	1.2	Demonstration	Ramsey Sound, Pembrokeshire, Wales	10 MW array is the next step. Dependent on array size	Robust. Patented rock foot mounting. Eco friendly.
Kepler Energy	Kepler Energy	2nd generation horizontal turbine	4.4-5.3 MW	Scale Model 1:20.	Newcastle University	Dependent on array size	Large unit capacity.
BlueTEC	Bluewater	Floating platform	N/A	Research and development completed	Hoofddorp, Netherlands	Dependent on array size	Easy to install, inspect and maintain turbines

2.2 Wave Energy

Waves are one of the most concentrated sources of renewable energy, and can be used to produced large amounts of electricity. Figure 2.3 shows how global wave generation potential varies throughout the oceans. In the UK most of the waves arriving onshore are produced in the mid-Atlantic and travel all the way to the UK without considerable loss of energy. The economically recoverable resource for the UK has been estimated at between 50 and 87 TWh per year.[7] [8] This is the largest estimated wave energy potential in all of Europe making potential wave power especially important for the UK.

Figure 2.3: Global Wave Potential



Source: Gunn & Stock-Williams, *Quantifying the Potential Global Market for Wave Power*, International Conference on Ocean Engineering 2012, p3.[9]

Waves are produced by wind blowing over the ocean, but since winds are often strongest in mid-ocean, waves often arrive at land on days when there is no wind in mid-ocean at all. This transport mechanism for wind and storm energy is remarkably efficient and is the reason why wave power is such a valuable resource. Because of the lag between wind and waves, both are unreliable as separate sources of energy; however together they represent a much more useful and constant source. The total power from wind and wave energy combined is not only more reliable than either separately, but also increases in the winter when energy demand is at its highest.

Furthermore, there are a number of potential situations where the existing infrastructure of offshore wind power can be used by wave power models to cut costs and increase efficiency and capacity. These possibilities will be explored in Chapter 3 of this report.

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[7] Ocean Power Delivery Ltd

[8] R.Gross, *Energy Policy 32,* 2004, p1906

[9] http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day3/POSTER%20SESSION%204/Clym%20Stock-Williams,%20E.On.pdf

Wave power can be produced at the shoreline, in the shallow sea (near-shore) or in the deeper ocean (offshore >40m). Each of these locations has advantages and disadvantages which are explored in Table 2.3. There is an extremely diverse range of technologies available, and under development. Some specific case studies are explored in Chapter 5 of this report.

Table 2.3: Comparison of wave devices by location

Location	Advantages	Disadvantages
Onshore	Easy access, low O&M costs, relatively stable conditions. Familiar construction techniques and environment lowers costs. Widely available turbines can be used and cheaply sourced.	The majority of the wave's energy has been dissipated before it reaches land. Low efficiency of oscillating air column model. High impact on coastlines.
Nearshore	Shallow water, access is easier than offshore, low mooring costs. High energy yield, less impact than onshore devices. No need for offshore substations, low infrastructure and transportation costs.	Complicated nearshore terrain, difficult conditions for full underwater foundation. Impact on coastline is noticeable and effect on other users may be greater still. Environmental concerns cause delays.
Offshore	Highest energy density, abundance of potential sites, larger potential resource. Low impact on other users and less environmental impact than nearshore devices. Possibility of combining with offshore wind.	Expensive and complicated mooring, transport and infrastructure procedures. High energy yields means increased wear on the device. High O&M costs.

One way of achieving commercial viability is by sourcing components from standard designs and improving the efficiency of the manufacturing stage as much as possible. It is also important to provide for efficient transport and assembly arrangements. Most wave power devices have a low capacity and must therefore be deployed in an array to meet commercial demand. The difficulties posed by this and recent developments in this field are explored in Chapter 3.

Wave power also has a number of niche markets open to it, especially those with innovative technology that provide more benefits than just power generation. Island communities and areas that are not grid connected can often benefit from wave energy generation and use this as one of their main sources of electricity. It is also possible that clean drinking water can be supplied as a by-product of generating electricity through wave energy. Specific examples of this type of market will be explored in Chapter 3 of this report.

2.2.1 Summary of Technologies

Much of the vital technology used in wave energy, such as bi-directional turbines or low head turbines, is common to most wave energy devices, as well as other renewable energy industries. The growing renewable market is driving advances in turbine technologies which will result in the wave energy industry becoming more efficient and economically viable. There are a number of technological difficulties which are also common to a large part of the wave industry. These include underwater foundations and electronic systems, which are important to the offshore wind and tidal energy sectors. Perhaps the largest technological difficulty is unique to the wave industry: the production of a device that can withstand the worst sea conditions and still generate electricity effectively over a wide range of wave sizes.

Broadly speaking, wave power technologies can be grouped into four categories: attenuators, terminators, point absorbers and overtopping devices. There are many devices that do not fit well into any of these categories and these are mentioned at the end of Section 2.2.1. There is a number of devices in each group and each brings something new to the field. Table 2.4 shows these categorisations listing common components of each.

Table 2.4: Common components by device category

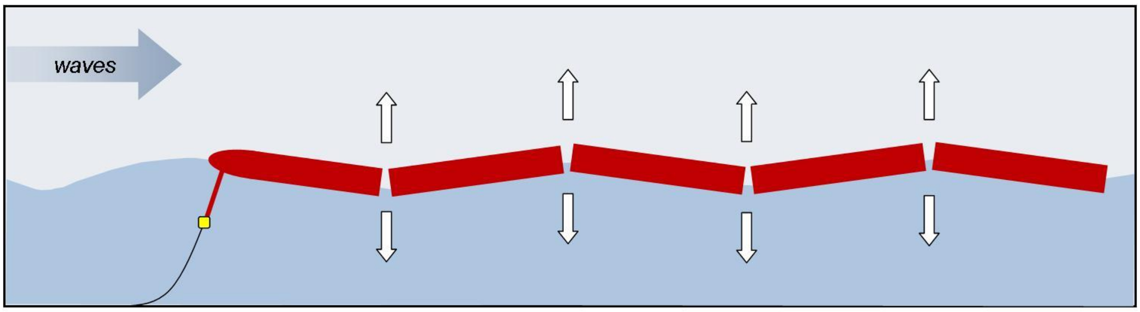
Attenuator	Terminator	Point absorber	Overtopping device
Hydraulic power-off devices, hydraulic motors, accumulators.	Oscillating air column, bi-directional air turbine.	Pump and turbine mechanism, often use sea-water as operating fluid.	Low head turbines, tapered channel.

2.2.1.1 Attenuators

Attenuators are long floating structures orientated normally to the oncoming waves and using hydraulic power-off devices. The vertical movement of the wave causes sections of the device to displace. The displacement of sections of the device in turn causes hydraulic fluid to be pumped through a motor generating electricity. Since the pumping is caused by the relative movement of different parts of the device, the production is dependent on the height and curvature of the wave. These devices are well-suited for offshore use because of their size. These devices operate efficiently in mild swells as well as high seas.

A good example of an attenuator is the Pelamis wave power generation method (Figure 2.4). A long, snake-like device floats on the water and is aligned perpendicular to the oncoming waves. The wave motion under it causes some sections to lift while others fall. Between the device sections, there is a hydraulic ram which resists the motion and pumps high pressure fluid through hydraulic motors thus generating electricity. This fluid is also pumped through smoothing accumulators so that the power generated is less erratic and therefore more useful. This particular device is designed to 'dive under' large waves, thus avoiding damage.

Figure 2.4: Pelamis Wave Device diagram



Source: Pelamis

Due to the high initial costs of these large devices, recent industry trends are moving towards smaller attenuators with a lower capacity. This reduces initial costs and therefore increases the target market. The WaveNET device developed by Albatern is a small attenuator device that has many similarities with Pelamis including the hydraulic motor generating system (see Section 5.2.5).

Research is ongoing into the use of such devices in large arrays to produce electricity on a commercial scale. Even before the commercial option is available, these devices provide a reliable, renewable source of electricity at competitive prices.

2.2.1.2 Terminators

Terminators are normally onshore devices which extract the last of the wave's energy. Most use an oscillating air column to drive a turbine and thus generate electricity. The incoming wave forces air through the turbine in one direction and then back in the other direction as it recedes. For this reason, most devices use a bi-directional turbine. This technique is widely used and well understood, with components readily available thereby helping lower costs.

The Limpet is a good example of the terminator device type and was the first wave energy convertor (WEC) to provide power to the grid. It was installed on the island of Islay in Scotland in 2000 (Figure 2.5).

Figure 2.5: Limpet Wave Device in Islay, Scotland

Source: Voith Siemens Hydro[10]

[10] http://voith.com/en/press/pictorial-material/energy-20358.html#energie

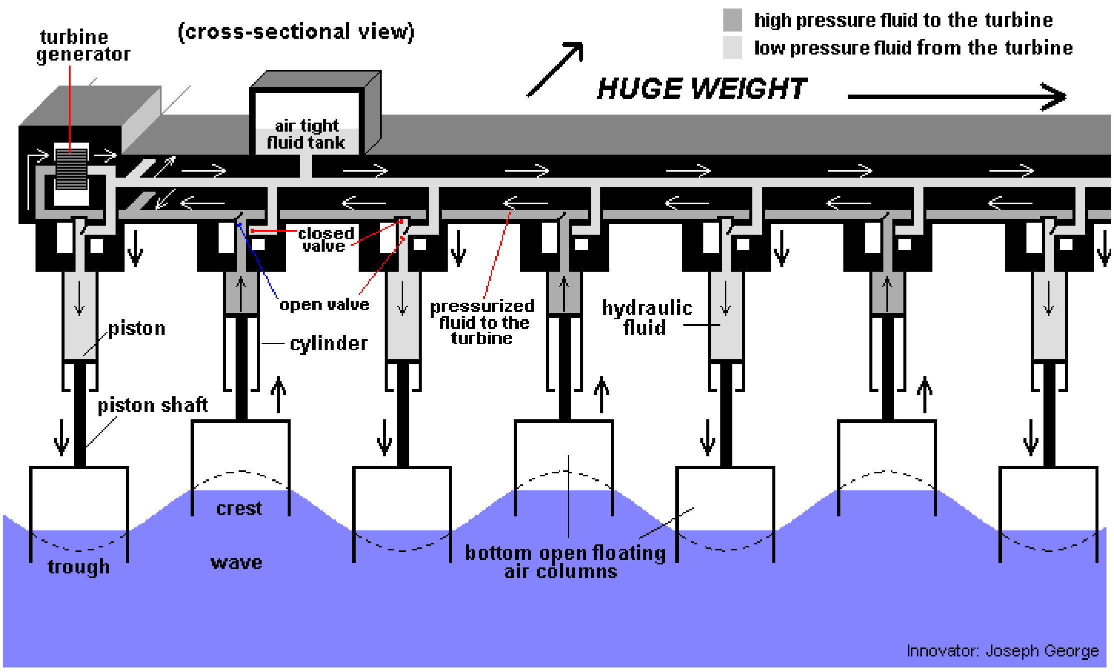
This kind of device causes significant impact on the coastline. For this reason it is not likely to be a major source of energy in the future. A similar technique can be used in offshore terminator devices, exemplified by Offshore Wave Energy Limited's (OWEL) Wave Energy Converter discussed in Section 5.2.3.

2.2.1.3 Point Absorbers

Point absorbers are offshore or near shore devices which are characterized by larger vertical than horizontal dimensions. They use the changing pressure to create vertical movement and thus generate electricity. The simple point absorber device consists of an anchored float which moves vertically up and down in reaction to the pressure differential induced by the waves. This float is attached to the seabed and its motion drives a hydraulic generator. Point generators of this sort are often designed to be deployed in an array to reduce infrastructure requirements.

A more complex use of the point absorber principle is shown in Figure 2.6. This is in effect an array of point absorbers all powering the same working fluid.

Figure 2.6: WEC extending the simple point absorber concept



Source: Joseph George, *Floating Wave Energy Extractor*[11]

The open containers are pumped up and down by the changing pressure of the waves, which occurs under the surface, while the bulk of the device floats on top. The waves in Figure 2.6 represent pressure gradients (not the water surface). This motion is transferred to a hydraulic fluid which is then driven around the system and through a turbine.

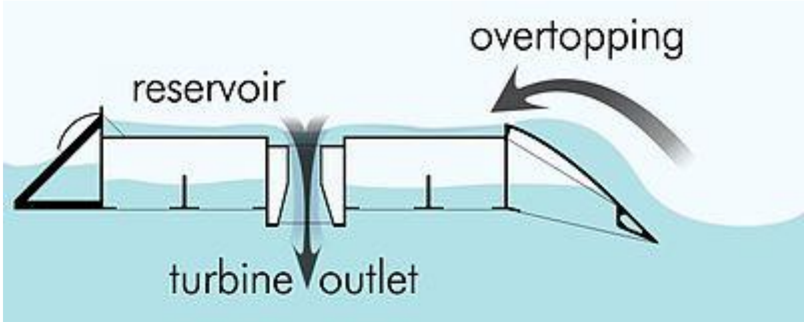
2.2.1.4 Overtopping Devices

Overtopping devices consist of a reservoir into which waves flow, with the water then released through a series of low-head turbines back into the sea (Figure 2.7). Overtopping devices can be used in the onshore, nearshore and offshore environments. The power output of these devices

[11] http://www.physics-edu.org/tech/ocean_wave_power_plants.htm

depends mainly on the height of the waves since this determines the effective head of water in the reservoir.

Figure 2.7: Overtopping type WEC



Source: Wave Dragon[12]

The effective head can be increased using a tapered channel: the wave flowing up the channel is forced to decrease in width and thus increases in height, therefore water can be transferred to a higher reservoir gaining more potential.[13] This method is commonly used in overtopping type devices.

As mentioned above, the definition of these four types is not exact and there are a number of devices that do not fit into any categories. The Oyster 800 is anchored similar to a point absorber but uses the horizontal motion of the waves to create electricity as opposed to the pressure differential. The Penguin by Wello has an eccentric weighting which causes it to spin when the wave impacts. Table 2.5 gives a list of the individual technologies that this report will focus on.

[12] http://www.wavedragon.net/index.php?option=com_content&task=view&id=6&Itemid=5
[13] Tapered Channel Wave Energy: http://taperedchannelwaveenergy.weebly.com/

Table 2.5: Specific wave device case studies included in Chapter 5 of this report

Device	Developer	Type	Capacity (MW)	Development stage	Location	Potential	Advantages
Oyster 800	Aquamarine Power Limited	Nearshore, High-pressure water pumped by wave kinetic energy.	0.8 per unit	Full Scale Testing	EMEC, Orkney	40 MW planned, Dependent on size of array	All electronics onshore. Low O&M costs.
Pelamis	Pelamis Wave Power	Offshore attenuator. Section displacement drives hydraulic motor.	0.75 per unit	2nd generation operational Further testing ongoing	Peniche, Portugal EMEC, Orkney	Dependent on size of array	Extensive successful testing: durable and commercially ready.
Offshore Wave Energy Limited	Wave Energy Converter	Offshore. Oscillating air column.	0.35	Demonstration	Cornish Wave Hub	2-3 MW by 2016, dependent on array size	No moving parts in contact with water.
40South Energy	40South Energy	Offshore / Nearshore, point absorber.	0.15	Commercially available. Larger model is developing	Scilly Isle Airport, various locations Italy	2 MW model planned for 2014	Operates underwater, long lifetime, high capacity factor.
WaveNet	Albatern	Offshore/ Nearshore attenuator. Individual 'Squids' connected in an array.	0.0075 per squid 0.045 per WaveNet	1st Generation Development of larger models	EMEC	0.075 squids and 10 MW arrays in 2015	Low initial cost and O&M cost.

CHAPTER 3: CURRENT ISSUES IN THE WAVE & TIDAL ENERGY INDUSTRIES

3.1 Combining Technologies

There is an increasing interest in combining marine wave and tidal technology with offshore wind turbines to produce electricity for the national grid. While there are currently very few developers actively manufacturing these hybrid technologies, academics and sector specialists are starting to show an interest and to carry out studies, and papers regarding the viability of such projects are beginning to surface.

Green Ocean Energy Ltd. has developed a proof of concept prototype facilitated by a £60,000 investment from NPower for its Wavetreader device. The device aims to effectively combine the wave energy converter (WEC) technology with wind turbine technology. The Wavetreader is comprised of two arms and sponsons which oscillate with the incoming waves in order to drive the hydraulic pistons that are attached to the arms of the device. The entire unit is vertically mounted to the seabed and features a wind turbine as shown in Figure 3.1.

Figure 3.1: Wind Turbine - Wave Energy Converter (WEC) hybrid concept

Source: Renewable-Technology, *Green Ocean Energy Wave Treader, UK.*[15]

Combining the devices would lead to many cost reductions and increased efficiency levels. An overview of the benefits of hybrid systems relative to a separate installation of the two technologies is contained in Table 3.1.

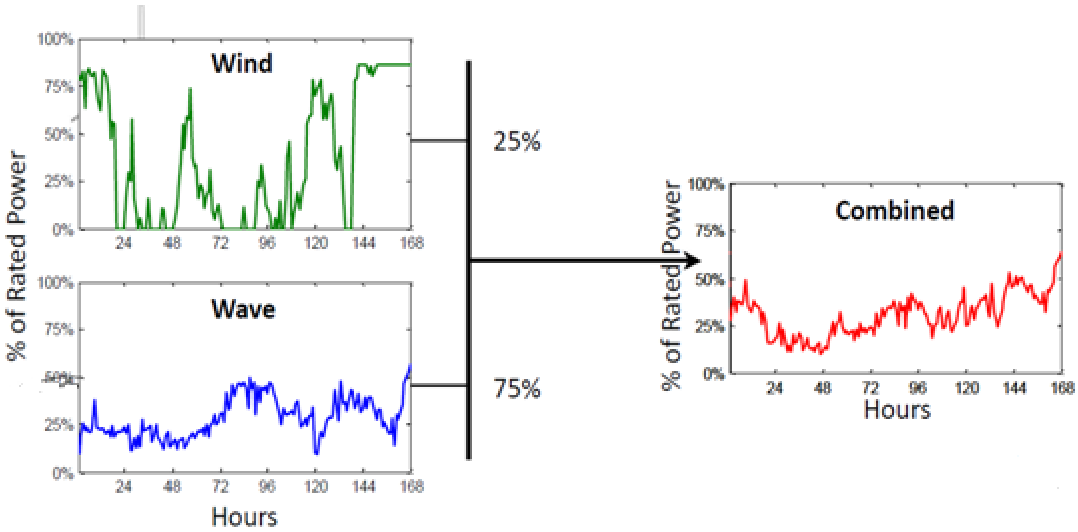
[15] http://www.renewable-technology.com/projects/green-ocean-wave-treader/green-ocean-wave-treader1.html

Table 3.1: Advantages of combined technology

Design and O&M costs	Area efficiency	Grid integration
Maintenance and repairs of the two devices can be scheduled together in order to reduce O&M costs. Only one installation mechanism is required, helping reduce costs.	Increased power generation per unit area. Reduction in site rental costs per kWh. Reduction in wake losses per kWh generated.	An electrical infrastructure for grid integration is common to both the WEC and wind turbine devices. A single infrastructure would reduce installation costs dramatically.

In addition to the increased efficiency achieved by sharing grid infrastructure, combined technologies could give a more reliable supply of electricity. Wind power and wave power are generally out of sync with one another, and therefore they naturally compensate for each other. A farm capturing both would have a more constant supply of electricity which would result in a decreased requirement for storage facilities and backup power stations. Installing the WEC and wind technologies in a 1:3 ratio is the most effective way of creating a smooth power production from the combined source. Figure 3.2 shows how the two unreliable and erratic energy sources combine to create a more consistent, and therefore more profitable, hybrid energy source.

Figure 3.2: Combining outputs of wind and wave devices



Source: Stoutenburg, *Combining offshore wind and wave energy farms to facilitate grid integration of variable renewables.*[16]

[16] http://energyseminar.stanford.edu/sites/all/files/eventpdf/EStoutenburg23Apr2012.pdf

3.2 Creating Arrays

For commercial-scale electricity production, individual wave and tidal energy devices must be placed in a large array. Current device capacities are approximately 2 MW for tidal, and 1 MW for wave devices. A total array capacity of 100-500 MW is thought to be desirable. The latest offshore wind energy arrays are commonly in excess of 500 MW and these are the benchmarks towards which marine energy is aiming.[17] The build-up to large arrays must take place in stages, so that testing and improvement of array design and installation procedures can take place.

As with wind turbines, wave and tidal energy devices will interact with each other when they are deployed in close proximity. This interaction has been extensively modelled. Tidal turbines are expected to produce an interaction similar to wind turbines, which has been directly studied. This interaction will be modified by the differences in design, the pressure and viscosity of water, and the effects of eddy currents and surface waves. Although this is difficult to model, it is thought that results will be similar to those of wind turbines.

In an interview with London Research International, Martin Murphy, Managing Director of Tidal Energy Limited, said that array modelling for tidal turbines was likely to be much more accurate than for wave devices and some models have been adapted straight from those used in the wind energy industry. Interactions between WECs are more difficult to predict since many of the devices represent completely new technologies and affect the waves in ways that are not fully understood. There are a large number of different types of WEC and each will have a different effect on the waves. For example, the floating Pelamis device will have different effects to the OWEL WEC, which is effectively an offshore terminator device.

Understanding detailed interactions between devices entails:

- Modelling multiple incoherent wave sources
- Reflected waves from sections of the devices
- Interference effects between these waves
- Amount of wave energy absorbed or captured
- Depletion behind device and the build up of the wave after depletion

Variables that can be altered to optimize an array's performance are:

- Device spacing (in two directions)
- Orientation of device (this may change between devices to take advantage of interference effects)
- Spacing between rows or blocks
- Individual device response to changing sea conditions

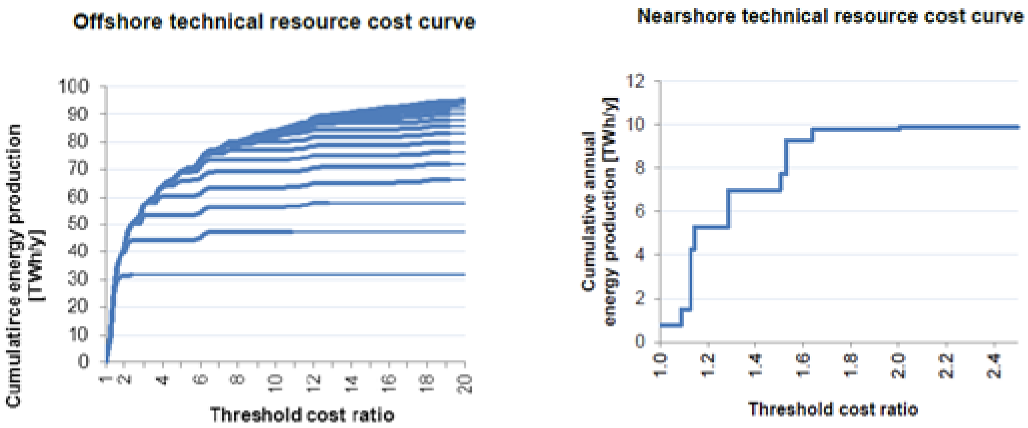
All of the considerations above will change significantly with device type and the sea conditions.[18] Clearly this is an extremely complex effect and its modelling is well beyond the scope of this publication. Some attempts have been made and the first significant arrays will provide data that will

[17] LRI, *Project Management and Supply Chain for Offshore Wind Power Projects (Kh04)*, May 2013
[18] Westphalen et al, *Control Strategies for Arrays of Wave Energy Devices*, Centre for Ocean Energy Research: http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/225.pdf

advance this field in the future.[19] This complexity represents an unavoidable source of uncertainty and risk for the commercial development of wave energy converters.

The Carbon Trust investigated the effect of adding more rows of devices for both the offshore and nearshore cases (Figure 3.3). A row of devices extracts energy from the waves and a generic device was assumed which limits the comprehensiveness of the study.

Figure 3.3: Technical resource cost curves for offshore and nearshore arrays



Source: Carbon Trust, *UK Wave Resource Study,* October 2012

In both cases the costs are normalized (non-recurring expenses are excluded). The energy produced by an additional row diminishes for every row added. If a large number of rows is added then the cost of adding one extra row will not justify the extra electricity produced. The inference from this research is that there are an optimum number of rows for a generic array, in excess of which the array will cease to be cost-effective. More detailed technology-specific studies based on real data are necessary to confirm this. Table 3.2 shows how the cost of arrays for the Oyster 800 WEC by developer Aquamarine are expected to change through each generation and array capacity.

Table 3.2: Estimated cost of Aquamarine's Oyster 800 arrays

Array generation	Array capacity (MW)	Cost (£ million)
1st	5-10	5.5 – 7.0
2nd	20-30	4.5 – 5.5
3rd	>20	3.5

Source: Interview with Aquamarine

3.3 Technological Challenges Facing the Industry

3.3.1 Biofouling

The coating of a structure's surface in algae, micro-organisms or plants in a water-based environment is called biofouling. Biofouling is an important consideration for all marine technology

[19] Child et al., *The development of a tool for optimising arrays of wave energy converter,* Garrad Hassan & Partners Ltd: http://www.gl-garradhassan.com/assets/downloads/The_Development_of_a_Tool_for_Optimising_Arrays_of_Wave_Energy_Converters.pdf

developers. The way in which this process affects different materials, as well as some preventative measures, are detailed in Table 3.3.

Table 3.3: Biofouling on relevant materials

Material	Biofouling	Preventative Measures
Metals	Metals are subject to the formation of biofilms.	Copper has a natural toxicity to marine life and so copper alloys are the preferential choice of material.
Composites	Polymers contain various additives and pigments which could seep out to the surface; these substances are nutrients for marine life. Biofouling on composite material has been observed at four times the quantity present on stainless steel.	Antifouling agents can be incorporated into the composite material.

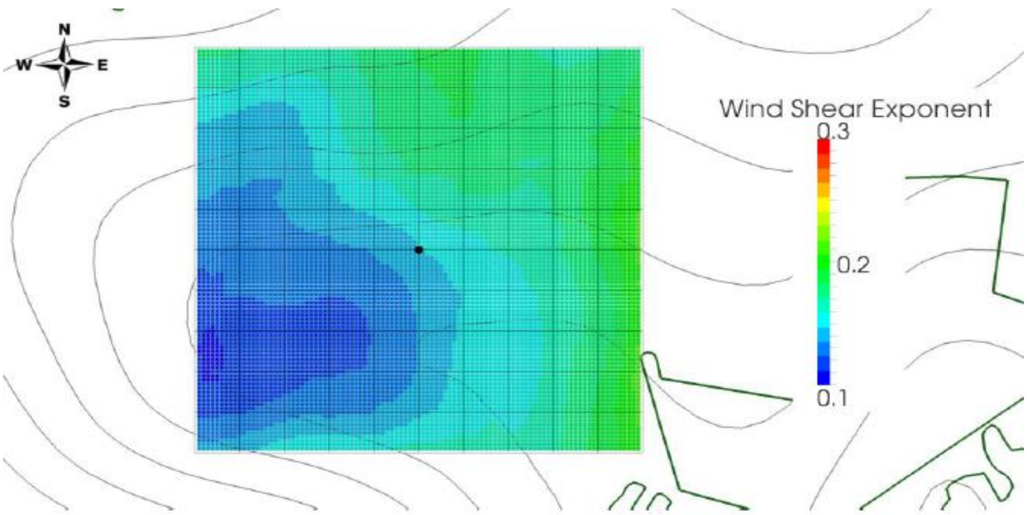
3.3.2 Stresses

Renewable marine energy technologies face harsher conditions than wind turbines due to the very nature of the medium from which they are extracting energy – water. Water has a density of over 800 times that of air, and therefore energy can be extracted at slower flow speeds than that of wind. However, this greater density also subjects the technologies to increased loads and stresses.

In order to withstand the stress levels, as well as the erosion and corrosion that is caused by the operational environment, marine technology materials require very high levels of engineering which is often expensive and can even compromise the performance of the system.

Companies, such as Bristol based 'Digital Engineering', carry out computational fluid dynamics (CFD) simulations to assess site suitability for project developers. Digital Engineering can prepare a site analysis for wind or marine turbine farm developers. An example of a wind shear exponent simulation is included in Figure 3.4.

Figure 3.4: Example of a Digital Engineering wind shear exponent simulation



Source: Digital Engineering

3.3.3 Turbine Blades

Tidal turbine blades are an expensive component of the tidal energy technology. The relatively high expense of marine turbine blades compared with wind turbine blades can be attributed to the environment in which they must operate. The density of water is 832 times that of air and this increased mass per unit volume subjects the blades to substantially higher stresses. As Figure 3.5 and Figure 3.6 show, when a turbine goes from the prototype development stage into commercial production, the material costs become a more substantial portion of the total costs. Once developers begin to produce arrays of their respective device, every effort should be taken in order to minimise the amount of materials used. Furthermore, an increased material usage creates the need for more labour hours.

Figure 3.5: Cost breakdown of a prototype turbine blade

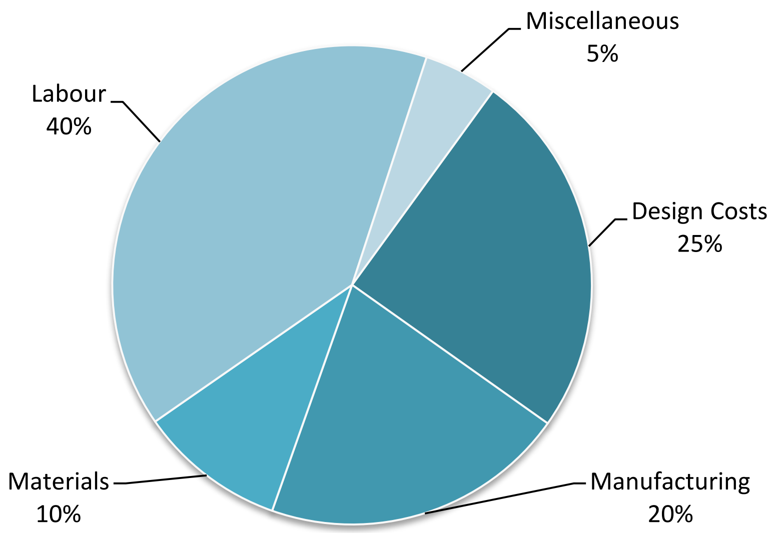
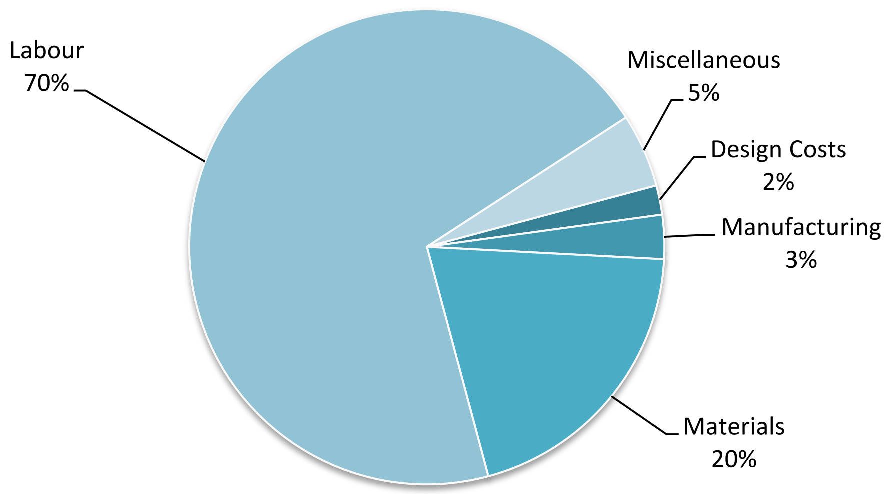


Figure 3.6: Cost breakdown of a commercial turbine blade



3.3.4 Flow Phenomena

Turbulence is the generation of chaotic and unsteady fluid flows. The magnitude of turbulence is characterised by a system parameter called the Reynold's Number: the greater the Reynold's Number the larger the turbulence is. The effect a turbine has on the flow as it recedes from the device – the wake effect – is a manifestation of turbulence. These wake effects put constraints on the feasible power generation, per unit area of an array, of the installation. Wake effects disrupt the homogeneity of the fluid flow such that a turbine located directly behind another will not have a smooth, incoming flow from which it can extract power; turbines have to be separated by distances that allow for the wake effects to substantially diminish. The Reynolds number is proportional to the length scale of the turbine device and the velocity of the tidal flow, but inversely proportional to the viscosity of the fluid.

$$Reynolds\ Number = \frac{Length\ Scale\ \times Flow\ Velocity}{Viscosity}$$

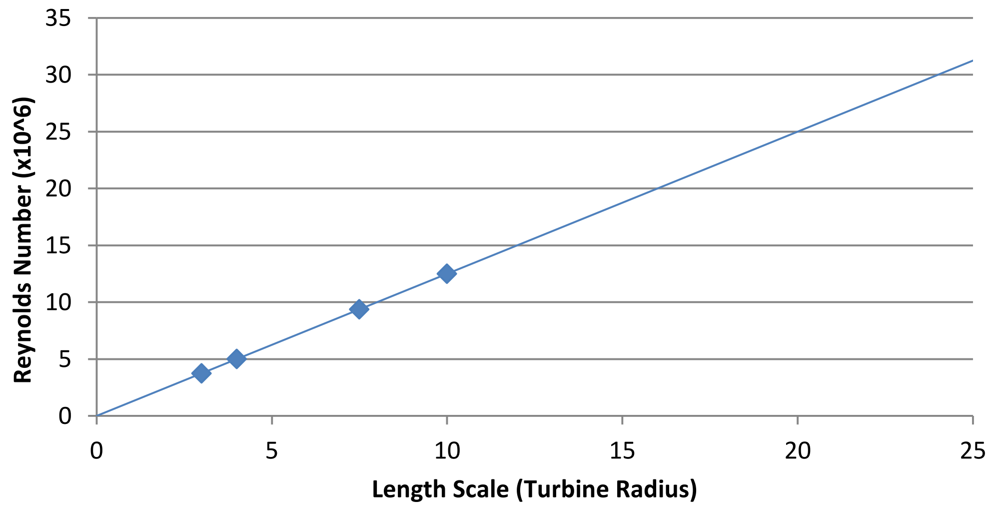
Table 3.4 contains some approximate values for the Reynold's number associated with a 2 m/s tidal flow velocity for tidal turbine technologies. Figure 3.7 shows how the Reynolds number scales with turbine radius.

Table 3.4: Reynolds Number experience by example tidal devices

Technology	Length Scale (Turbine Radius)	Capacity	Reynolds Number ($\times 10^6$)
Tocardo T200	3.0m	200 kW	3.75
Flumill	4.0m	2.2 MW	5.00
DeltaStream	7.5m	1.2 MW	9.38
SeaGen	10.0m	2.0 MW	12.5

[Using a Kinematic Viscosity of Sea-water, at 3.5 degrees Celsius, $\mathbf{1.6 \times 10^{-6}}\ \boldsymbol{m^2/s}$]

Figure 3.7: Relationship between turbine radius and Reynold's Number in sea-water at 3.5 degrees Celsius



In addition to the Reynold's number, the power density generated is of great importance when assessing the feasibility of an array of a particular technology. Although the Tocardo T200 turbine technology produces less turbulence, it has a far smaller capacity factor than that of the others in Table 3.4. It is obvious that of the above technologies, the Flumill device is the clear winner in terms of power density generation. Flumill's advantage has arisen from the innovative Archimedes screw design on which it is based. A case study of the Flumill is included in Section 5.1.2.

A further aspect of flow that can be detrimental to marine technology is cavitation, which is the creation of bubbles of vapour within a liquid. These liquid voids implode when subjected to higher pressures, such as those present around tidal turbines. Cavitation implosions can cause significant wear to the components of TSGs which increase O&M costs.

Turbulence and cavitation effects caused by turbines cannot be completely eliminated, and the vibrational response from these flow phenomena can cause significant damage over a long period of time. The best way to combat this is to optimise the hydrodynamic design of the device.

These phenomena do not significantly affect WECs. Once array deployment begins it is possible that these will become more important in wave as well as tidal energy generation.

3.3.5 Certification

Some authors consider certification to be a key issue in the development of the wave and tidal energy industry.[20] Although not strictly a technological issue, the development of coherent, industry-wide standards is an important ongoing challenge. In the wind industry there was initially a large variation in the types of turbines and information about these turbines. The number of blades, axis of rotation and other aspects were often different between projects. Also, the output and the data acquired for each device was not easily comparable. The introduction of standards helped the wind industry find the best technological solution: the three-bladed turbine that has become commonplace in the last 20 years.

At present the technological variance, especially in the wave industry, is similar to that of the wind industry in its infancy. Although a single ubiquitous device may not be the best solution in this case due to the complex nature of the resource, clearer standards in assessing each device's capabilities would benefit the entire industry.

This process is already underway. The system currently used by Det Norske Veritas (DNV) is risk-based, drawing heavily on the standards used in offshore oil and gas, maritime and wind industries.[21] Aquamarine Power and number of other industry leaders have identified this need and are actively developing these standards.[22] EMEC are also giving the benefit of their outside view on a range of different devices and suggesting solutions that would benefit the industry as a whole.[23] These organisations are working towards the establishment of impartial certification bodies to apply industry-wide standards to evaluate each project from both technological and financial points of view. Further information on the suggested certification techniques and authorities can be found in the EMEC guidelines.[24]

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[20] J. Flinn, *Risk Management in Wave and Tidal Energy*

[21] J. Flinn, *Risk Management in Wave and Tidal Energy*

[22] Aquamarine Power, *Environmental Statement: Oyster 2 Wave Energy Project,* June 2011: http://www.aquamarinepower.com/sites/resources/Reports/2880/Oyster%202%20Array%20Project%20ES%20-%20Main%20Document.pdf

[23] EMEC: http://www.emec.org.uk/services/consultancy-and-service-provision/

[24] EMEC: http://www.emec.org.uk/download/6%20Certification%20%20Guide%20-%20Published%20Form.pdf

3.4 European Marine Energy Centre (EMEC) & Other Support

EMEC was established in 2003 and has deployed more grid-connected marine energy converter devices than any other site in the world . These facilities consist of:

- Five cabled test berths for wave energy converters at Billia Croo. These are located 2 km offshore and 0.5 km apart, with an additional nearshore berth closer to the substation. This site has two waverider buoys which provide detailed wave data to the developers.
- Eight tidal testing berths at depths 12-50m at the Fall of Warness. This site has a high tidal velocity due to a funnelling effect produced by the surrounding islands. Detailed current measurements have taken place to characterise the conditions and an onshore weather station provides real-time data for the site.
- Scale test sites for wave and tidal energy converters in comparatively gentle conditions adjacent to the Orkney mainland. These sites are equipped with berths and mooring foundations.
- Substations at the full-scale wave and tidal sites which monitor the output from the devices. The quality of the electricity is analyzed to ensure the devices can provide a smooth and reliable supply. If this requirement is met, these substations have the capability of providing this electricity to the national grid.
- A suite of offices and data acquisition facilities located mainly in Stromness. These facilities allow real time monitoring of the conditions and device performance.

EMEC carries out Wildlife Observation Programmes to ensure each of the devices is operating in a non-harmful way. The Programmes include monitoring species and observing behaviour around the devices and infrastructure. Inshore crustaceans are also monitored and EMEC works with the local fishing communities to ensure that the two projects can not only co-exist, but also profit from mutual benefits.

During the testing of the Oyster wave energy device, acoustic characterisation was carried out to monitor the operational noise in the context of the ambient background. The testing provided a robust and repeatable methodology to enable to developers at EMEC to monitor the noise output from their device.

EMEC also has a set of procedures and practices in place for gaining consent, installation, operation and decommissioning of wave energy devices at the test centre. In cognisance of these, Aquamarine Power is developing in-house procedures which will be implemented in parallel to ensure a high standard of practice across the organisations and compliance with contractual obligations, health, safety and the environment.

EMEC was founded with public money but has been self-supporting since 2010. So far it has contributed more to the economy of Scotland and the UK than the value of the initial set-up costs. Over the period 2003-2012 there was approximately £140 million gross value added to the economy, 86% of which was to Scotland and 43% to Orkney alone.[25] As further evidence of Orkney's investment potential, it was announced in September 2013 that permission had been granted in the region for the largest tidal energy project in Europe. Aquamarine Power Ltd and Pelamis Wave

[25] Renewable UK, *Wave and tidal energy in the UK*, February 2013

Power are to share the £13 million investment by the Scottish Government's Marine Renewables Commercialisation Fund.[26]

Some other facilities similar to EMEC are noted in Table 3.5. At present there are plans to build centres in a number of countries, all of which should be in place within 5-10 years. According to Tidal Energy Limited, one of the key reasons the DeltaStream project was not taking place at a testing facility was the limited availability of berths and the waiting list for these facilities. This experience exemplifies the popularity of testing facilities such as the site operated by EMEC, and their importance to the development of the wave and tidal energy industry. Table 3.6 summarises some other funding sources available to marine energy developers.

Table 3.5: Marine energy test facilities

Facility	Resources
Pacific Marine Energy Centre, Oregon, US	Wave and tidal converter test site, open for developers by 2016.[27] The Marine Energy Centre will belong to the Northwest National Marine Renewable Energy Centre (NNMREC) constituted of Oregon State University and University of Washington.
Fundy Ocean Research Centre for Energy, Nova Scotia, Canada	Able to support 3 tidal turbines totalling 5 MW at present. Grid connection is also currently being developed.[28]
South West Marine Energy Park, SW UK	Hydrodynamic test facility at Plymouth University. Scale WEC test site at Falmouth Bay. Tidal test site at Lynmouth with a peak flow of 2.5m/s. Wave Hub with four grid connected, full size berths for WECs with a capacity of up to 5 MW.
Hawaii National Marine Renewable Energy Centre	The island of Kaneohe can support up to four WECs between 300-500 kW. Maui, Makapu'u islands are in the process of establishing test facilities for WECs. 60m and 80m grid-connected berths in December 2014.
National Ocean Technology Centre, Tianjin, China	Four tidal test berths each with 1 MW capacity in Zhoushan, Zhejiang. Testing site of 3 WECs test berths each with 100 kW capacity in Dawanshan, Guangdong. More than £8 million funding was provided by the Chinese government for test site construction up to 2013.
Bimep, Basque, Spain	Test centre with 4 grid-connected berths totalling 20 MW set up. Floating offshore wind trials are planned for.

[26] Philip, *Europe's largest tidal energy project gets go-ahead in Scotland*, Financial Times, 15/09.13: http://www.ft.com/cms/s/0/abb0b554-1e05-11e3-85e0-00144feab7de.html?siteedition=uk#axzz2fQSD9vc8
[27] Oregon Wave Energy Trust, *Wave Energy Advocates Set Funding*, August 2013: http://www.oregonwave.org/tag/pacific-marine-energy-center/
[28] Fundy Ocean Research Centre for Energy: http://fundyforce.ca/technology/

Table 3.6: Funds available for marine energy development

Fund	Source	Scope
Saltire Prize	Scottish Development International	£10 million for the team who produces most energy from marine sources in Scottish waters. Minimum 100 GWh and 2 years continuous supply
Marine Renewable Proving Fund	UK Government	£22 million to speed up the development of full-scale prototypes
WATERS 2	Scottish Enterprise	£6 million for renewables in Scotland, focusing on wave and tidal power
Marine Renewables Commercialization Fund	The Scottish Government	£18 million to promote prototype devices for use in commercial arrays
European New Entrants Reserve	European Commission	€4.5 billion total for various energy technologies including wave and tidal energy generation
Marine energy: Supporting array technologies	TSB, Scottish Enterprise and Natural Environment Research Council	£10.5 million for innovative technologies that can be deployed in arrays
Low cost tidal stream arrays	ETI	Unspecified amount intended to support the development of tidal stream arrays
Taking wave energy to 10 MW	ETI	Unspecified amount to improve the capacity of wave energy converters
European Regional Development Fund	European Commission	Amount based on requirement, designed to benefit regional or local economies
Low Carbon Innovation fund: Marine Energy Demonstration Fund	DECC	£20 million between two projects focusing on developing arrays

3.5 Niche Markets & Novel Uses

Although the marine energy industry has huge potential for commercial electricity generation, many argue that its key strength is its ability to take advantage of niche markets. The current generation cost of marine energy electricity is not competitive compared with electricity generated through other sources. Small and remote communities might not be connected to the grid and electricity generation by a marine energy converter may be an attractive option over grid-connection at the present level of costs.

The WaveNET developed by Albatern is a small WEC that does not have a high capacity at present. The company is primarily looking to increase the capacity and commercializing their devices. They also believe that a strong market will be in the supply of electricity for remote communities. The WaveNET device has a levelised cost of electricity (LCOE) comparable to that of a diesel generator.

Aquamarine's Oyster 800 works by pumping high pressure water through a shore based generator. This system generates electricity, however with some modifications, it could also be used to provide a supply of high-pressure sea-water onshore. The desalination of sea-water requires high-pressure. Therefore, for an island community, the Oyster system could provide both the electricity and potable water. The company has identified potential markets for desalination using their device in Oceania, South Africa, the Middle East and North Africa.[29] According to Aquamarine Power however, the principle opportunity for their device relies on utility-scale developments, the goal of commercial electricity generation takes precedence in most cases.

Currently, Tocardo produces tidal turbines rated at 0.1 and 0.2 MW. They are planning to increase this capacity in 2014 to have 10 MW arrays functioning by 2018, and 100 MW arrays by 2023. The smaller models can be used in rivers with slight modifications to the rotor design. The market for TSGs in rivers is thought to be large and Tocardo are actively exploring this possibility.

3.6 Summary of the Technology Outlook

Wave and tidal technologies have reached an advanced stage, capable of providing an output of the order 1-2 MW. Many devices have been tested and are, or are close to being fully commercially available. Some devices have identified niche markets they can work towards. These advances and the possibility of combining marine technologies with other renewable energy technologies are exciting prospects for the future of the industry.

The more immediate priority of the industry is to achieve commercial viability. This will be achieved by creating and testing the first arrays, and then developing arrays of increasingly large capacities (Figure 3.8). It is therefore hoped that the benefit from the economies of scale and the increasing experience with the devices will lead to lower electricity generation costs. To be a significant source of renewable energy, wave and tidal must provide electricity at a rate comparable to that of the other sources, as well as becoming capable of providing a large, reliable supply.

[29] Aquamarine Power: http://www.aquamarinepower.com/sites/resources/Reports/2470/Renewable%20desalination%20market%20analysis%20-%20Oceania%20South%20Africa%20Middle%20East%20and%20North%20Africa.pdf

Figure 3.8: Possible array of tidal turbines

Source: Scottish Power Renewables

According to Aquamarine Power, the potential for commercial-scale electricity generation should attract major investment which is essential for the development of the technology. Aquamarine is well on the way to developing a technology that is cost effective and reliable. Once the technology has been developed the company will look into niche markets and other issues will be addressed.[31]

Some key areas in lowering the cost of wave and tidal energy electricity are the sourcing of components from existing manufacturers, the set-up of an efficient supply line, the limitation of transport and installation costs and the development of coherent industry-wide standards. It is important at this stage in the industry that communication within a wider industry including manufacturers, with investors and with relevant government organisations, takes place with the aim of stimulating growth and attaining commercial viability.[32] The potential of the sector and the investment environment will be addressed in Chapter 4.

[31] Correspondence with Martin McAdam of Aquamarine Power

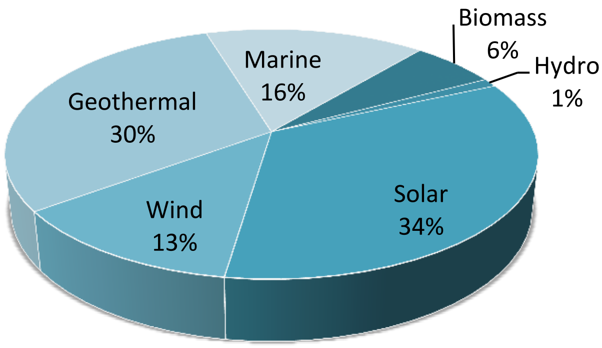
[32] Huckerby et al., *Implementing agreement on ocean energy systems: Next five* years: http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/424.pdf

CHAPTER 4: PROSPECTS OF THE SECTOR

4.1 Potential of the Resource

The potential of wave and tidal energy as a resource has been the subject of much debate over the past few decades. Estimates have been made at significantly differing levels, although more recently estimates have tended to be closer with the intermodal dispersion becoming narrower. Figure 4.1 shows marine energy's share of global power potential as compared with other renewables. Table 4.1 looks more closely at the theoretical potentials for different types of marine energy.

Figure 4.1: Global technical potential comparison for renewable energies



Source: Frils-Madsen et al., *Wave Dragon Multi-MW Ocean Energy Power Plant*[33]

Table 4.1: Estimates of the global theoretical marine energy power and generation potential

Capacity (GW)	Annual energy generation (TWh)	Source
5,000	50,000	Marine Current Power
20	2,000	Osmotic Power
1,000	10,000	Ocean Thermal Energy
90	800	Tidal Energy
1,000 – 9,000	8,000 – 80,000	Wave Energy
17,000	15,0000	Oceanogenic Power

Source: Implementing Agreement on Ocean Energy Systems (IEA-OES), Annual Report 2007

Of this total resource, the UK is generally considered to possess a large portion due to its fortunate positioning. The Carbon Trust estimates the global value of this resource to be £340 billion by 2050 and the UK's share at about £76 billion.[34] It is therefore important for financial as well as environmental reasons to develop this industry and realize this potential.

This section evaluates this potential separately for tidal and wave energy for the world, and for selected countries including the UK.

[33] http://www.slideshare.net/ErikFriisMadsen/icoe-2012-wave-dragon-b
[34] *Wave and Tidal Energy in the UK,* Renewable UK

4.1.1 Tidal

In global terms, the Bay of Fundy on the Atlantic coast of North America receives the highest tides on the planet. Numerical simulations by Justine M. McMillan and Megan J. Lickley, of Arcadia University, Canada, revealed that the bay and the surrounding area called the Gulf of Maine have high tidal energy potential. [35] In particular, the Minas Passage was identified as a viable site for high velocity, turbine installations. It is estimated that 6.9 GW of power can be extracted from the passage. However, in order to extract this quantity from the available power resources, the use of turbines would cause a resonance in the surrounding tidal system. This resonance would result in the Minas Basin tidal amplitude subsiding by 35%, and a 15% increase along the coast of Maine and Massachusetts which would have a significant, harmful impact on the environment. Utilising a fraction of this 2.5 GW potential would only give rise to a 6% change in tidal amplitude. The output of 2.5 GW would be enough to power 800,000 homes.[37] Table 4.2 outlines regions of the globe which have seen or are expected to see advanced marine generation project development.

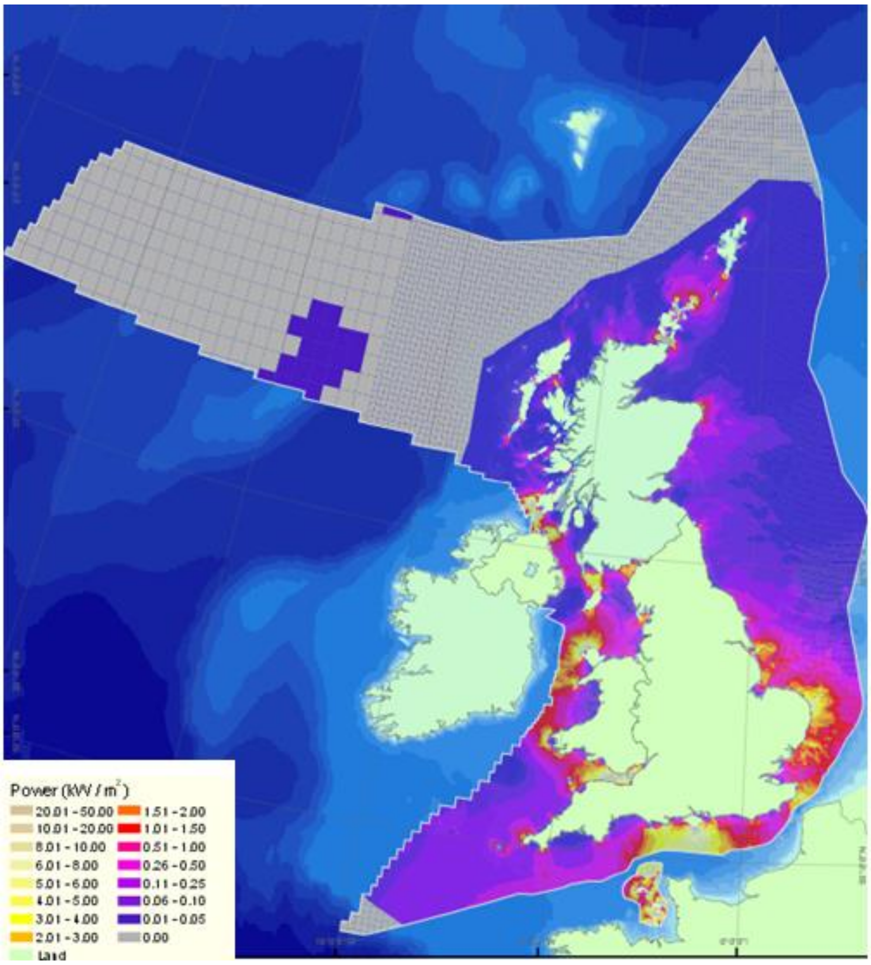
Table 4.2: Specific areas of high potential and advanced development

Country or Continent	Sites of Significant Potential	Current Installations
Australia	West Kimberly	Plans for a 40 MW tidal dam power station have been approved
North America	Bay of Fundy	18 MW tidal dam
France	Rance River estuary	240 MW tidal dam
South Korea	Sihwa Lake, Gyeonggi Province Uldolmok, Jindo County	254 MW tidal dam 1 MW tidal power station to be expanded to 90 MW.
UK	Strangford Lough, Northern Island Pentland Firth, Scotland Bristol Channel/Bristol Channel, England Fall of Warness, Orkney Islands	SeaGen Turbine 1.2 MW Operational lease for 400MW array awarded to Atlantis Resource Corporation until 2035. The site, as a whole, has the potential to produce 1.9 GW according to Oxford University researchers. Various plans for promising barrages of TSGs. Various - EMEC marine energy technology test site.
Norway	Kvalsund, Finnmark	HS300, Hammerfest turbine, 300 kW prototype.

[35] McMillan & Lickley, *The Potential of Tidal Power from the Bay of Fundy*: http://www.math.mun.ca/~rhaynes/siamundergrad08.pdf
[37] Nova Scotia Energy

Within Europe there are already tidal energy projects totalling 2 GW under development; between 2009 and 2013, the installed capacity of marine energy technologies has tripled. Approximately half of Europe’s resources are found along the coastlines of the UK. Figure 4.2 shows the major tidal flow patterns which can be used to optimise the positioning of the tidal turbines.

Figure 4.2: Mean power density map for Spring Tide

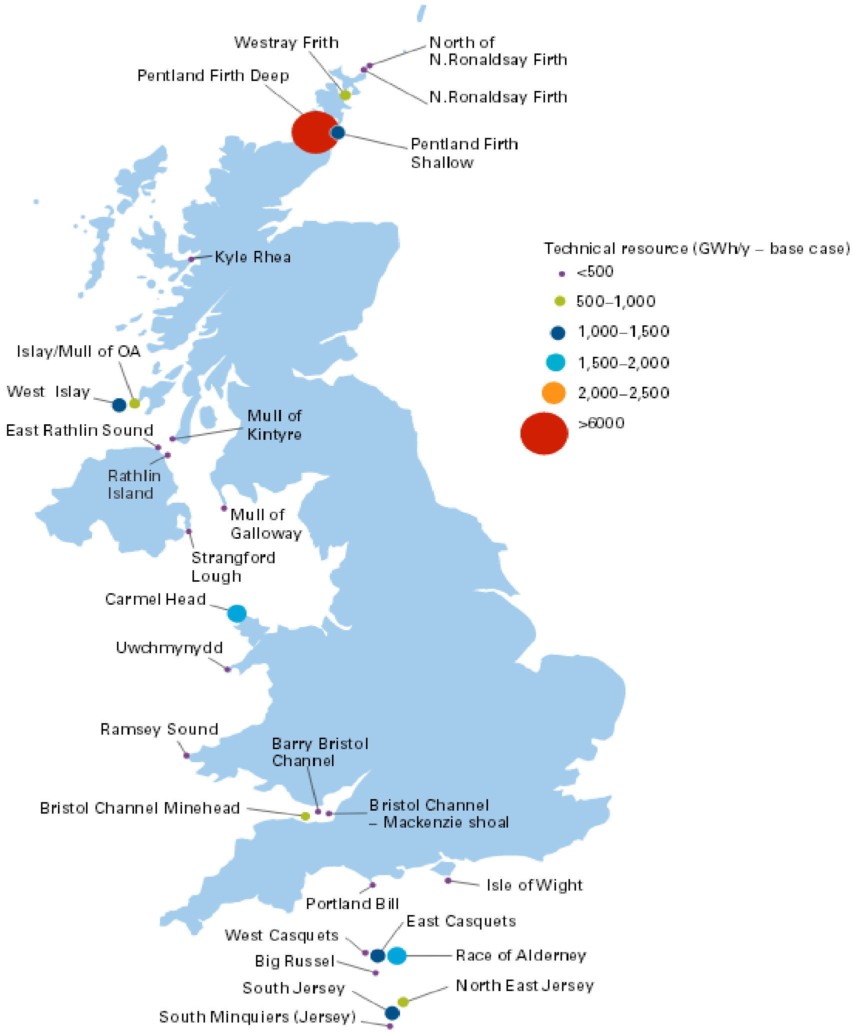


Source: National Archives[38]

The United Kingdom presents itself as a country abundant in exploitable tidal energy resources. A large portion of this potential resides on the coasts of northern Scotland where the EMEC facility is located. Figure 4.3 shows the major sites of exploitable tidal power resources around the UK coastline. It is estimated that of the UK’s resources, the Scottish coast may provide up to 18 GW of tidal power, approximately 25% of Europe’s total tidal potential. It will take several decades to fully exploit the massive potential. However, conservative estimates expect Scotland to harness 1.3 GW by 2020.

[38]http://webarchive.nationalarchives.gov.uk/+/http://www.dti.gov.uk/renewables/publications/pdfs/meanspringtidalpowerdensity.pdf

Figure 4.3: UK marine energy sites by capacity



Source: Carbon Trust, *Accelerating Marine Energy*

The estimate of technically exploitable resources available in the UK depends on the assumptions made as shown in Table 4.3. Current lower-end estimations exceed 16 TWh/year. The practically viable estimate of the resources reflects the inability to harness the tidal power from areas that are not suitable for a technology installation.

Table 4.3: Estimates of UK tidal energy potential

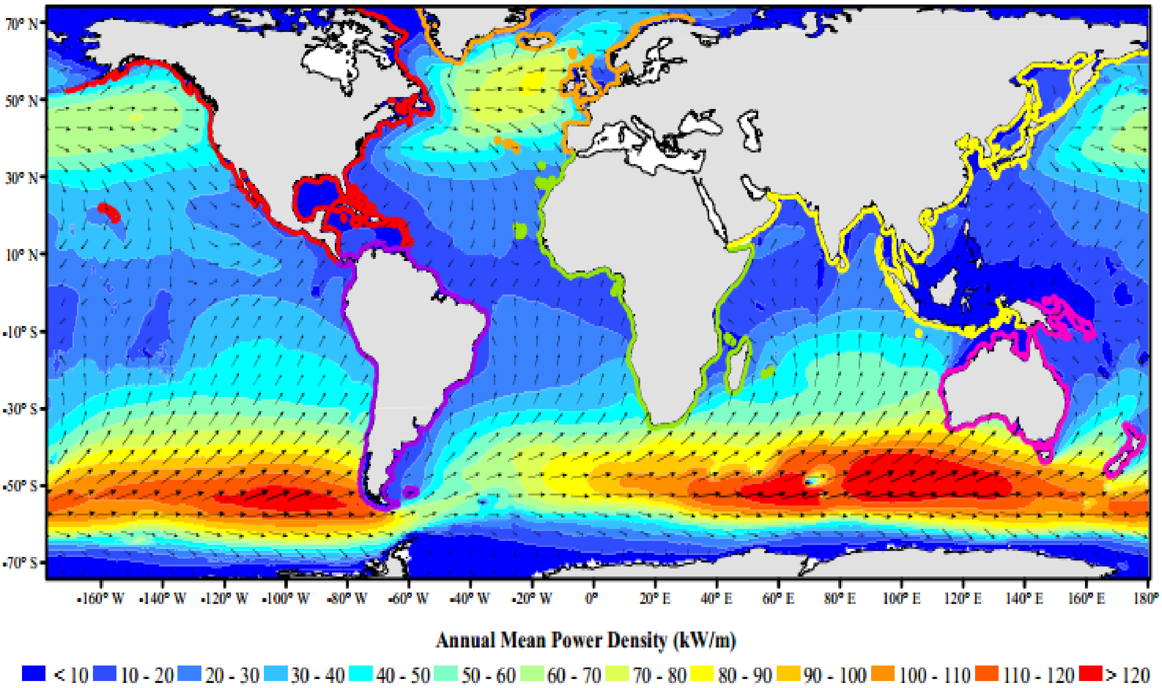
Assumption Level	UK potential resource (TWh/year)
Pessimistic	16.4
Average	29
Optimistic	38.4
Practically Viable	20.6

4.1.2 Wave

This section gives a general view of the global potential; an in-depth view of the UK potential; and finally a summary of other countries with significant resources.

Figure 4.4 was produced by using outputs from the NOAA WaveWatch III global model. Details of the calculation of the power density can be found in the report. It is clear from Figure 4.4 that the extra-tropical zones have the highest potential for producing wave energy electricity, in particular Western Europe, South Africa, Australia, New Zealand, Chile and the west coast of the USA. The UK is very well situated to take advantage of this resource.

Figure 4.4: Global wave power map

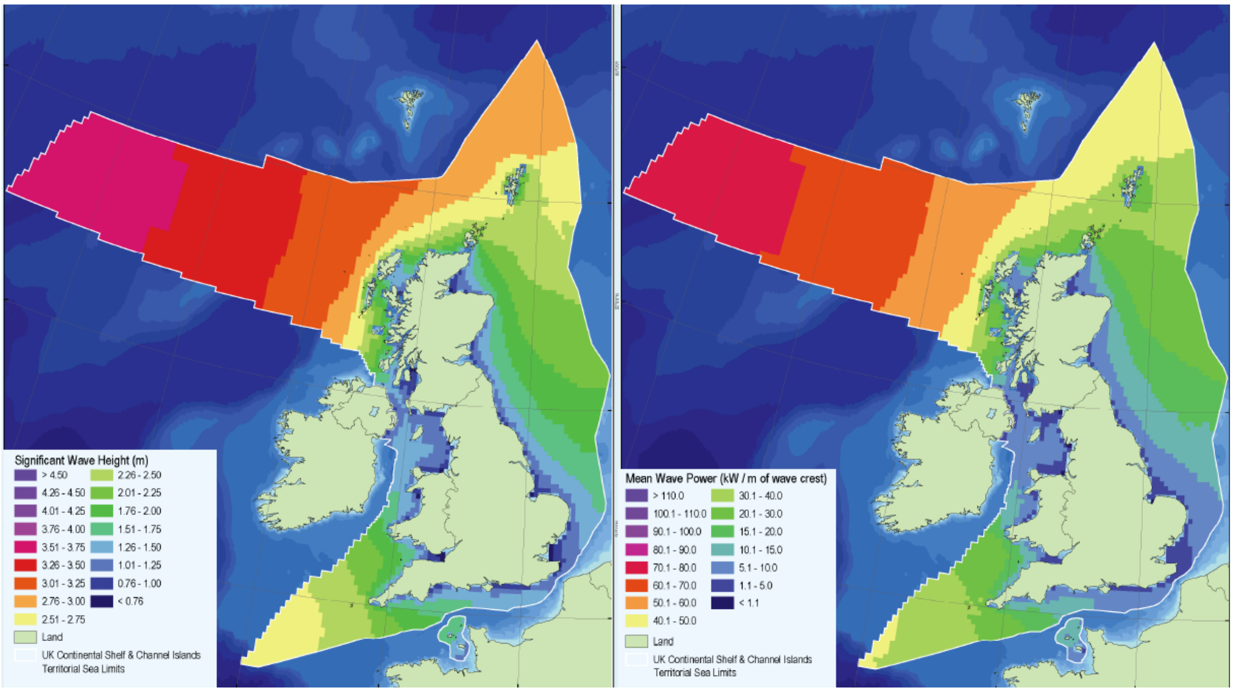


Source: Gunn & Stock-Williams, *Quantifying the Potential Global Market for Wave Power*, International Conference on Ocean Engineering 2012, p3[39]

Figure 4.5 shows the resource available extending westward from the coast of Scotland. The resource available to Ireland is not shown on this figure but is similar to the wave resources extending from the Scottish coast. The available wave energy in the UK is estimated at 230 TWh per year. This estimation is similar for the offshore and nearshore wave farms although the energy clearly cannot be gathered at both. Approximately 1,000 km of fetch is required to regenerate the waves and this is not possible between offshore and nearshore wave farms due to the depth of the sea at these distances.

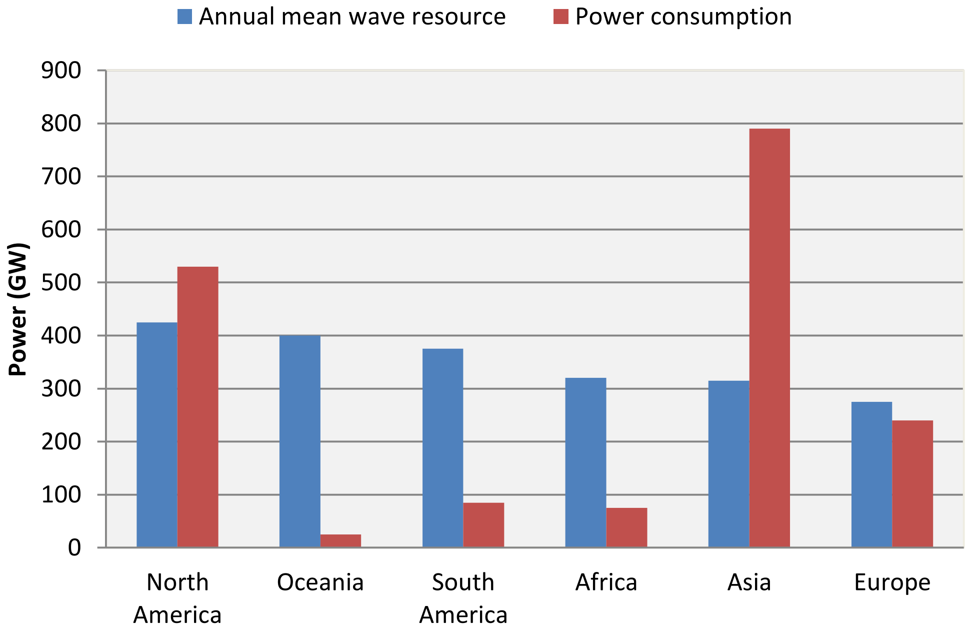
[39]http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day3/POSTER%20SESSION%204/Clym%20Stock-Williams,%20E.On.pdf

Figure 4.5: UK wave significant height and mean power



Source: Atlas of Marine Renewable Energy Resources[40]

Figure 4.6: Total wave power potential compared to power consumption by continent



Source: Gunn & Stock-Williams, *Quantifying the Potential Global Market for Wave Power*, International Conference on Ocean Engineering 2012[41]

[40] Atlas of UK Marine Renewable Energy Resources, ABPmer, 2008. Reproduced from http://www.renewables-atlas.info/ © Crown Copyright

[41] http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day3/POSTER%20SESSION%204/Clym%20Stock-Williams,%20E.On.pdf

Figure 4.6 shows that there are vast amounts of wave power potential available, enough to fully supply every continent except North America and Asia. These estimates do not represent the recoverable amount of resource or the forecasted supply of wave power but the whole potential. The reasons why these vast amounts of energy cannot be fully realized are given below.

The first reduction from the total potential is known as the **theoretical potential**. This takes into account:

- The necessary compromise between distance from shore and cost. The deeper the sea, the more energy is available. The cost of extracting this energy also increases with depth so that a compromise must be reached. In the north of the UK, the limit is the Rockall Trough, approximately 100 km offshore. In the south west the limit is taken to be the edge of the UK continental shelf.
- The difficulties inherent in situating a large wave farm on the complex, rocky nearshore seabed. These difficulties are much more difficult to estimate, although Aquamarine Power have conducted an in-depth study which is used in the model.

The theoretical potential for the UK is estimated at 146 TWh per year for offshore, and at 133 TWh per year for nearshore tidal energy production.

The next reduction in potential is known as the **technical potential**, which takes into account:

- The efficiency limit of arrays and their maximum power output.
- Capacity factors of each device individually and in an array.
- Average weather conditions at each location and variability.
- Ability of the device to deal with all weather conditions. Many devices are likely to reduce their output in high seas for self-preservation.

The technical potential is estimated at 95 TWh per year for offshore production and 10 TWh per year for nearshore in the UK. The difference between theoretical and technical potential is therefore substantial for the nearshore.

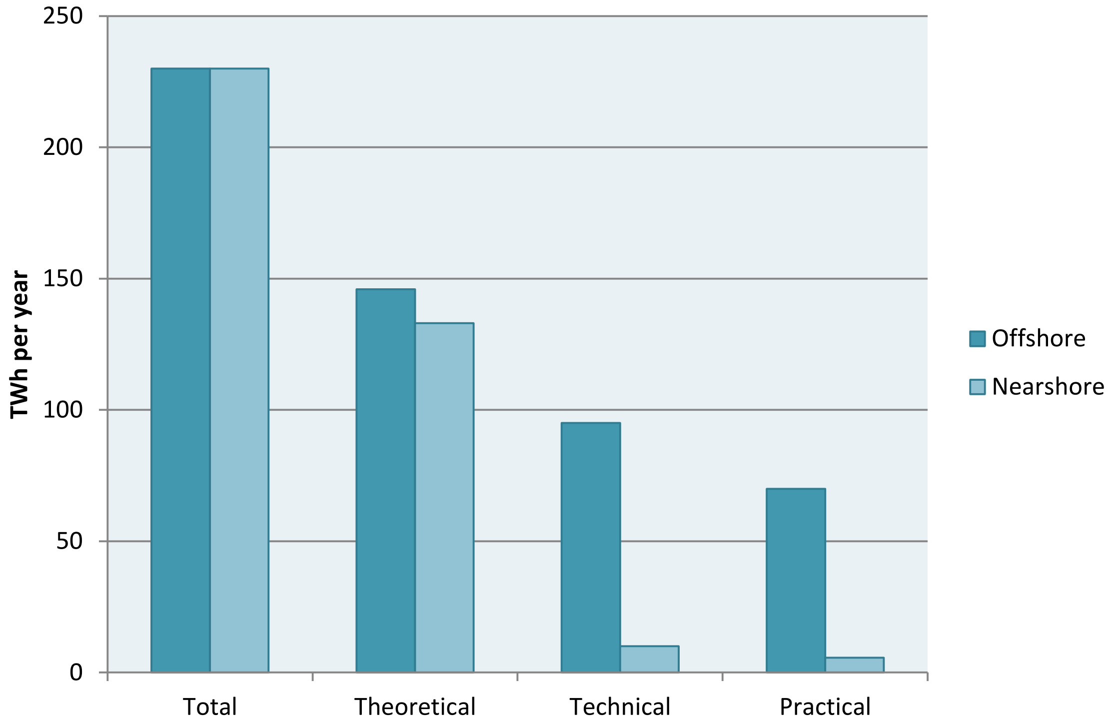
The final reduction in the available potential is known as the **practical potential** which considers:

- Required gaps between marine energy devices for nearby shipping lanes and highly frequented areas.
- Fishing requirements for access to the fishing ground around the UK, both nearshore and offshore.
- Marine life and the need to allow migration patterns to continue undisturbed as much as possible.

Practical potential is calculated within the technical potential due to the above reductions. Ethical issues concerning the proper use of the sea and detailed investigation of the migration of species are not included. Final values of 70 TWh per year and 5.7 TWh per year were found for offshore and nearshore sites respectively, and are to be used as a guide for the potential of the marine energy industry in the UK (Figure 4.7). This data comes from an estimation of the potential resource by the Carbon Trust, formed from an amalgamation of numerous other reports as well as a more detailed treatment of some of the issues.[42]

[42] The Carbon Trust, *UK Wave Resource Study,* 2012

Figure 4.7: Wave energy potential resource reduction stages



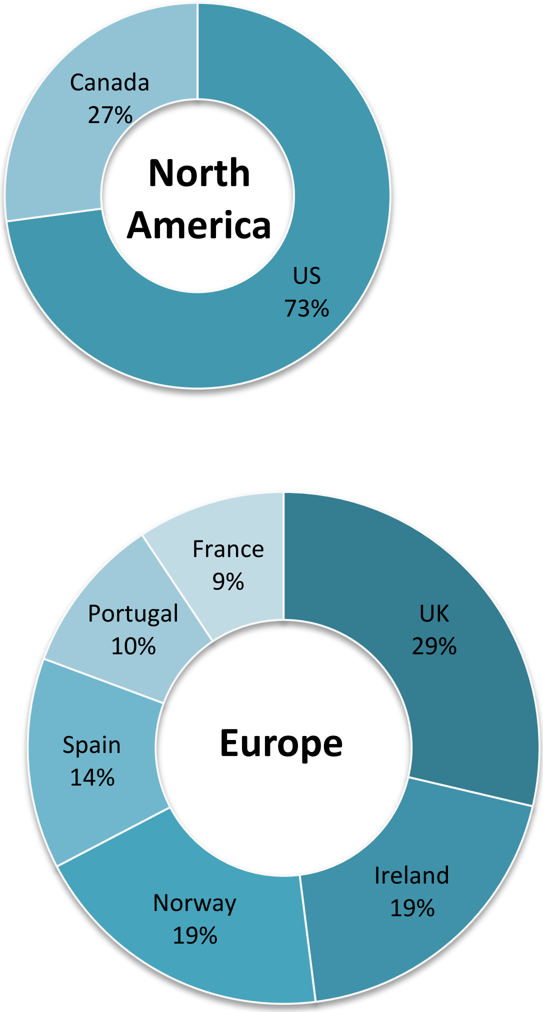
Source: Carbon Trust, *UK Wave Resource Study*, 2012

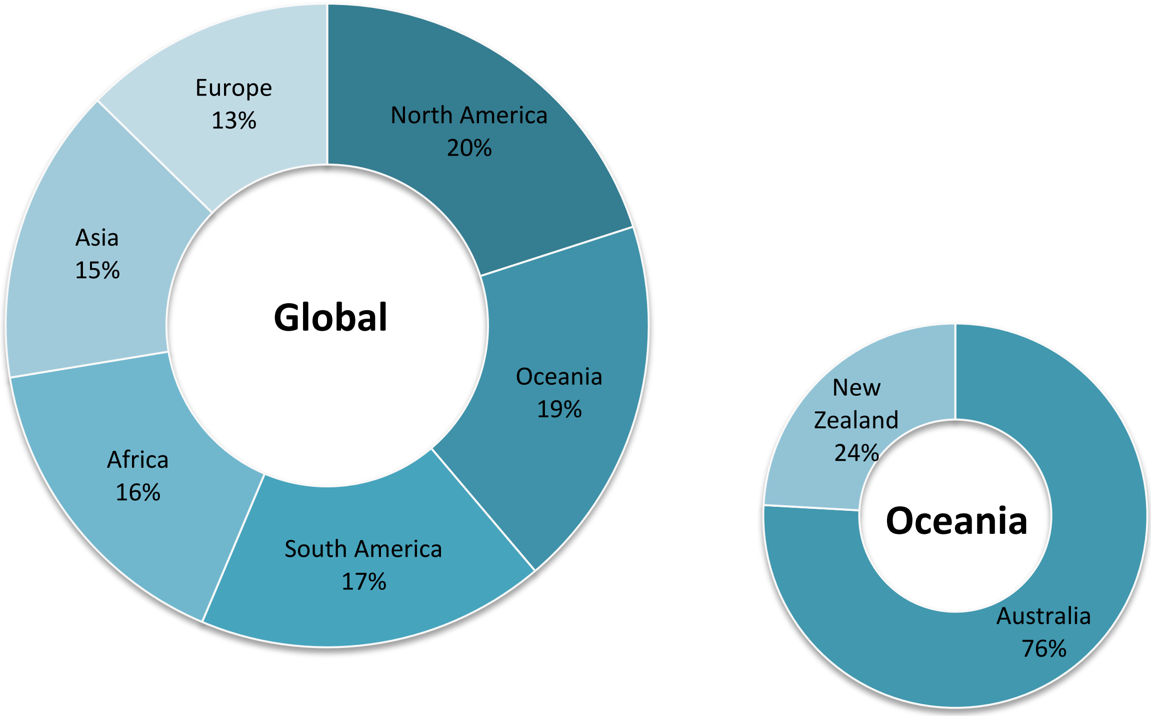
Figure 4.8 shows the potential resource by continent and, in the cases of North America, Oceania and Europe, the potential wave resources for each country. The total global power potential in Figure 4.8 is 2,131 GW. These estimates have an error of up to 10%.

The amount of the 2,131 GW that is recoverable with current technology is estimated at 3-5% of the total wave power potential for each continent. This represents both the reduction from total to practical potential, as well as the limitations of current technology.

Some continents have not been divided into countries due to the dominance of a single country. South America's potential wave power resources are predominantly located near Chile; Africa's resources are mainly found near South Africa.

Figure 4.8: Distribution of global wave energy potential





Source: Gunn & Stock-Williams, *Quantifying the Potential Global Market for Wave Power*, International Conference on Ocean Engineering 2012: http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day3/POSTER%20SESSION%204/Clym%20Stock-Williams,%20E.On.pdf

4.1.3 Regional Difficulties

One complication inherent in this industry is the competing sea usage. Although one of the main advantages of marine energy is that each project is much less limited in terms of size than land-based electricity production, there are still some constraints. The onshore environment is used by fishermen, small communities, walkers and farmers and any device in this location is likely to receive significant objections based on its visual impact.

Nearshore devices are less constrained but still face competition from sailing centres, swimmers, recreational sports, the fishing industry and objections on the ground of their visual impact. Offshore devices are the least constrained but still face compromises with fishing, shipping and sailing interests. For example, the planned Admiralty Inlet Pilot Tidal Project in the state of Washington in the USA has faced recent opposition from the company Pacific Crossing. Pacific Crossing owns and maintains a high-capacity fibre optic cable which runs from the west coast of America to Japan. The company is concerned that little or no research has been undertaken to establish safe distances between subsea turbines and other underwater installations.[43]

According to Tidal Energy Stream, the choice of location of the DeltaStream device had been heavily influenced by some of these issues. Furthermore the lease of the berth was permitted only for one year due to uncertainties concerning the environmental disruptions the device could cause. The area has a number of marine mammals and close monitoring will take place throughout the testing year. They hope to demonstrate that no disruption has taken place and thus extend the company's lease.[44]

Figure 4.9: Seagulls perch on the Oyster 800 in calm weather

Source: Aquamarine Power

[43] Bayar T., *U.S. Tidal Energy Project Could be Derailed by Lack of Proximity* Standard, Renewable Energy World, 08/10/13: http://www.renewableenergyworld.com/rea/news/article/2013/10/u-s-tidal-energy-project-could-be-derailed-by-lack-of-proximity-standard?cmpid=WNL-Wednesday-October9-2013
[44] LRI Interview

Aquamarine Power stated that although competing usages is a serious issue, they received no objections but instead a good deal of local support for their Oyster 800 planned for deployment off the Isle of Lewis. This support came from conservation groups, fishermen and the local community.[45] An example of a typical environmental assessment for the Aquamarine Power project at EMEC can be found in the company's Environmental Statement.[46]

4.2 Road Map for Commercial Deployment

The commercial deployment of wave or tidal energy converters is a complex process and involves a wide range of aspects aside from the technological strength of the device in question. No marine energy project has yet reached a stage in which the electricity produced covers the project costs. In order to reach this maturity, experience in the industry must be gained. There are a number of private and public funding sources for marine energy electricity, with Government support the most common, as discussed in Chapter 3. Permissions for moorings, environmental leasing and planning are all important considerations, as is the opportunity to connect to the grid. These are all discussed in this section, and a summary diagram of the roadmap to commercial development is shown at the end of this section in Figure 4.12.

4.2.1 Grid Connection

Connection to the grid is a prerequisite to providing energy on a commercial-scale. Although some of the devices included in this report may be used in a niche market situation, such as supplying remote off-grid locations, grid connection will be necessary in the vast majority of cases for commercial viability.

Connecting to the grid involves a number of complications (Table 4.4), the first of which is the physical connection. Many sites with large wave energy electricity potential are remote, with the nearest substation a long distance away. Offshore sites may be up to 100 km from the coast and the cabling required to achieve the connection is extremely expensive. Remote locations in many cases have a lower capacity for transporting electricity and new infrastructure must be put in place to transport the electricity to areas of high demand.

The second problem is the tariff for the use of the transmission and distribution network. These are ongoing charges for the transmission and distribution of electricity. Plans to harmonise electricity markets across Europe could cause large changes to the tariffs charged for the use of the UK grid in coming years. These uncertainties pose a high level of risk for the developer and investor alike. This risk is increased by the time required to complete the connection which necessitates an initial outlay often before consent has been fully given for the project.

The final problem with grid connection is the quality of the electricity provided. Electricity must be smoothed to predefined standards to be transported on the national grid and this entails complex electrical engineering at substation locations. The complexity of this task is increased by the variation of the supply with weather conditions. In general, electricity generated through wave energy increases with demand, with larger waves in winter coinciding with a greater need for heating. This is an extremely attractive benefit for the industry but is also a key difficulty in achieving a grid connection.

45 LRI Interview

46 Aquamarine Power, *Environmental Statement: Oyster 2 Wave Energy Project,* June 2011: http://www.aquamarinepower.com/sites/resources/Reports/2880/Oyster%202%20Array%20Project%20ES%20-%20Main%20Document.pdf

Table 4.4: Difficulties of grid connection

Difficulty	Description	Example of possible impact	Delays, Costs & Concerns
Physical connection	This is costly and takes a long time to complete. Large initial outlay must be provided and corresponding risk accepted. This difficulty is common to many projects with delays of up to a few years in some cases.	Initial expenditure may be lost due to denial of consent for other aspects of the project. Delay in connection may result in loss of funding or revenue or even lapses of other permissions. Some projects may miss the Renewables Obligation Certificate deadline due to delay in grid connections.	Initial expenditure is approximately £17,000 for small projects and is higher for large arrays.[47] Delays of 6-12 months are common and up to 3 years have been known.[48] This could mean 3 years revenue and progress lost.
Transmission charges	These can be extremely high due to site location and higher than transmission charges for other technologies. Uncertainty in transmission charges is another source of risk for developers and investors that is unlikely to be resolved in the near future.	Due to the variability of the wave resource, the transmission charges can be higher for marine energy than for other resources, thus disadvantaging it against its competitors. Scotland is the world leader for marine-based electricity generation but its transmission charges are proving a large problem for new entrants.	In 2011, transmission charges were £56 million and this is set to increase to £107 million by 2020 in UK.[49] The European Union has raised concerns about the level of these charges in the UK. Orkney and the surrounding areas have experienced a massive rise in charges since its development of marine energy.
Quality of Electricity	This is primarily a technical problem and solutions already exist. The cost of these solutions is occasionally very high. This problem applies mainly to wave energy.	Changes in electricity output characteristics may incur lengthy delays and costs, as substation must be updated. Expansion of arrays and combined sources subject to the same problem.	Delays of less than 6 months are expected for both situations and the cost of these changes will decrease as experience in transmitting electricity produced from marine energy increases. This is discussed in Chapter 3.

[47] O'Sullivan & Dalton, *Challenges in the Grid Connection of Wave Energy* Devices, Hydraulics & Maritime Research Centre, 2009: http://www.see.ed.ac.uk/~shs/Wave%20Energy/EWTEC%202009/EWTEC%202009%20(D)/papers/162.pdf
[48] *Wave and Tidal Energy in the UK,* Renewable UK
[49] BBC News, 18/09/12: http://www.bbc.co.uk/news/uk-scotland-scotland-business-19628178

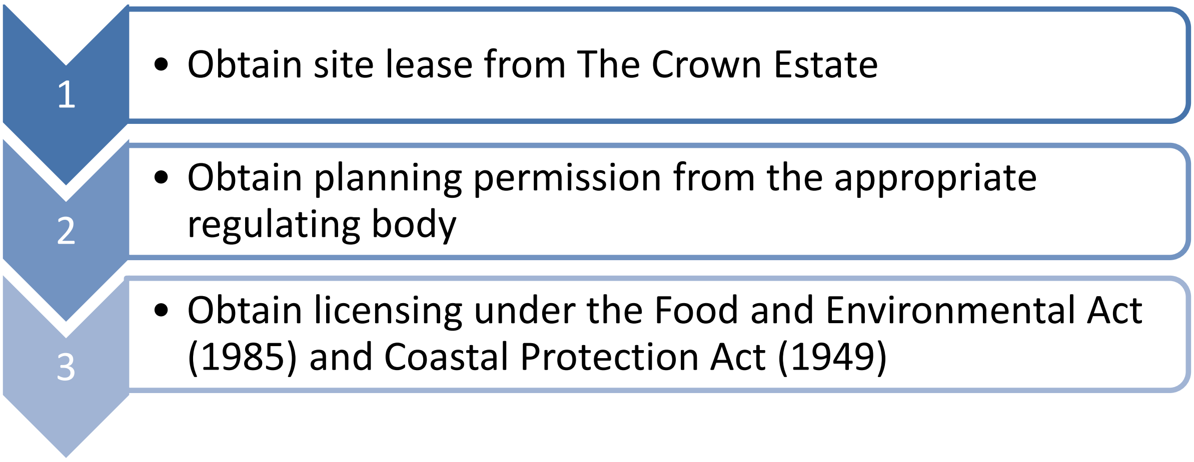
4.2.2 Consent

In order for a developer to start their project, they must obtain a site lease, planning permission and the necessary environmental permits.

Using the UK as an example, the vast majority of the seabed and approximately half of the estuary beds are within 12 nautical miles of the shore. These waters are owned by The Crown Estate, and in order for a tidal power unit to be installed, the developer must obtain rights to the portion of seabed they wish to use. Furthermore, The Crown Estate also has the right to license any electricity generation from renewable energy up to 200 miles from the coastline - the boundary of the UK Renewable Energy Zone.

Once a developer has reached an agreement for the leasing of a site, it must obtain planning permission. For wave and tidal renewable power projects, this will be subject to the Electricity Act 1989. When the rights to an area of the seabed have been given to the developer, they must obtain two further licenses from the government: a license under the Food and Environment Protection Act 1985, and a license under the Coastal Protection Act of 1949. Figure 4.9 summarises this marine energy development consent process.

Figure 4.9: Procedures to obtain consent for marine energy device on The Crown Estate



4.2.3 Risk Management

Risk management methods have been developed in several industries and can be usefully deployed in the generation of electricity from wave and tidal energy sources. Flinn, Bittencourt and Waldron suggest that a framework could be introduced to this industry through the use of risk-based standards.[50] The framework would provide assurance to investors and this method has been partially implemented by Det Norske Veritas (DNV) and the Institute for Energy Systems (IES).

Different stages of the development of a product are characterized by varying degrees of risk. This information is based on the EquiMar protocols which have been developed alongside the framework

[50] Flinn, Bittencourt & Waldron, *Risk Management in Wave and Tidal Energy*, Det Norske Veritas, 2011: http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/376.pdf

used by the IEC technical committee. The three different stages and the important aspects of each stage are summarised below, with their associated risks given in Table 4.5.

Table 4.5: Project development stages and their associated risks

	Technology Risks	Risk Level	Financial Risks
Tank Testing	Time spent developing technology at this point is small and aspects of the device can be altered or modified without too much impact. The environment is controlled and responses can be accurately predicted and monitored.	Low	Investment in the project at this stage is small; loss of equipment is unlikely to cause much financial damage.
Sea Trials	Large or full-scale models are at risk, the environment is not controlled. Monitoring and even access to the device becomes more difficult. Failure at this stage can result in the failure of the entire project.	Medium Medium-high	Large or full-scale models are expensive. Development costs at this stage might have been high. Upfront costs of grid-connection and consenting costs may have been made for the next stage and this investment is at risk if sea trials incur long delays or failure.
Multi-device arrays	The number of devices deployed and infrastructure required increases. The performance of WECs in an array is not understood but this will probably not pose a risk to the technology.	Medium-high High	Level of investment required at this stage is very high. Array testing experience is extremely limited and underperformance could result in economic failure.

1. Tank testing

During this stage many aspects of the device's performance can be monitored. Structural response, component design, performance in different conditions and indications of the power output can all be investigated. Reporting on limitations and suitability under different conditions is essential at this stage to minimize risk in the sea trials.

2. Sea trials

Full-size or realistic scale models with compatible sea state trials provide information about the actual performance and the survivability of the device. During this stage, tank modelling data should be confirmed. O&M costs, availability, capacity factor and survivability of the device can all be tested during this phase and should be optimized before progressing to multi-device arrays. This stage also provides information and experience of the installation, mooring and infrastructure requirements (unless conducted at a purpose built test facility) which will help improve the accuracy of cost forecasts for the next stage.

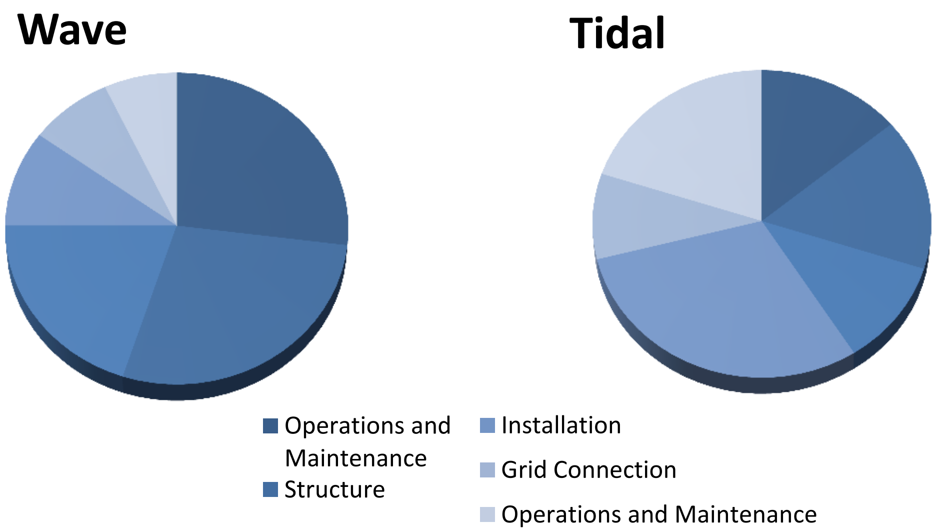
3. Multi-device arrays

This stage has not been reached by many projects so far and none have built a large, successful array for commercial generation. Interaction effects between devices can be investigated alongside farm configuration, efficiency improvement and confirmation of the theoretical model. The large production rate aspects, such as the supply chain, component sourcing and production costs, can all be optimized during this stage.

4.2.4 Project Costs

The costs associated with small tidal and wave commercial arrays are broken down in Figure 4.10. The segments represent the various capital costs. The darkest segment is an indicator of the O&M costs incurred by the array, including leasing and insurance.

Figure 4.10: Breakdown of the cost of small wave and tidal arrays.



Source: Accelerating Marine energy, Carbon Trust

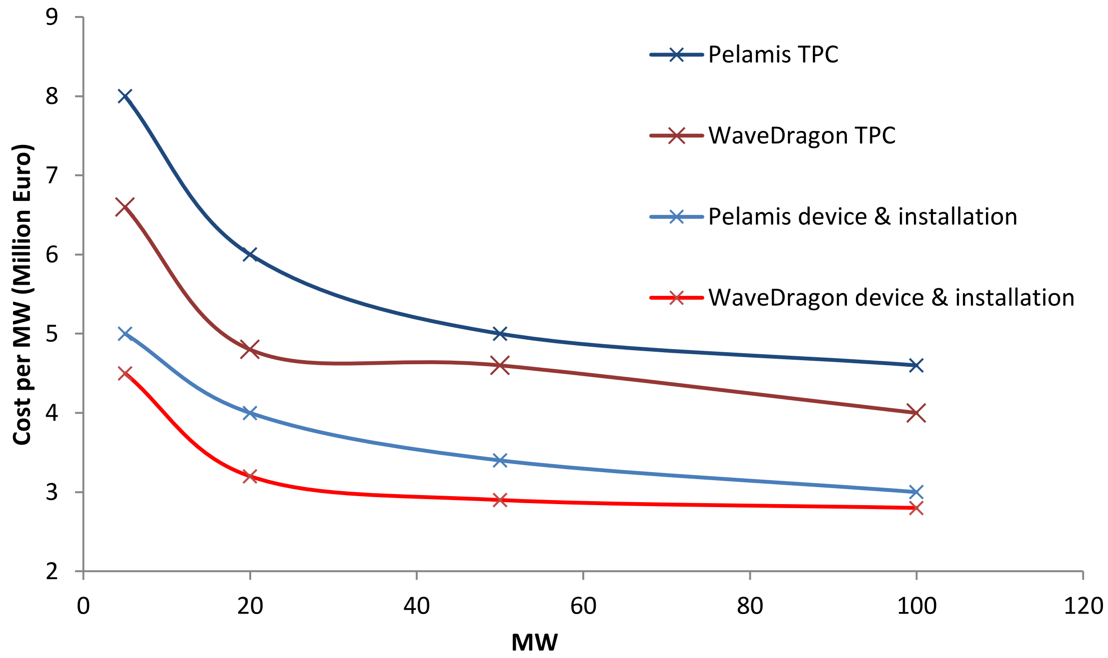
A comparison of the cost breakdown of two wave energy converters is given in Table 4.6. Wave Dragon is no longer active in the industry. These costs are quoted for illustrative purposes only.[51]

Table 4.6: Typical capital costs (million Euros)

	Pelamis (0.75 MW)	Wave Dragon (7 MW)
First Device	€3.2	€19
Installation	€1.6	€1.46
Mooring	€1.38	€7.03
Management	€1.26	€3.2
TPC+cable	€12.6	€32

Figure 4.11 shows how costs are influenced by changes to capacity. As expected, it is clear that the cost per MW decreases with total power produced. The total project costs are necessarily higher than device and installation and this will always be the case. As experience in the industry is built up, it is expected that these costs will approach one another. Current device and installation costs represent the approximate level overall costs are expected to reach once the more expensive first stage is passed. This does not take into account the reduction in costs expected from technological advances since this is difficult to quantify.

Figure 4.11: Cost per MW decrease with capacity



Source: Dalton & Lewis, *Performance and economic feasibility of 5 wave energy devices off the west coast of* Ireland, Hydraulics & Maritime Research Centre, 2011[52]

[51] Dalton & Lewis, *Performance and economic feasibility of 5 wave energy devices off the west coast of* Ireland, Hydraulics & Maritime Research Centre, 2011: http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/36.pdf

[52] http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/36.pdf

Figure 4.11 also shows that the rate of reduction declines rapidly as the capacity is increased. As such, devices over 100 MW will not have a significantly lower cost per MW. This level of cost per MW, just below €30,000, is competitive with offshore wind and other electricity sources.

Other costs incurred in electricity generation from wave and tidal energy includes cable laying, substation construction and connection costs, and estimations of these costs are given in Table 4.7. These estimations come from a comparison of five WECs on the western coast of Ireland and are therefore specific to this region and only rough estimates for the industry in general.[53]

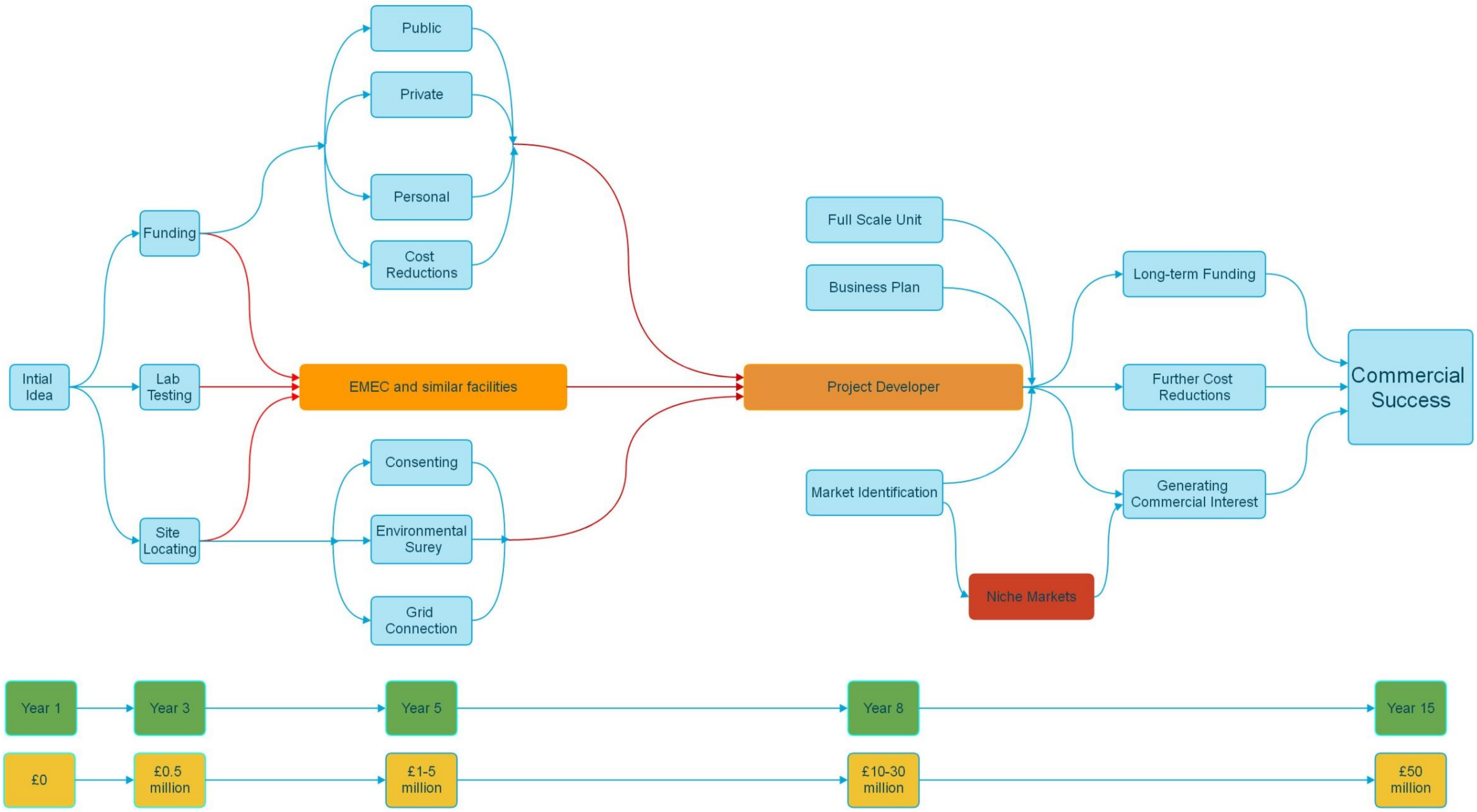
Table 4.7: Cost of cables and substations

Procedure	Cost
Cable 0.5-8 MW, 20 kV	€53,200/km
Cable 8-20 MW, 38 kV	€90,491/km
Cable 21 -110 MW, 110 kV	€212,790/km
Trenched cable laying	€282,000/km
Untrenched cable laying	€100,000/km
Cable coverage (required for first km)	€939,000/km
Floating substation construction <5 MW	€0.5 million
Floating substation construction >5 MW	€0.06 million/MW

The roadmap for the commercial success of marine energy technology is displayed in Figure 4.12 for a fifteen year period.

[53] http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/36.pdf

Figure 4.12: Roadmap to Commercialisation



4.3 Investment Outlook

Siemens Energy Hydro and Ocean Unit stated that '*the whole [marine energy] industry would like to see greater certainty for the investment environment… I would like to see grid access being driven forward by infrastructure investment by the central government'.*[54] Siemens have already made important investments in the marine sector through the Limpet, produced by Wavegen, a subsidiary of Voith.

Banks and investors looking to invest in tidal and wave energy power projects will need to have accurate information on a number of factors to be able to gauge the risk and likely return of their investment. These factors include:

- **Initial capital expenditures and installation assumptions**
  These costs are often the main difficulty for investors. Since many of the devices are extremely new technologies, the costs can be large and may not be accurately estimated.
- **Lifetime and construction period**
  The lifetime of a wave energy electricity generation device is unknown, although many companies claim it is likely to be 20-25 years. The construction period can be gauged for a few advanced technologies and will decrease with time.
- **Capacity factor**
  The percentage of the time the device can operate over a year. This is an important quantity in economic modelling, but in the case of extremely new technology it is very difficult to estimate accurately. The current test runs are not only too short to give accurate data on the power produced by the majority of wave energy devices, but also in many cases the rated power is still variable. The Carbon Trust resource estimate discussed earlier in this report assumes a capacity factor of 30%.
- **Constraints on the resource**
  Wave power does not have important constraints on the resource since it is in such an early stage of development.
- **O&M costs**
  These costs vary significantly among devices but overall the cost is expected to fall as experience with the device accumulates. Some authors predict that the O&M costs would be equivalent to those in the wind industry by 2045.[55]

Much of the above data is extremely variable and uncertain in such a new industry as the wave and tide energy market. This risk will deter investors and slow the progress of the field. Experience and time is required for these uncertainties to become resolved.

4.3.1 Government Policy Relating to Wave & Tidal Energy

To encourage the initial growth of the market, there are a number of government incentives in place for companies and investors in this industry. In the UK this is done by Renewables Obligation (RO). Operators of accredited electricity facilities receive Renewables Obligation Certificates (ROCs) for each MWh of electricity they produce.[56] These awards are banded so that newer and more costly technologies gain more support. Renewable UK claim that every £1 of public money invested in the

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[54] Tidal Today: http://social.tidaltoday.com/governmental/achim-woerner-ceo-siemens-energy-hydro-and-ocean-unit
[55] Hayward, *Economic modelling of the potential of wave power* , Renewable Energy 48, 2012, p238
[56] G. Allan et al, *Energy Policy 39,* 2011, P23

industry unlocks £6 of private investment. Feed-in tariffs are a common feature of European energy policy allowing renewable energy producers to sell their electricity to the grid and receive a set amount per MWh. Levels of support differ among countries and the current levels are summarized in Table 4.8.[57]

Table 4.8: Summary of marine and offshore support by country

Country	Marine energy (Euro per MWh)	Offshore wind energy (Euro per MWh)
France	150	130 for first 10 years, site dependent thereafter
Italy	214.5	189.4
Spain	No new projects may obtain FIT. Previously 76.47	No new projects may obtain FIT. Previously 91.7
United Kingdom	2 ROCs for wave and tide, equivalent of 84. Wave power in Scotland receives 210	2 ROCs if established before April 2014, 1.5 thereafter
Denmark	80.57 for first 10 years, 53.71 thereafter	141.13 (negotiated on a project basis, this is a recent sample value)
Portugal	Demonstration: 260 Pre-commercial: 191 Commercial, First 100 MW: 131 Next 150 MW: 101 Thereafter: 76	-
Ireland	220	162.9

From these statistics it would appear that Italy and the United Kingdom have the most favourable government policy relating to wave and tidal energy. Although these policies are designed to support the industry, there are a number of reasons why developers and investors do not rely too heavily on the continuation of this support. The recent economic crisis caused Spain to halt their feed-in tariff and a similar economic or political event could influence policy in other countries as

57 *Renewable Energy Incentive in the OECD, China and India, 2011/2012,* London Research International

well. In the UK, the feed-in tariff for Solar PV was dramatically cut in 2011 leading to a huge decline in the industry and widespread condemnation.[58]

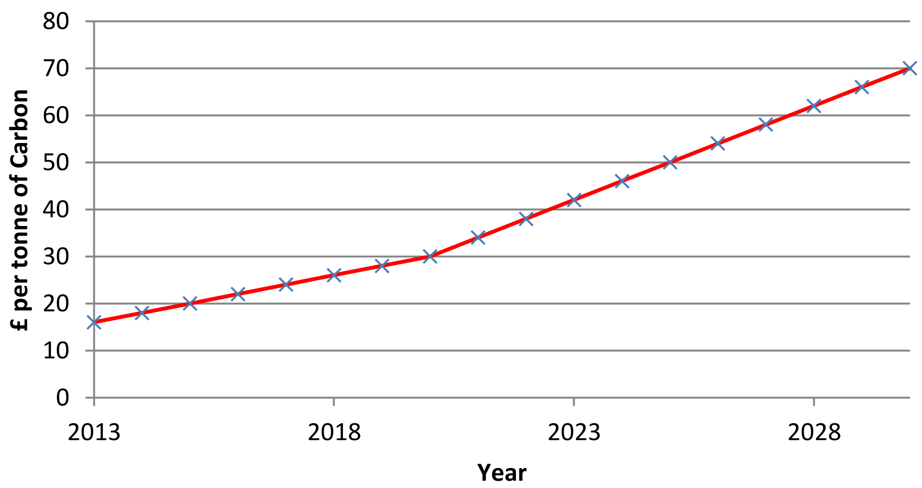
4.3.2 Electricity Market Reform (EMR) in the UK

It is clear from Table 4.8 that the UK Government is leading the field in the encouragement of marine energy electricity generation. This lead is increasing with the Electricity Market Reform in the UK. The new law passed in December 2013 will go further towards encouraging all sorts of electricity production from renewable sources and is expected to be particularly beneficial for the marine energy sector. This is essential for its growth, since the LCOE from marine energy continues to be well above that of other energy sources. A reduction to the same level as that of offshore wind is necessary if marine energy is going to become viable on a commercial-scale.

In order to achieve this, experience is required; the rate of cost reductions in the learning stages is estimated at about 9%, so the cost of producing electricity is expected to decline annually by approximately this much from the previous year. This estimate is taken from the experience of offshore wind and is subject to change. To gain experience, companies must continue to operate while making a loss on the electricity they sell to the grid. Through the Electricity Reform, the Government will supplement the sale price of electricity and provide the income required for the continued existence of the company. The sector can continue to thrive in the short-term, only if this government investment continues.

The EMR introduces a number of tools to reform the electricity market in the UK. The most important of these for the future of the wave and tidal energy industries are the Carbon Price Floor (CPF) and the Contracts for Difference (CfD). The Carbon Price Floor levies emissions of electricity production processes, which in time will increase the cost of highly polluting methods and make renewable energies more competitive (Figure 4.13).

Figure 4.13: Projected progression of carbon price



Source: Atkearney[59]

[58] Harvey, *Solar companies to sue UK government for £140m over feed-in-tariff* cuts, The Guardian, 23/01/13: http://www.theguardian.com/environment/2013/jan/23/solar-companies-feed-in-tariff-cuts

[59] http://www.atkearney.co.uk/documents/872085/1395284/FG-UK-Energy-Policy-8.png/7c0e73a7-29aa-494e-a069-7deca2143b65?t=1371657830065

The centrepiece of the EMR is the introduction of Contracts for Difference. These are long-term contracts for which the first applications will be made in late 2014. The current Renewables Obligation scheme will be closed to all new generation from 2017. During this interim period developers will have the opportunity to change to the new system. This period is also one of higher risk and uncertainty for investment in renewable energy and this is discussed in Table 4.9. The main differences of the EMR can be seen through a comparison of the ROCs and CfDs.[60]

Table 4.8: Definition of terms

Term	Definition
Strike Price	The fixed price level for generators intended to stabilize revenue
Reference Price	Market price of electricity
PPA	A Power Purchase Agreement is the contract for the purchase of electricity
CfD Levy	Cap on the amount of CfD and continuing ROC payments

Table 4.9: Comparison of ROCs and CfDs

Currently used ROCs	The replacement CfD	Advantages	Risks
Available for Renewable Energy projects only	Available for all low carbon electricity generation	Broader criteria will encourage all low carbon generation	Nuclear power will be eligible and may increase competition for funding
20 year contracts, 10% artificial excess demand, investors exposed to risk of variable wholesale price	Contracts are long-term, CfD strike price is locked for 15 years (partially indexed to inflation and fuel prices)	Significantly reduces price risk for investors	Market fluctuation risk is transferred to government body
With fixed levels of support, the cap on total payments is unlikely to cause a problem	With variable support the cap on total support is more likely to play a role	Variability allows support to be as widely spread as possible and vary appropriately in time	Reduction in wholesale price larger than anticipated may result in support drying up
Developers exposed to long-term changes in wholesale prices	Support payments are variable based on market reference price and fixed strike price	Long-term risk for developers is removed	Possible advantages for developers removed
Developers sell power at day-ahead or month-ahead price	CfD will pay the difference between strike price and reference price	Short-term price risk removed from the developers and investors	Risk is transferred to UK consumers via CfD levy

60 Baringa Viewpoint, *UK Contracts for Difference: Risks and Opportunities:* http://www.baringa.com/sites/default/files/Viewpoint%20UK%20Contracts%20for%20Difference_FINAL.pdf

Securing long term PPAs with large energy supplier is increasingly difficult	CfD will provide supplier a hedge against the CfD levy.	DECC suggests there may be lower PPA discounts under CfDs	The plausibility of this advantage is unclear and the problem may continue

Although the reform is expected to increase investment incentives in renewable energies, the period between policies is a period of uncertainty and risk for investors. To minimize this uncertainty, the Government issued statements of its intention and of the interim method for giving support to renewable energy power generation. They set out that any technology qualifying for support under the previous RO's will still qualify in the future.[61] Also, any new project must be able to show:

- The project is located in the UK
- There are credible plans in place to start generating electricity by 2014-2019
- Without support from the government there is a significant risk that this generation will not occur or will be significantly delayed
- The project is not already accredited under the appropriate RO
- The project has an expected capacity of at least 50 MW nearshore or 100 MW offshore (to focus on the aim of utility-scale generation)

The CfD Counterparty (or before full implementation the Secretary of State) will be obligated to enter into investment contracts with any company that meets the requirements set out in the Energy Bill. This obligation is subject to the terms set out in the Final Investment Decision Enabling for Renewables report issued by the DECC.[62]

Aquamarine Power issued a statement concerning EMR.[63] The key points were:

- The ROC should be extended until 2020
- The switch from ROCs to CfDs could take some time for the industry and could cause an investment hiatus
- A feed-in tariff sceheme is a well-understood mechanism and would be adopted more easily
- Auctions are undesirable as part of a price discovery mechanism
- Volume overshoot concerns could be overcome through a cap on the marine energy sector, suggested at 500 MW

4.4 Projected Industry Size

The projected industry size is the subject of much ongoing research. The Commonwealth Scientific and Industrial Research Organization (CSIRO) have developed two models for predicting the growth in an emerging market. The Global and Local Learning Model (GALLM) is an international and regional economic model that projects the uptake of electricity generation technologies in a given

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[61] UK Dep. of Energy & Climate Change, *Final Investment Decision Enabling for* Renewables: *Invitation to Participate*, 14/03/13: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/141873/FIDeR_update_doc_Invitation_to_Participate_2013_-_03_-_14_FINAL.pdf

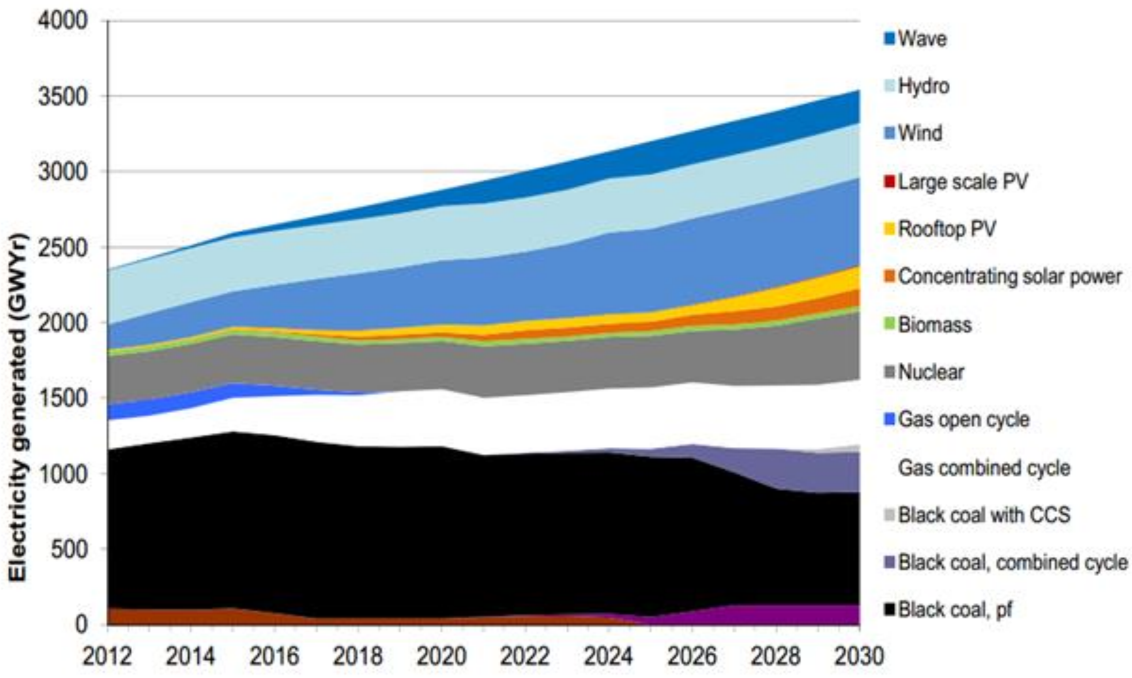
[62] UK Dep. of Energy & Climate Change, *Final Investment Decision Enabling for* Renewables: *Investment Contract Allocation*, 14/03/13: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209367/2013_-_06_-_27_FIDe_Update_2_Master_Draft__2_.pdf

[63] Aquamarine Power: http://www.aquamarinepower.com/sites/resources/Consultation%20responses/2977/Aquamarine%20Power%20Consultation%20response%20on%20Electricity%20Market%20Reform.pdf

policy environment. The Energy Sector Model (ESM) uses more detailed constraints on local energy resources and trade to predict the same outcome. Details on both of these models can be found on the CSIRO website.[64]

Using these two models, Jenny Hayward of CSIRO has predicted the changes in global electricity generation up to 2050. Her model accounts for the need to lower carbon emissions by the use of carbon price schemes.[65] The low price path is consistent with a target of CO_2 concentrations of 550 ppm and the high price path with 450 ppm of CO_2.[66] All of the factors discussed earlier in this report were taken into account in these forecasts and details of the assumptions made can be found in the original paper. Figures 4.14 and 4.15 show this forecast up to the year 2030.

Figure 4.14: Projected global electricity generation, low price path

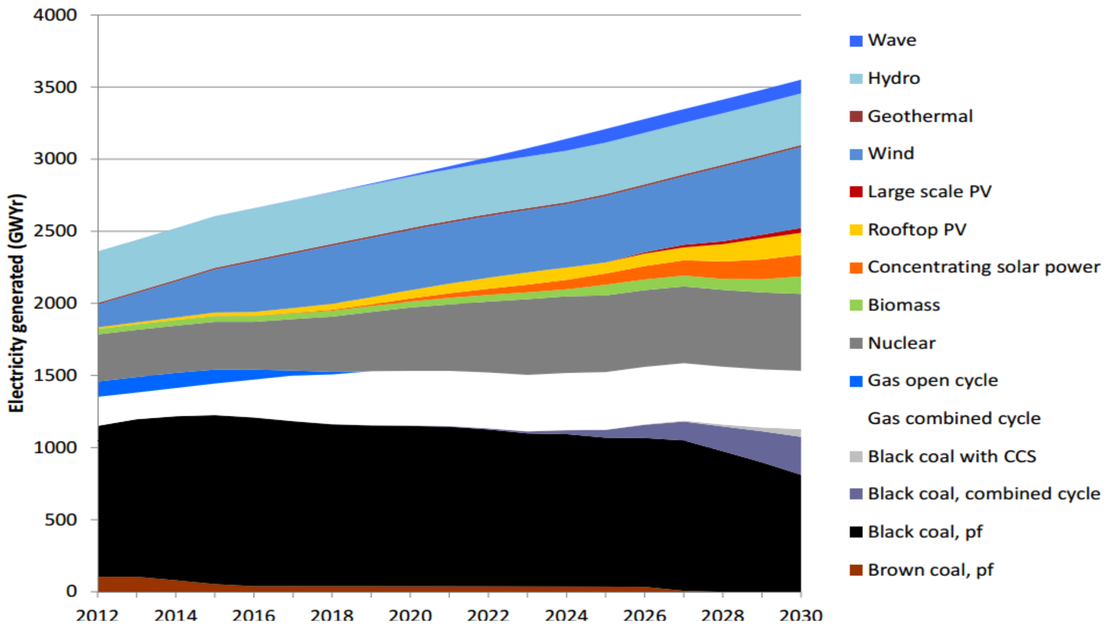


Source: J. Hayward[67]

As can be seen in Figures 4.14 and 4.15, both price paths predict that global marine energy will not play a large part in the energy mix up to 2030. Under the low price path, wave and tidal start to grow in 2014-15, whereas this growth begins in 2022 under the high price path. Both figures agree that marine energy will be important at least until 2030 although the 2050 projections forecast that other sources will inhibit this growth in the long term. It is likely that the growth will take place in the countries that are leading the industry today and that have the resources necessary to exploit this energy source.

[64] Commonwealth Scientific and Industrial Research Organisation: http://www.csiro.au/
[65] Bowen, *The case for carbon pricing*, Grantham Research Institute on Climate Change and Environment Policy Brief, Dec 2011: http://www.lse.ac.uk/GranthamInstitute/publications/Policy/docs/PB_case-carbon-pricing_Bowen.pdf
[66] Hayward, *Economic modelling of the potential of wave power,* Renewable Energy 48, 2012, p238
[67] Correspondence with Jenny Hayward

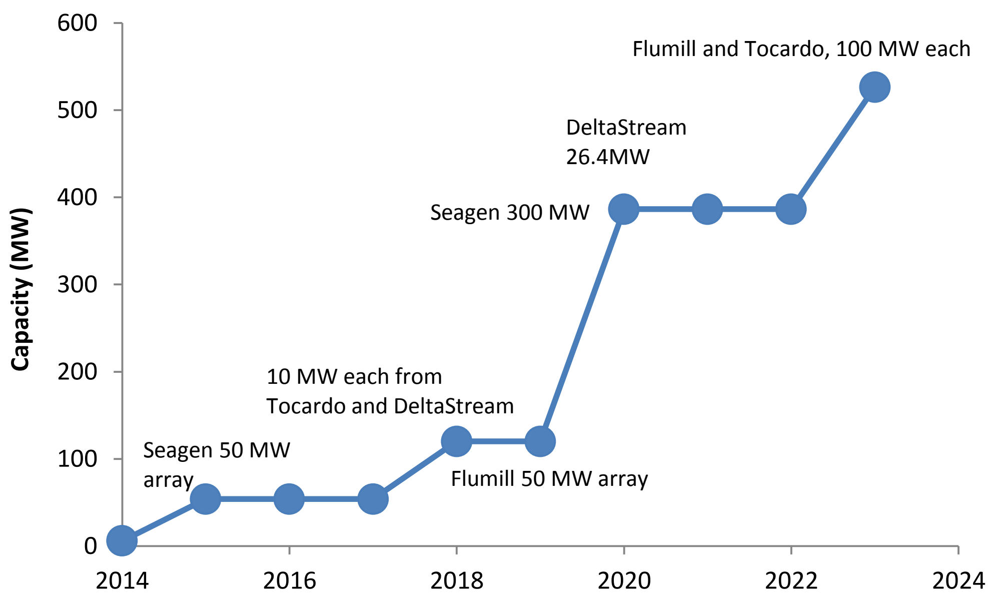
Figure 4.15: Projected global electricity generation, high price path



Source: J. Hayward[68]

Long-term predictions are highly uncertain and the development of new technologies is not easily quantifiable. Prices of other energy sources, discovery of new sources and government support must all be assumed. Complex models such as those developed by CSIRO are capable of providing the most accurate forecast of all these factors available, but there is still considerable room for error. This report will attempt to forecast the UK market size and using this forecast it will predict growth in other countries and globally.

Figure 4.16: Projected tidal capacity from case study companies



[68] Correspondence with Jenny Hayward

Figure 4.16 shows the increase in projected tidal capacity in the UK over the short-term. Information was obtained from the companies researched for case studies in Chapter 5, representing their own company forecasts. Data to produce a similar summary for wave energy companies was not available.

The vast majority of forecasts overestimate the sector's growth rate; no forecasts from five years ago predicted growth would be as slow as it has been experienced to date. This report therefore assumes a much slower growth rate and takes a conservative estimate wherever possible. Figure 4.17 draws on other models for confirmation of the predicted growth rate, and assumes that the Government-fuelled growth spurt will occur in 2017-2018.

Figure 4.17: Projected UK wave and tidal energy capacity

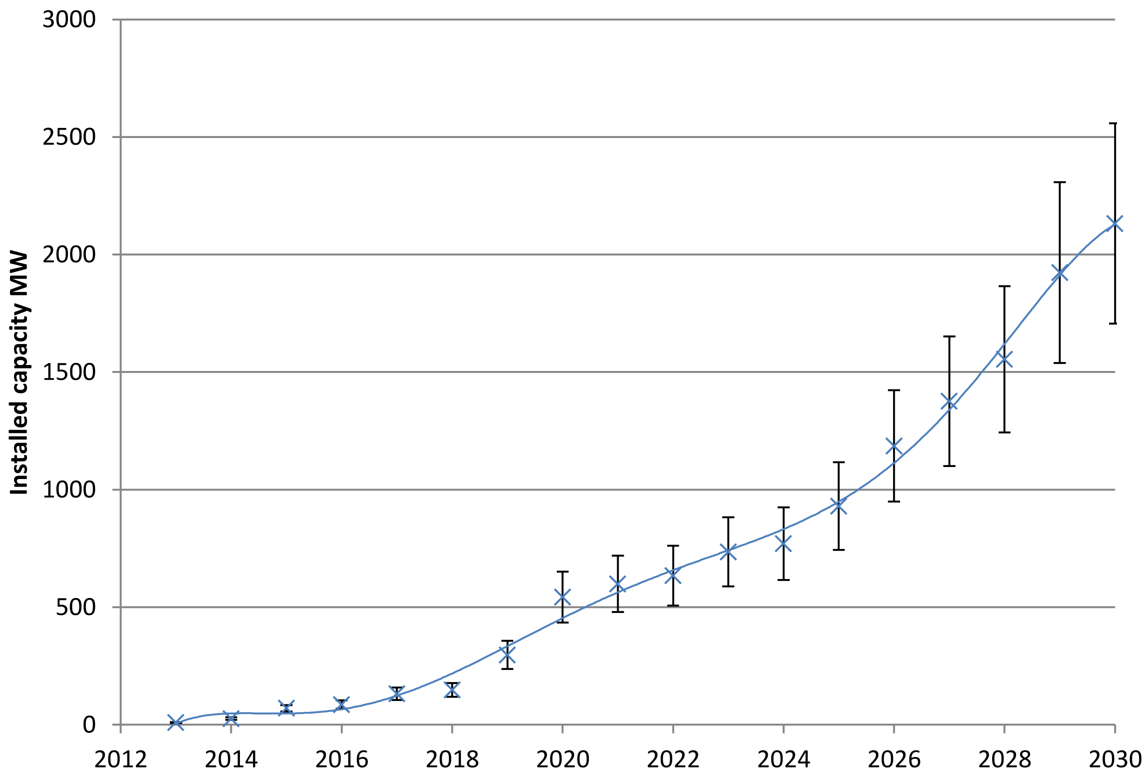


Table 4.10 shows industry outlook by device location. This projection takes into account companies' expressed intentions and forecasts over the next 5-10 years.

It is expected that nearshore wave power will grow quickly due to the Oyster 800's deployment in small-medium arrays. However, there are not many other well-developed nearshore technologies and the growth of this division is expected to be limited in the long-term by its lower technical potential.

Onshore wave power is not expected to develop to a great extent due to concerns about its visual impact.

Offshore wave power is expected to grow slowly in the short-term, due to the current cost of installation and O&M, however it will increase its growth rate and be contending with tidal power by 2030.

Table 4.10: Outlook by device location

Division	Outlook
Onshore Wave	Well-established technology, low energy density. Unlikely to supply any considerable proportion of the capacity due to objections to the visual effect on the shoreline.
Nearshore Wave	Tested technology; leading companies predict small arrays in 2015. Likely to form a significant part of the marine energy mix until at least 2030. Limited technical potential may limit this division's deployment in the long run.
Offshore Wave	One well-established technology and a number of tested technologies. Small arrays predicted for 2015. This division has a very high technical potential and is likely to supply the bulk of our marine energy from 2030 onwards.
Tidal Stream Generators (TSG)	Technology is gaining significant interest; innovative and robust designs surfacing. It is expected that 50 MW arrays will be installed by 2020 and 100 MW arrays by 2030. TSGs are likely to form the majority of new tidal energy developments in the coming decades.
Tidal Barrages	It is unlikely that we will see the development of new tidal barrage projects due to the success of TSGs. The capital costs associated with the dam structure are high, impact on the local ecosystem is significant, and they are considered to be an eyesore.
Dynamic Tidal Power	Very unlikely to see development of a DTP station. Capital costs are extremely high; the technology is only economically viable at a length greater than 30 km. Scale testing is not profitable. TSGs provide more lucrative alternative.

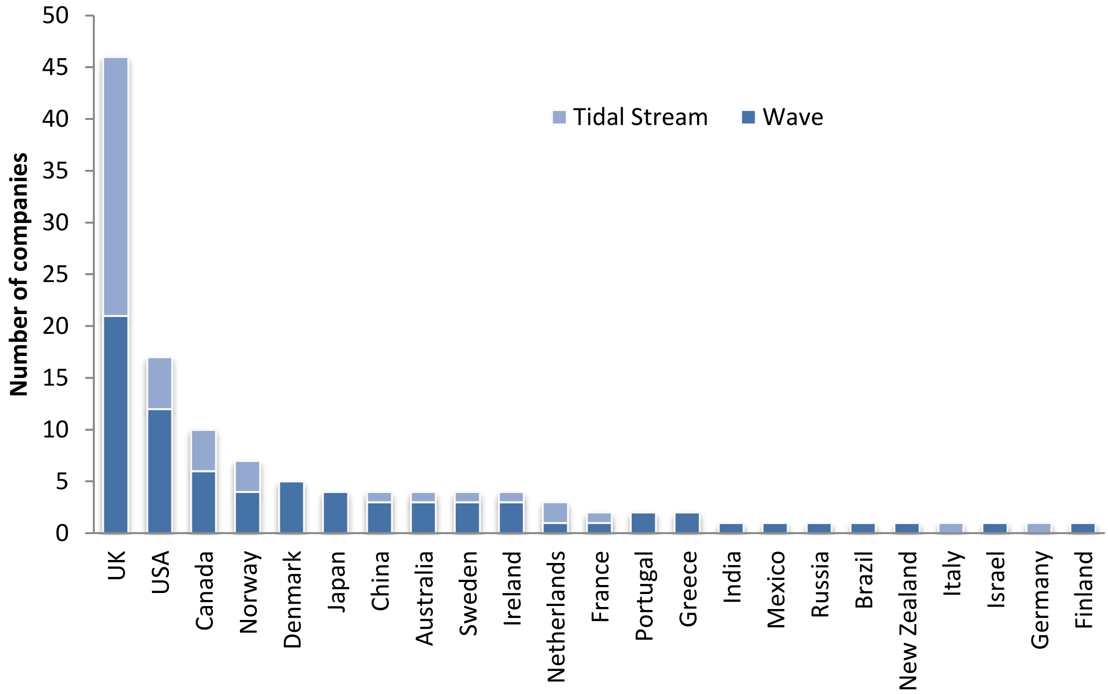
Both of the industries with highest potential - tidal stream and offshore wave - are expected to increase their growth rate around 2018-2020 due to familiarity and confidence with government incentives. The period prior to this is difficult to predict since the change in the framework of support creates an uncertain investment environment.

The UK is currently the market leader and is expected to remain so until at least 2030. Outside of Europe, the US, Canada, Australia and China are expected to have considerable capacity installed by 2030 due to their success with offshore wind, high resource potential and expected government support for wave and tidal projects.

The UK's position in the industry is clear. In the offshore wind industry, the UK and Europe were the first movers and have led the market since. This example is used as a model to predict the global wave and tidal energy market size by country. The countries included in this model are those that have significant resources and are likely to implement government incentives similar to those in the UK. The growth rate has been scaled by the countries' technical potential and a similar growth spurt as expected in the UK industry is assumed. The growth rate is also scaled by the number of companies currently operating in the wave industry (Figure 4.18). The delay between each region entering the market is taken to be the same as that experienced in the offshore wind industry.[69] Until at least 2030, government support will be required to make the majority of projects financially possible. Future government support in these countries is unknown and will play a large part in the progress of this industry.

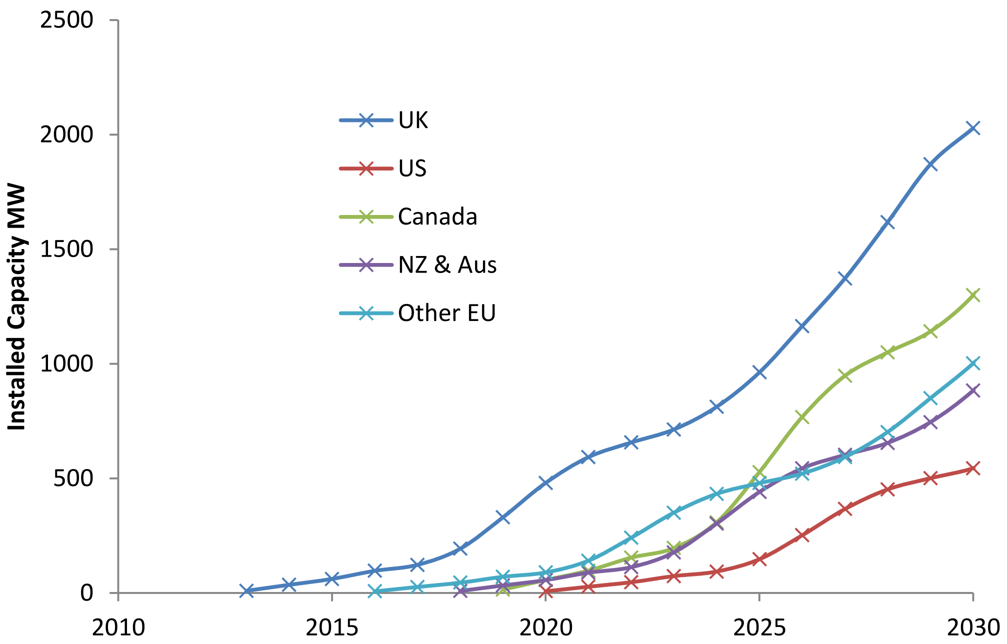
[69] Asmus, *Will Clean Energy Survive the Euro Crisis?*, Navigant Research, 26/10/11: www.navigantresearch.com/blog/will-clean-energy-survive-the-euro-crisis

Figure 4.18: Number of companies active in marine energy



Source: Carbon Trust, Accelerating Marine Energy Report, July 2011

Figure 4.19: Projected capacity by country / region



The data used to create Figure 4.19 was calculated using the UK forecasted growth rate as a basis. Each region's growth was then scaled by its wave technical potential and yield estimates.[70] Each

[70] Gunn & Stock-Williams, *Quantifying the Potential Global Market for Wave Power*, International Conference on Ocean Engineering 2012:

region was then assigned a delaying factor derived from experience in the offshore wind industry. Comprehensive information on tidal potential could not be found so the scaling factors used above are based solely on wave data. This will introduce a bias for some countries that have large tidal resources and low wave resources or vice-versa. The category 'Other EU' contains Spain, Portugal, Ireland, France and Norway.

The total marine power produced by 2030 from the countries considered above is forecasted to be 10.2 GW. This is equivalent to 89 TWh per year, which is a conservative estimate and represents a very small proportion of the total available energy. Nevertheless, this would provide a good alternative to fossil fuels and would represent a 2.1 GW output to the grid in the UK.

Developments to harness marine energy for power in the Asia-Pacific region are given in Table 4.11. EMEC has signed five Memorandum of Understandings to help to set up testing facilities in five locations across Asia, including the Ocean University of China.

Table 4.11: Marine energy developments in the Asia-Pacific region

Country	Current marine capacity	Targeted marine capacity	Details
Australia	0.25 MW	N/A	Two tidal and wave centres were operational as of early 2014. Small-scale and pilot projects have been installed in Australia. There are four commercial wave energy power generation projects and three tidal energy power generation projects planned with the first due to come online in late 2014. Of these, 25 MW of wave energy projects are scheduled for the coming decade and 535 MW of tidal energy projects are in the early planning stages.[71] Carnegie Wave Energy Limited signed a power purchase agreement to sell electricity from their Perth Wave Project to the Department of Defense. The power plant will have an installed capacity of up to 2 MW.
Indonesia	0.02 MW	N/A	The Indonesian Ocean Energy Association (INOCEAN) was set up in January 2011 to research, develop and promote the use of marine energy in Indonesia. It has estimated the practical marine energy power potential of Indonesia to be 49 GW, which is composed of 4.8 GW of tidal power, 1.2 GW of wave power and 43 GW of ocean thermal power. It believes that 6 GW can be exploited by 2030. INOCEAN proposed a pilot grid-connected marine energy power plant. It will begin operating in the course of 2014 and at least 1 MW of power will be generated from tidal currents and 1 MW from wave power. In October 2013, the Government was involved with a focus

http://www.icoe2012dublin.com/ICOE_2012/downloads/papers/day3/POSTER%20SESSION%204/Clym%20Stock-Williams,%20E.On.pdf

[71] http://www.ey.com/Publication/vwLUAssets/EY-Ocean-energy-Rising-tide-2013/$FILE/EY-Ocean-energy-Rising-tide-2013.pdf

			discussion group concerning their role in the proposed South-East Asia Marine Energy Centre (SEAMAC). The Government has proposed contributing finance to the SEAMEC.
Japan	N/A	N/A	EMEC signed a Memorandum of Understanding with the Ocean Energy Association of Japan (OEAJ) in 2012 to help develop Japan's first marine energy test centre. The second Asian Wave Tidal Energy Conference Series will be held in Tokyo on 28th to 30th July 2014. The updated 2014 Japanese Energy Policy does not provide specific renewable energy electricity generation targets. OEAJ's roadmap targets for wave energy converters are 51 MW by 2020, 2,176 MW by 2030 and 7,350 MW by 2050; the targets for tidal energy turbines are 130 MW by 2020, 760 MW by 2030 and 2,400 MW by 2050; and the targets for ocean thermal energyconverters are 510 MW by 2020, 2,550 MW by 2030 and 8,150 MW by 2050. Kawasaski Heavy Industries is testing its tidal energy system at EMEC. The front end engineering design has been completed but no turbine has been deployed as of July 2014. Torcardo delivered their first tidal turbine to Japan in October 2012. The company has signed a dealership contract with Spectol Power Design Company. Together they hope to secure 18 MW of supply deals by 2015.
New Zealand	0 MW	N/A	Three tidal projects are in the early planning stages for New Zealand. The total combined installed capacity of the projects is 211 MW.
Phillipines	0 MW	70.5 MW by 2030	35.5 MW of the targeted installed capacity is planned for Luzon by 2020. By 2025, Visayas and Mindanao will host a further 11 MW and 24 MW, respectively. All the planned projects are under 10 MW. The Phillipines targets the operation of its first ocean energy facility for 2018.
Singapore	1 MW	N/A	In November 2013, Professor Subodh Mhaisalkar, Executive Director of Singapore's Energy Research Institute at Nanyang Technological University signed a Memorandum of Understanding with Stuart Baird, the Operations Director at EMEC, to set up a testing centre in Singapore for marine energy technology, known as South-East Asian Marine Energy Centre (SEAMEC). Nanyang Technological University has been researching two sites as future marine power generation sites.
South Korea	344 MW	~3 GW, 15.86% of the installed capacity of new renewable energy	South Korea has large-scale tidal barrage projects operating and under construction. The Uldomok tidal plant opened in 2009, which began generating 1.5 MW but was increased to 90 MW in 2013. The Shiwha Lake Tidal Barrage power plant, which began operating in 2011, has a capacity of 254 MW and is the largest tidal power plant in the world. South Korea has high potential on the west and south

		sources by 2024	coasts. The 1,320 MW Incheon Bay and 840 MW Gangwha tidal power stations are under construction and due for completion in 2017. A 50 MW tidal stream project will be developed in Wando. Korea East-West Power and Daewoo Engineering & Construction will develop the 254 MW Ashan Bay tidal power plant. EMEC signed a Memorandum of Understanding with Incheon Metropolitan City in 2012 to provide technical assistance on the establishment of a tidal energy testing facility.
Taiwan	N/A	200 MW by 2025	The north-east offshore region region has high wave energy power generation potential, whereas Kuroshio path and the Pescadores Channel on the east coast have very high tidal energy power generation potential. EMEC signed a Memorandum of Understanding with the National Taiwan Ocean University (NTOU). A further agreement was signed by Taiwan's Industrial Technology Research Institute (ITRI) and Aquatera, an Orkney-based consultancy. ITRI is developing a point absorber wave energy converter which has been tested at a site located near to NTOU.
Thailand	0 MW	2 MW by 2021	The Thai Government will invest in a 2 MW of marine energy installed capacity as part of its Alternative Energy Development Plan: AEDP (2012-2021). The 2 MW can be generated in any form (tidal, wave or ocean thermal energy conversion). The absence of a quantative assessment of Thailand's marine energy resources means that no other projects are planned. Companies have approached the Government but the Government's assessment criteria were unfulfilled, such as the requirement for previous projects completed.

4.5 Summary of the Investment Outlook

The wave and tidal energy industry is growing, both in the UK and globally. It requires considerable government support at the current stage and will continue to do so for the foreseeable future. Many industry leaders claim devices will be cost competitive by 2020. In countries where this support is available, the potential of the sector is vast.

Tidal energy technology is more advanced than wave energy techology and has a lower level of risk due to fewer uncertainties. This industry is likely to produce the highest capacity for the next five years and be a large producer until at least 2030. Government support is available for tidal energy and is promised throughout this period. In Scotland, the level of support for wave power was increased from two to five ROCs, equivalent to 21.01p/kWh. This increased support demonstrates both the higher potential and the greater need for advances in this technology.

As shown in Figure 4.8, the potential for electricity production from wave energy in the UK and globally is huge (80 and 2,131 GW respectively). Most of this potential is offshore and so difficult to access. The current cost of wave energy is considerably higher than that of tidal due to the more challenging conditions in which the devices must survive. There is also a much greater variety of devices in the wave energy industry, demonstrating a higher level of uncertainty and risk. Only the most efficient devices will be successful in the long-run and although the diversity of the conditions will allow for some variety in technologies, there will undoubtedly be companies who struggle to compete.

The Pelamis is the most advanced offshore wave device, whilst the Oyster 800 is the leader in the nearshore environment. Both companies are planning to deploy small-scale arrays in the next five years. Array effects are understood to an acceptable level in the tidal energy industry. In the wave industry they are unstudied and will therefore present more difficulties. The most advanced onshore device, the Limpet, has been in operation for over 20 years; however it has proven unpopular due to its visual impact.

According to Aquamarine Power, waves are the most advantageous resource because waves hold advantages over both of tidal and wind energy sources. They are more predictable than winds and will be available when tides are not flowing fast enough to generate electricity. The scale of opportunity is much greater than the tidal opportunity.

Table 4.11 compares the industry to offshore wind using the Oyster 800 as a model, and Aquamarine Power's predicted cost of arrays. Since government support will ensure the industry's survival for the foreseeable future regardless of profitability, this prediction will only serve to demonstrate whether these technologies may be deployed without this support. High cost is taken at £7 million per 5 MW array, medium cost at £5 million per 20 MW array, with low cost at £3.5 million per 20 MW array. Capacity factor is assumed to be 30% year round and the capital cost of offshore wind is modelled at £100/MW.

Table 4.11: Capital cost projections for the Oyster 800

	Capacity (MW)	Energy (MWh)	High Cost (£million)	Medium Cost (£million)	Low Cost (£million)	Offshore Wind (£million)
Oyster 800	1	2629.5	1.4	0.25	0.175	0.263

This projection shows that if the expected medium price reductions occur, the Oyster will be self-sufficient, and if the lower estimate eventuates, it will be highly advantageous over offshore wind.

CHAPTER 5: TECHNOLOGY CASE STUDIES

Table 5.1: Tidal case studies

Project	Developer	Type	Capacity (MW)	Development stage	Location	Potential	Advantages
SeaGen	Marine Current Turbines	Dual turbines mounted onto a crossbar which is attached to the mast	2	Commercial unit has been operational for 4 years	Strangford Lough, Northern Ireland	Dependent on array size	Easy turbine access for maintenance. 4 years of successful testing. Demonstrated to have minimal impact on local ecosystem
Flumill	Energy Project Management	TSG, Archimedes Screw	2.2	Demonstration. Commercial, 2.2 MW unit to be completed in 2014	Commercial development, Rystraumen near Tromsø, Norway	Dependent on array size	Design minimises turbulence and prevents vapour cavitation
SR-2000	Scotrenewable Tidal Energy Ltd	Floating 2 turbine units	2 MW at 3 m/s flow	250 kW prototype deployed	EMEC, Orkney, Scotland, UK	Dependent on array size	Streamline device for storm condition survivability
Tocardo Turbines	Tocardo Tidal Turbines	TSG, Singular turbine units	0.1 – 0.2	0.1 MW available for deployment. 0.2 MW to be completed in 2014	Den Oever, Netherlands	Dependent on array size	Direct drive system (no gearbox)
Delta Stream	Tidal Energy Ltd	TSG, 3 turbines per unit, arranged onto a triangular base	1.2	Demonstration	Ramsey Sound, Pembrokeshire, Wales	10 MW array is the next step. Dependent on array size	Robust. Patented rock foot mounting. Eco friendly
Kepler Energy	Kepler Energy	2nd generation horizontal turbine	4.4-5.3 MW	Scale Model 1:20	Newcastle University	Dependent on array size	Large unit capacity
BlueTEC	Bluewater	Floating platform	N/A	Research and development completed	Hoofddorp, Netherlands	Dependent on array size	Easy to install, inspect and maintain turbines

5.1 Tidal[72]

5.1.1 SeaGen, Marine Current Turbines

5.1.1.1Technological features and competitive advantages

The SeaGen turbine was developed by Marine Current Turbines (MCT), a subsidiary of Siemens since March 2012. It consists of a 54.6m surface penetrating central tower which houses a crossbeam and a dual turbine configuration - a turbine is attached at either end of the crossbeam. Each turbine has a rotor diameter of 16m. It allows for easy turbine access for maintenance, which lowers costs by allowing all necessary repairs to be conducted onsite.

The turbine blades can be pitched through 180 degrees, using a patented mechanism, in order to face the tidal current when it changes direction.

The main tower provides a winch system that permits the crossbeam to be lowered or raised whenever it is necessary to do so. The crossbeam is composed of erosion protected steel and iron, and weighs 92 tonnes. The freedom associated with the ability to raise and lower the crossbeam allows the turbines to be positioned at a depth where the tidal stream velocity is greatest, optimising the amount of energy it can harness.

All electrical infrastructures that are required to create grid-compliant electricity are housed on the SeaGen mast. Without the requirement for external power conditioning it is easy to link together several SeaGen in series, reducing cabling costs.

The Seagen has been deployed in its operational environment for over four years in Strangford Lough, Northern Ireland. During this time Seagen has been subjected to substantial and rigorous marine environmental testing and has been found to have little or no impact on the local marine ecosystem.

5.1.1.2 Development status

The SeaGen technology has been developed over many years, with an increment in capacity at each stage of development. Initially a 15 kW proof-of-concept device was installed at Loch Linne, followed by a 300 kW system at Lynmouth, Devon. MCT has now had their 1.2 MW commercial SeaGen unit installed at Strangford Lough, Northern Island for several years. The development process for a 2.0 MW commercial variant of the unit installed at Strangford Lough is currently underway. The scaled-up unit will possess an increased turbine diameter of 20m which will require deeper waters for deployment.

MCT intends to apply for a site lease in Pentland Firth for the development of an array. They have proposed to start the project by developing a 50 MW array of the 2.0 MW Seagen units, which they hope to be complete by 2015. Furthermore, they hope to expand this initial array to 300 MW by 2020. Agreements for Lease for three new commercial-scale tidal projects were agreed with the Crown Estate. The projects will be located in Mull of Galloway on the west coast of Scotland, Portland Bill on the south coast of England and Strangford Lough in Nortern Ireland.

[72] Unless otherwise stated, all material in this chapter is from direct interviews with each company, or sourced from company promotional material.

MCT agreed to jointly develop a 2 MW floating tidal turbine with Bluewater in April 2014. The turbine known as SeaGen F will be installed in the Bay of Fundy, Canada.

Table 5.2: Timeline of SeaGen

Development Stage	Location	Capacity (MW)	Year
Commercial Unit 1.2 MW	Strangford Lough	1.2	In operation now
Commercial Unit 2.0 MW	TBC	2.0	2014/2015
Small Scale Array	Pentland Firth	50	2015
Full Scale Array	Pentland Firth	300	2020

Figure 5.1: SeaGen device in raised position

Source: Siemens Press Picture[73]

5.1.1.3 Finance and Business strategy

In 2010, Siemens invested in shares of MCT, and in 2012 Siemens decided to purchase all shares of the company in order to become a leading original equipment manufacturer in the tidal power market.

In April 2014, MCT received £1 million from the Regional Growth Fund for research and development into blades and to establish a tidal turbine manufacturing facility.

The 2.0 MW commercial SeaGen devices, which are to be developed for deployment in arrays, will incur smaller capital costs because the designing stage of the process has been completed already.

Owing to the winch system, any maintenance of repairs that the SeaGen unit requires can be carried out onsite. Due to this versatility the expensive vessel transportation of components back to shore is

[73] http://www.siemens.com/press/en/feature/2012/energy/2012-11-seagen.php

not required, minimising the O&M expenditure. The SeaGen produces energy at a very competitive levelised cost.

5.1.2 Flumill, Energy Project Management (EPM)

5.1.2.1 Technological features and competitive advantages

Flumill is unlike any other type of tidal turbine currently in operation or undergoing testing. It is a helical device based on the Archimedes Screw architecture, which is fastened to the seabed at one end and floats buoyantly at the other end. The helix experiences drag from tidal streams, causing it to rotate. The mechanical energy is converted into electricity by a generator.

A single Flumill unit is a module consisting of a foundation, which is pre-installed on the seabed, a steel transition plate, which houses the helical devices, two generators, two helical devices, and a top fin which controls the buoyancy of the devices.

When there is a slack tide the device sits vertically upright in the water, and when under load from a tidal stream the device pitches at around 45°. The device pivots in two different directions allowing it to generate electricity from an ebbing or flowing tidal stream.

Figure 5.2: Diagram of Flumill device

Source: EPM

The Flumill design is optimised for tidal streams located 2-3km away from shorelines. At this distance it is not necessary to install substations to transmit electricity to the shore.

The Flumill's helical design produces slow mechanical rotation, which requires a gearbox to turn the generator to an optimal number of revolutions per minute.

Owing to an innovative helical design, the Flumill minimises production of turbulence in its surroundings. It also minimises cavitation effects, increasing survivability and reducing expenditure on repairs. The Flumill can be orientated vertically or horizontally; mounting the Flumill horizontally, to its foundation, allows for exploitation of waters shallower than most other devices in the market. The Flumill uses a quick release mechanism to detach itself from the foundation unit. The quick release mechanism makes any necessary repairs and maintenance a quick process. While a Flumill unit is under repair or inspection, a secondary device can be deployed to the same foundation unit in order to minimise downtime.

5.1.2.2 Development Status

EPM has deployed and tested a 300 kW demonstrator model of the device within the intended operational environment at the EMEC facility, just off the coast of Orkney in Northern Scotland. The demonstrator has been subjected to substantial and successful testing, as well as a number of computational fluid dynamic (CFD) simulations. These CFD simulations agree that the Flumill's robust design can stand up to the harsh conditions, experiencing minimal turbulence and no cavitation damages. The CFD simulations were performed by two separate and independent facilities, using different software.

Once funding has been found then the construction and deployment of the commercial model can commence. EPM hope to achieve the deployment of the 2.2 MW device in late 2014.

Provided investors come forward and show interest in the project, EPM believe commercial arrays of Flumill devices could be deployed in the coming decade. The expected capacity of commercial units is 2.2-3 MW, although smaller-scale units of approximately 300 kW will be able to be installed. Initial arrays in the next two to three years are expected to be about 10 MW and arrays in the 2020s are expected to be over 100 MW.

Figure 5.3: Full size Flumill device

Source: EPM

5.1.2.3 Finance and Business Strategy

The current cost estimate by EPM for the development and deployment of the first commercial Flumill unit is £16 million. According to EPM, the cost of the subsequent commercial units, with array potential will cost £5 million as design costs are no longer required, which is equivalent to £1.6-2.27 million/MW. The costs of deployment are minimised by the use of a multicat vessel, which can be used as the device is buoyant; these vessels cost £4,000-£5,000 per day to charter. Furthermore, the company's Chief Financial Officer, Neil Madden, has suggested that the O&M costs of the Flumill can be as low as £485,000 over a period of five years. The small size of these expenditures reflect many innovative design features of the device, such as the absence of moving parts in the turbine, the low RPM required to generate substantial quantities of power, and the helical shape minimising turbulence. The levelised costs of electricity are £0.08-0.18/kWh.

EPM are currently seeking an investment partner to aid with both the design and financing of the commercial Flumill device. They are looking for an investment of £8 million to contribute towards the £16 million they require for the design and construction of their first commercial device. It is hoped that this investor could provide added value in the direct development of the Flumill, including the design, engineering and construction of the device.

Neil Madden has said that the ideal investor would bring value to the company; the value that EPM are looking for could be in terms of support in the direct development, design, engineering, construction or installation and operation processes.

EPM considers one of the main difficulties of finding an investor to be the hesitancy towards the innovative design of Flumill. With a design that differs substantially from the standard wind turbine architecture, the device has a far shorter history of successful operation. However, the Flumill has been tested successfully, as mentioned above, and investors should not be deterred by the innovative and robust structure.

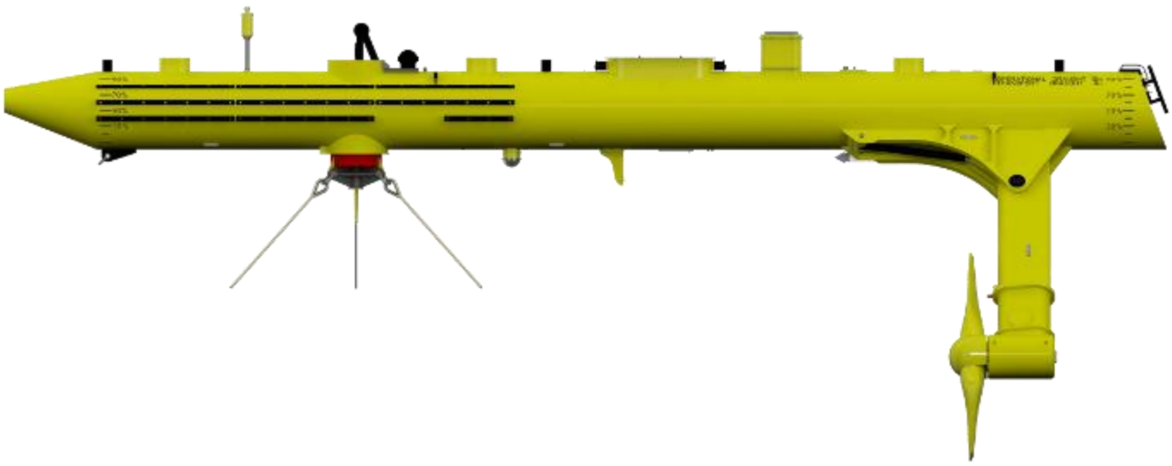
5.1.3 SR-2000, Scotrenewables Tidal Power Ltd

5.1.3.1 Technology Features and Competitive Advantages

The SR-2000 unit was developed with minimal installation and maintenance costs. It weighs 100 tonnes and consists of a floating cylinder body, approximately 33m in length. The main body hosts two arms with a turbine attached at the end of each arm. The arms fold in when the unit is transported or in storm conditions to prevent the device becoming subjected to excessive stresses. It has been designed to be deployed offshore, and to survive harsh open ocean conditions. It has a design life of 20 years. The floating platform architecture allows the device to utilise the highest tidal velocities that are present close to the water surface, which typical seabed mounted devices cannot reach.

The SR-2000 has a fixed pitch rotor designed to minimise the number of moving parts in the unit. This reduction in design complexity results in lower O&M costs. The typical number of units per array will be 5-15.

Figure 5.4 The SR-2000 concept



Source: Scotrenewables

The catenary mooring system consists of several lines that are cast from a single turret on the unit to the seabed. Quick mechanical and electrical disconnection and reconnection, typically a 30 minute process, is facilitated by this patented mooring method. The turret connection allows the SR-2000 to rotate itself in order to face the tidal flow. Furthermore, the survivability of the unit is vastly increased by the high levels of elasticity of the mooring method. This mooring method is also significantly less expensive - both to install and to construct - than traditional seabed mounted or piled structures.

5.1.3.2 Development Status

In March 2011, Scotrenewables deployed a full-scale 250 kW prototype of their SR-2000 unit, the SR250, at the EMEC facility. This unit was preceded by numerous smaller-scale models. The SR250 has demonstrated fully operational behaviour in gale force conditions with no failures, and even managed to surpass its 250 kW rating to powers greater than 280 kW in strong spring tides.

The development, deployment and testing of the SR250 has been a useful experience for the company in preparation for their 2 MW commercial project. In 2014, a scale model of 2 MW SR-2000 is under construction and will be demonstrated at EMEC from 2015. SR-2000 is designed to be fully commercial. It is predicted that the capacity of the SR-2000 unit will not increase up to 2020 but might increase to 5 MW in the 2030s. Installation of the first array will take place in 2015. The process undertaken for the SR250 to reach the deployment stage has allowed Scotrenewables to gain experience in all procedures associated with the construction, design and testing of the device.

Table 5.3 Model comparison

Device Property	SR250	SR2000
Power (kW)	250	2000
Mass (Tonnes)	100	400
Rated Tidal Velocity (m/s)	2.5	3.0
Rotor Diameter (metres)	8	16

Table 5.3 shows that the SR-2000 will have a much greater power to mass ratio which will drastically decrease the cost of electricity production.

5.1.3.3 Finance and Business Strategy

Scotrenewables have made their technology very cost competitive by striving to keep their technology simple and robust. Due to the high power-to-weight ratio for the SR-2000, the installation cost per MW of power generation is substantially lower than competing technologies, which also reduces the cost of materials. Installation costs are reduced further by the patented quick release connection mechanism with the mooring lines. Installation costs will be under £500,000 for a 2 MW unit.

The relatively lightweight design of the SR-2000 allows it to be deployed and retrived using a multicat vessel as opposed to the DP vessels that are used in the oil industry. These small vessels cost just £2,500-£4,000 per day to charter, in contrast to the DP vessels, which can cost up to £150,000 per day.

The execution cost of a single SR-2000 unit will be £6 million. Due to the floating design of the SR-2000, any maintenance required can be carried out on site without returning it to land which is convenient and also keeps O&M costs down. O&M costs will be £200,000/MW at the beginning but will quickly go down to £100,000/MW. 80% of the maintenance costs have been for the replacement of small components. The levelised generation costs for a 10 MW array will be £150-200/MWh. Table 5.4 shows an overview of the estimated costs for the development of the first 10 MW array project which will be installed by 2017.

Table 5.4 Expected costs of the first 10MW array

	Optimistic	Expected	Pessimistic
Capital cost (£million)	25.02	26.03	28.02
Capital cost per MW (£million)	2.50	2.60	2.80
Operating cost per annum (£million)	1.60	1.98	2.35
Decommissioning cost (£million)	0.89	0.93	1.0
Annual Energy Production per year (GWh/year)	30.59	24.85	19.12

Source: Scotrenewables, *Technology Update*, May 2012[74]

Figure 5.5 Cost breakdown of the SR-2000 lifecycle

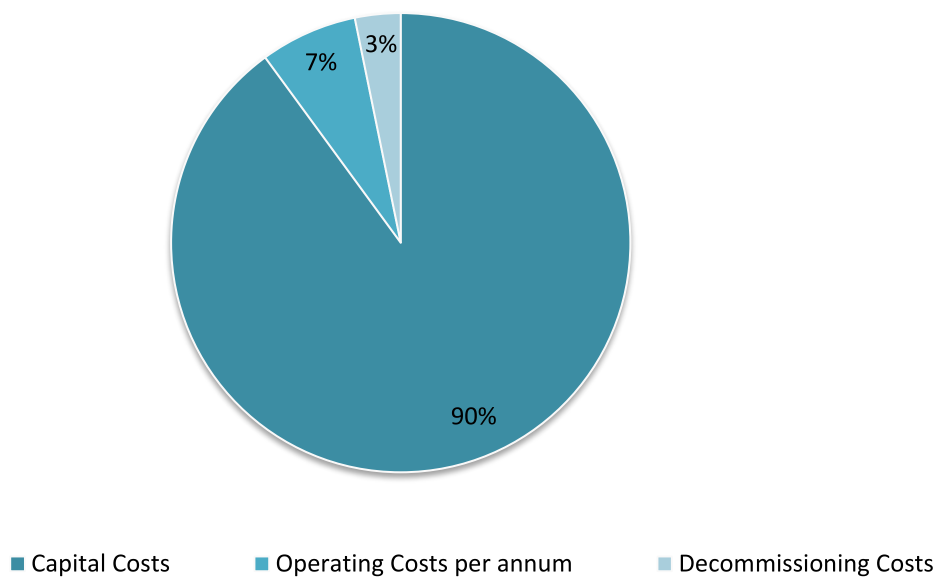


Table 5.6 Generation costs

Discount rate used in calculating cost	Indicative generation cost (p/kWh)		
	Optimistic	Expected	Pessimistic
8%	13.62	18.73	27.34
15%	18.32	24.75	35.76

[74] http://www.all-energy.co.uk/_novadocuments/14981

5.1.4 Tocardo Turbines, Tocardo

5.1.4.1 Technological features and competitive advantages

Tocardo's vision for their turbine was to create a device with minimum costs and a simplistic design. The Tocardo Turbine is a dual bladed, horizontal axis turbine. Its rotor design, which is patented by the company, is such that the blades can rotate about an axle in order to change their direction to face the tide. It features a direct drive system between the rotor and generator, requiring no intermediate gearbox. Preventing gearbox failure is one of the most difficult technical challenges manufacturers have to face. Gearboxes are also a source of inefficiencies.

The turbines can be either installed onto buoyant structures or fixed to the seabed. Four different types of foundation are offered by Tocardo depending upon the project site. The turbines produced by Tocardo are available in various sizes and capacities, ranging from 0.1 MW river and inshore tidal current turbines to 1 MW offshore tidal current turbines. Turbines mounted onto buoyant platforms are easy to recover and return to shore for maintenance and repairs, which helps to minimise O&M costs.

Figure 5.6: Tocardo turbine

Source: Tocardo Tidal Turbines

Tocardo's initial commercial-scale projects will have foundations that hold two turbines capable of producing 1 MW. Depending on the site, a single foundation could hold up to 2 MW of turbine capacity. Since January 2014 Tocardo received orders for 11 turbines and are expecting more orders. Commercial sale units will be between 100-500 kW per Tocardo turbine and commercial projects are likely to be 30 MW.

Table 5.7 exhibits the various turbines that Tocardo offer including the area that each turbine sweeps out.

Table 5.7 Tocardo turbine model comparison

Turbine Technology	Power Output Range	Site Suitability	Development Stage	Area Swept (m^2)
T100	42 – 98 kW	Rivers, Canals, Shallow Tidal sites	Available	7.7 – 31.2
T200	87 – 200 kW	Inshore and Offshore Tidal Sites	Available	15.8 – 63.7
T500	232-520 kW	Offshore	Available in 2014	39.9 –158.5

5.1.4.2 Development Status

Tocardo has developed a commercial 100 kW model that is currently available for deployment as well as a 200 kW model that is under development and is expected to be deployed for testing in the second quarter of 2014. Tocardo presently has an on-going project in Den Oever, Netherlands. The project, which commenced in 2005, began with the installation of a proof of concept turbine but was then replaced with a commercial T100 turbine that could produce power outputs of 98 kW. This turbine has been producing electricity for the Dutch grid ever since.

Tocardo's Oosterschelde Storm Barrier project that is currently in the planning stages will consist of a 1 MW array of their T200 turbines. It is anticipated that once the turbines are in place at the Dutch Delta Works the array will be capable of producing electricity for an estimated 700 Dutch homes.

5.1.4.3 Finance and Business Strategy

Tocardo has become a strong competitor within the industry by creating a versatile range of turbines that can exploit almost any tidal stream, from a small river to an entirely offshore expanse of seabed.

The capital expenditure required of a typical 10 MW nearshore array can be broken down as shown in Table 5.8. Developing a project at a greater distance from the shoreline would cause an increase in all components contributing to the capital expenditure, except the device. This increase would arise due to an increase in the quantity of cabling required and the added complexities of installation at greater depths. The installed cost per MW of a commercial-scale Tocardo turbine is estimated to be £4 million.

Table 5.8 Cost breakdown of a 10 MW array

Cost Breakdown	Percentage of Capital Expenditures
Turbine/Energy Converter Device	30.0
Installation	17.5
Foundation	17.5
Offshore Substation	17.5
Cabling	17.5

According to Tocardo representatives, the levelised cost of electricity generation of the turbines based on their models would be less than that of offshore wind or solar PV, regardless of government incentives such as ROCs, but higher than that of onshore wind and grid parity. There are four main considerations for Tocardo in the development of demonstration projects and cost estimations for commercial projects: capital expenditure, operational expenditure, tidal energy project yield and cost of capital. The turbine has been the most costly capital expenditure and the foundation cost was said to be 70% of the turbine cost. The only maintenance cost is an oil change after ten years. However, a partner Repsol is developing an oil that will last 20 years, so it will no longer be a problem.

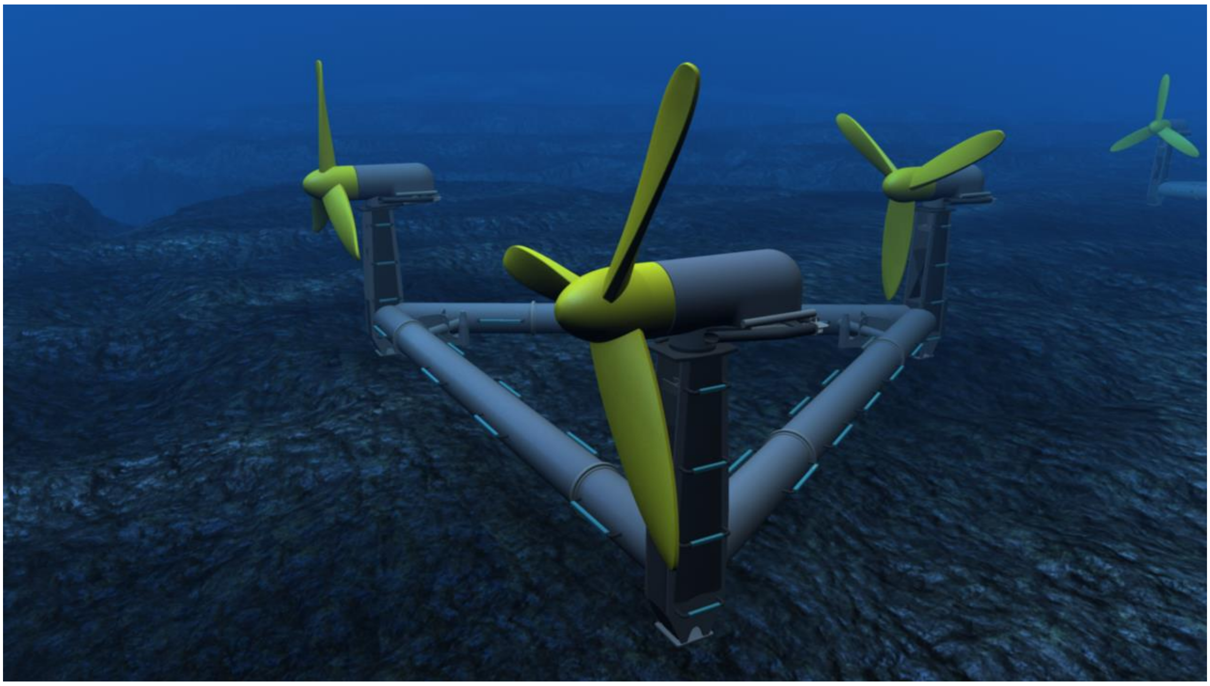
5.1.5 DeltaStream, Tidal Energy Ltd

5.1.5.1 Technological features and competitive advantages

The DeltaStream unit has a triangular steel main base frame with rock feet. Sitting on the seabed, the frame supports three independent turbine generators. The Fibre Reinforced Plastic nacelles, which host DeltaStream's rotors, are built to withstand the stresses experienced in the challenging underwater environment. The use of three smaller turbines instead of one with a larger swept area gives DeltaStream a technological advantage over its competitors; the lower stresses increase the lifetime and reduce the need for maintenance. The blades are fitted onto a mechanism that allows for a variable swept area, and fold in or out at an angle to their rotational axis. The angle can be adjusted to suit the state of the tide and to maximise energy production while minimising cost.

Tidal Energy Ltd doesn't manufacture any of the components of the DeltaStream technology. Generators are sourced from a company that makes submergible generators for underground mines. The blades themselves are designed by Tidal Energy Ltd but manufactured by a company that possesses a long history of wind turbine blade production. This sourcing ensures high quality components at industry prices. Furthermore, developments in any of the relevant industries could lead to better components for DeltaStream without the need for extensive research.

Figure 5.7 The DeltaStream concept



Source: Tidal Energy Ltd

The DeltaStream device mounts all of its electrical and control systems onto its triangular base. It is a nearshore device utilizing a submarine power cable to transmit electricity back onshore for conversions and transmission to the grid. This has a significant cost advantage over the alternative, an offshore substation.

DeltaStream also features an automated control system that minimises the stresses exerted on the generators to prevent damage. Due to the triangular base together with the innovative rock foot design, drilling or piling is not required for it to remain secured to the seabed.

Extensive CFD testing has been carried out on scale models of the DeltaStream technology, at the French Research Institute for Exploitation of the Sea (IFREMER). The device also supports a marine environment monitoring system that distinguishes wildlife, such as dolphins, from debris.

The unit as a whole will generate 1.2 MW once it is ready for commercial deployment. In ten years, Tidal Energy Ltd hopes to upgrade the capacity of each nacelle to 1 MW, giving the unit a total capacity of 3 MW.

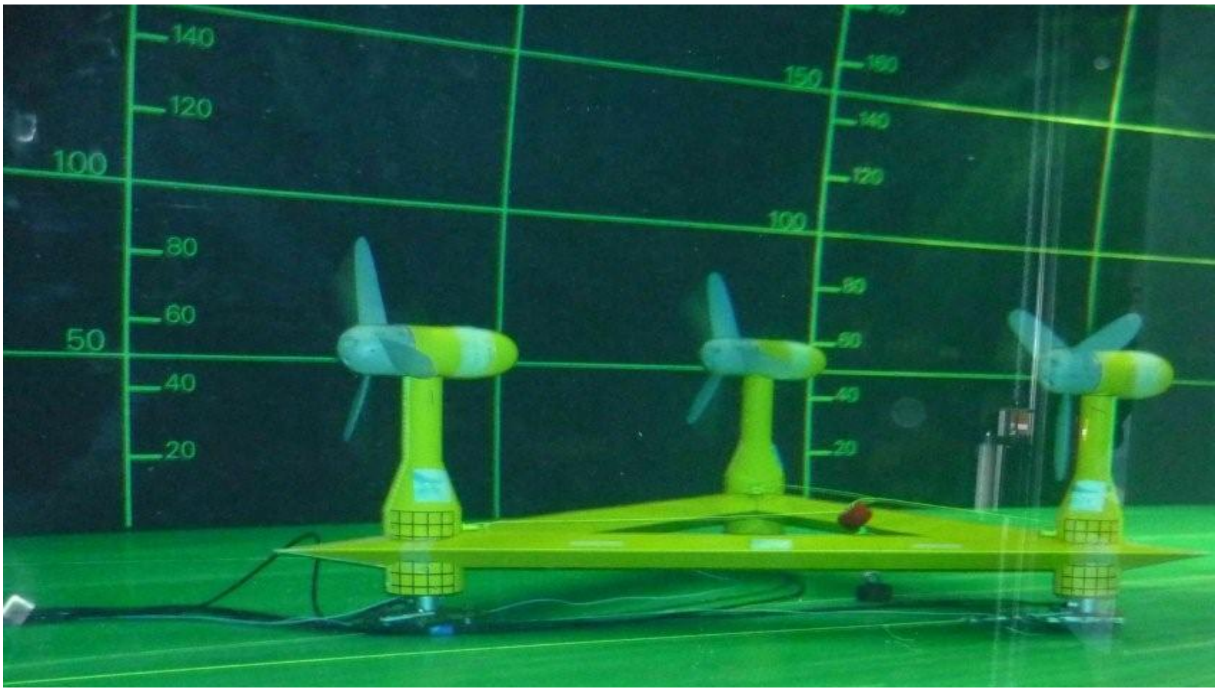
5.1.5.2 Development Status

Work is currently underway to enable the first commercial-scale DeltaStream unit to be completed by the end of 2013 or the beginning of 2014 at Ramsey Sound (Table 5.9). The device will be connected to the local electricity distribution grid to aid the Welsh Government with their renewable energy targets.

Table 5.9 DeltaStream development timeline

Development Stages of the DeltaStream Technology		
Stage	Capacity	Date of Deployment
Single Nacelle Prototype	400 kW	Spring 2014
Single Commercial Unit	1.2 MW	2014-2015
Commercial Array	≈10 MW	≈2018

Figure 5.8: Testing of the DeltaStream device



Source: Tidal Energy Ltd

5.1.5.3 Finance and Business Strategy

According to Tidal Energy Ltd, once the first commercial unit has been completed and subjected to testing, there will be a substantial reduction in capital costs for future units due to the absence of design costs. Tidal Energy Ltd also estimates the proportion of funding that would go into certain aspects of the construction and deployment of units. These estimations are presented in Table 5.10.

Table 5.10 Cost breakdown of DeltaStream deployment

Cost Breakdown	Percentage of Total Expenditures
Components and Assembly	40%
Installation (Inc. site leasing and consent licenses)	35%
Internal Management Costs	25%

The funding of the first commercial unit has been vastly aided by the Welsh Government. The Welsh Government, through the European Regional Development Fund, was able to grant Tidal Energy Ltd £8 million. Tidal Energy Ltd said that the Government had been incredibly helpful in the financial facilitation of the project and that their support systems were on par with those of the Scottish Government.

At present, the company cannot give a figure for the levelised cost of electricity for the device as the design costs are currently their most significant expenditure, but it is expected to be competitive with the other devices within the industry. Once the first commercial unit is deployed in summer 2014, Tidal Energy Ltd will be in a better position to estimate the cost of electricity generation.

Tidal Energy Ltd currently holds a year long license for the deployment site of their first commercial unit. Once DeltaStream proves that it has minimal effect on the local environment, they expect to extend this license for the purpose of continual electricity generation. The full-scale prototype is under construction in Pembroke Port and will be deployed in Ramsey Sound, Pembrokeshire in summer 2014. Moorings, cables and deployment of the device will be completed in separate operations by August.

Tidal Energy Ltd and joint venture partner Eco2 have been awarded a lease by the Crown Estate to develop a 10 MW array at St Davids Head. It is due to be completed by 2017 at the project site two miles north of the Ramsey Sound project. Because the architecture of tidal turbines is so similar to that of wind turbines, they believe the deployment of tidal technologies, in an array configuration, will be substantially easier than that of wave energy technologies. They also commented that wave energy devices had a long way to go in terms of survivability to catch up with tidal energy technologies.

The light weight design combined with the innovative rock foot patent ensure that DeltaStream technology can be as light as possible while also not requiring any piling or drilling to the seabed. These features ensure that both installation and O&M costs are minimised. Furthermore, as the device is lighter than competing technologies, material costs are also substantially lower.

By 2020, Tidal Energy Ltd aim to have 25 devices deployed, which they envisage to be approximately 10% of the tidal energy market.

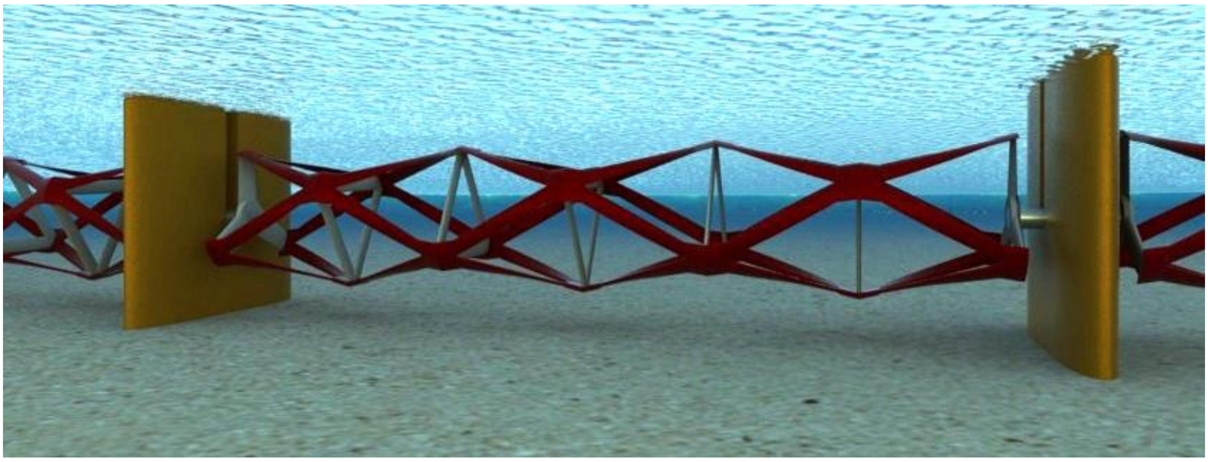
5.1.6 Kepler Energy Turbines

5.1.6.1 Technological features and competitive advantages

The Kepler Transverse Horizontal Axis Water Turbine (THAWT) is a second generation, horizontally orientated, device based on original research carried out at the University of Oxford. The commercial unit is a 60m long cylindrical, horizontal axis turbine with a diameter of 10m; the device has a large, 600m^2 cross-sectional area to capture the energy of the tidal flow. The cylindrical symmetry that the technology exhibits also means that a pitch changing mechanism is not required in order to match the direction of the tidal flow. At each end of the rotor, there is a turbine which drives a central generator. The generator is direct drive and thus does not require a gearing mechanism. The system's generator and control systems are housed on a surface penetrating column at the end of each rotor. The column allows for dry hosting of these important features, improving their survivability and reducing O&M costs. Due to its large cross-section, the device can potentially generate more power than its competitors, and in shallower water.

The twin rotor unit is estimated to produce power of 4.4-5.3 MW in flow speeds of 2-2.5 m/s. The THAWT design is such that the device maintains good efficiency levels even at low tidal flow speeds. Once manufactured, the THAWT is designed to be submerged in waters of 20-25m deep in order to optimise its efficiency. There are very few devices that utilise these shallower waters to the extent that THAWT does. Due to the modular nature of the technology, multiple devices can be strung together with ease, creating a long chain of turbines.

Figure 5.9: Kepler Energy turbine simulation



Source: Kepler Energy

5.1.6.2 Development Status

Kepler Energy has developed a 1:20 scale model prototype which has been tested in a flume tank at Newcastle University. Stress and power measurements have also been carried out on the device.

The next stage of development will be to create a fully commercial unit to be deployed in its operational environment, moving on to develop full-scale arrays. The company hopes to have a 30 MW demonstrator unit completed in 2018. After a successful demonstration, and gaining financial backing, Kepler Energy plans to exploit the Bristol Channel's tidal energy electricity generation potential with a 1.8 GW array. The Bristol Channel peak spring tidal velocity of 2-2.5 m/s is the THAWT's optimum allowing it to make efficient use of the tidal flow for power generation. A £30,000 award from the Shell Springboard competition will be used to assess in detail the potential power output from a tidal fence in the Bristol Channel using the THAWT's turbine.

5.1.7 BlueTEC, Bluewater

5.1.7.1 Technological features and competitive advantages

BlueTEC is a floating platform on the underside of which tidal turbines can be installed. It facilitates easier access to turbines compared to tidal turbines attached to the seabed, which makes installation, inspection and maintenance easier. A further advantage is that energy production increases as 75% of potential tidal energy is in the upper 50% of the sea level. The floating platforms are open architecture so may be integrated with any tidal turbine. For each project, Bluewater works together with the turbine manufacturer to ensure the floating platform can hold the turbine.

The floating platform measures 45-55 meters long and 30-40 meters wide. The expected lifetime of BlueTEC is 20 years and the device is designed to withstand 50 year storm conditions in the harshest tidal environments. It is mainly constructed from steel and is secured to the seabed by a mooring spread. The mooring spread consists of two or four anchor points depending upon the site and turbine characteristics. The mooring system allows for multiple mooring lines to be connected to a single mooring point, which helps to reduce the number of mooring points and the installation time of a tidal turbine farm. Consequently, there is a significant reduction in installation costs. Mooring points can be shared by multiple floating platforms in an array configuration.

The company has experience working in the offshore oil and gas industry, supplying FPSOs. Bluewater has installed fixed, floating and dynamic-positioning mooring systems. Mooring systems have been installed by Bluewater in hostile sea conditions where the height of the waves is over 10% of the water depth.

5.1.7.2 Development Status

BlueTEC has been under development since 2008. The research and development phase, including extensive model testing and the detailed engineering phase, has been completed. Bluewater is working on the interfaces for the integration of the platform with market-leading turbines. BlueTEC is a fully engineered product which is scalable to large-scale tidal turbine farms.

Bluewater is looking for stakeholders to join the company for the development and installation of BlueTEC platforms at tidal sites with commercially viable farms. Bluewater is jointly developing a tidal turbine with Marine Current Turbines, called the SeaGen F. The 2 MW turbine will be installed in the Bay of Fundy, Canada. Plans are under development for the installation of an array close to the Fundy Ocean Research Centre for Energy (FORCE).

5.2 Wave

Table 5.11: Wave device case studies

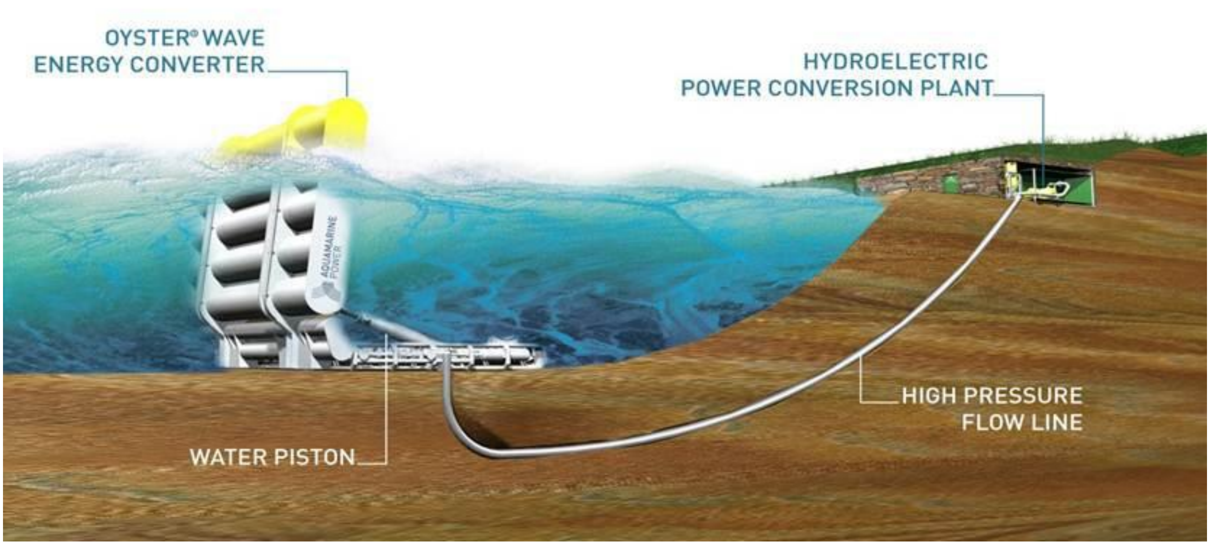
Device	Developer	Type	Capacity (MW)	Development stage	Location	Potential	Advantages
Oyster 800	Aquamarine Power Limited	Nearshore, High-pressure water pumped by wave kinetic energy	0.8 per unit	Full-scale testing	EMEC, Orkney	40 MW planned, dependent on size of array	All electronics onshore. Low O&M costs
Pelamis	Pelamis Wave Power	Offshore attenuator. Section displacement drives hydraulic motor	0.75 per unit	2nd generation operational Further testing ongoing	Peniche, Portugal EMEC, Orkney	Dependent on size of array	Extensive successful testing: durable and commercially ready
Offshore Wave Energy Limited	Wave Energy Converter	Offshore. Oscillating air column	0.35	Demonstration	Cornish Wave Hub	2-3 MW by 2016, dependent on array size	No moving parts in contact with water
40South Energy	40South Energy	Offshore / nearshore, point absorber	0.15	Commercially available. Larger model is under development	Isles of Scilly Airport, various locations Italy	2 MW model planned for 2014	Operates underwater, long lifetime, high capacity factor
WaveNet	Albatern	Offshore/nearshore attenuator. Individual 'Squids' connected in an array	0.0075 per squid 0.045 per WaveNet	1st Generation Development of larger models	EMEC	0.075 squids and 10 MW arrays in 2015	Low initial cost and O&M cost

5.2.1 Oyster 800, Aquamarine Power Ltd[75]

5.2.1.1 Technological features and competitive advantages

The Oyster 800 is a nearshore wave energy converter device. A large, buoyant flap stands upwards from the foundation and acts as a wave-powered pump. This flap is mostly underwater but a small portion is visible above the surface. The flap is orientated horizontally to extract the maximum amount of kinetic energy from the oncoming wave. The flap is then pushed forward by the wave and falls back in time for the next wave. This motion is then used to pump water under high pressure through a pipeline to the turbine and generator which are situated onshore. The fact that they are situated onshore reduces both the installation and O&M costs and allows for easier monitoring of the device through its R&D stages.

Figure 5.10: Oyster set-up diagram



Source: Aquamarine Power

The idea for the Oyster came from research conducted by Professor Trevor Whittaker at Queens University, Belfast. This progressed to scale testing of the Oyster 1 in 2003 which drew considerable interest and funding for the project. The feasibility of the technology was confirmed by 2011 and full-scale sea trials of the Oyster 800 began in 2012. These trials were carried out at the EMEC test facility in Orkney. In 2013 the Oyster began to deliver power to the grid. Each device has a maximum capacity rating of 800 kW and is 26 metres wide, weighing approximately 1,000 tonnes. In ideal conditions the Oyster 800 will be situated 500 metres from the shore in water 13 metres deep. This necessarily varies depending on location.

In 2013, Aquamarine Power upgraded underperforming components of the Oyster 800 after severe winter testing in which the Oyster experienced record 9m waves. These upgrades included new cable connectors, flexible hoses and new accumulators. In June 2014, the device was removed for a summer product improvement programme to increase its reliability. The improvements include cylinder and accumulator modules, onshore works and control and instrumentation upgrades.

[75] Unless otherwise stated, all material in this chapter is from direct interviews with each company, or sourced from company promotional material.

The main technological advantage of the Oyster 800 is that all of the electrical equipment is based onshore. This significantly reduces installation and maintenance costs and avoids one of the largest problems facing the wave industry: how to build electronic devices that have a long lifetime in harsh, underwater environments. Since the electronics are the most common cause of faults and downtime in both wave and tidal energy, this fundamental difference in the Oysters design represents a considerable competitive advantage.

This advantage is further enhanced by the design of the Oyster 800: it has removable modules which enable parts to be detached easily and maintenance to be carried out onshore. The final design will be fully detachable from its foundation but at the current stage only some parts of the device are removable.

5.2.1.2 Development status

In the long term, Aquamarine Power is considering changing the construction of the device to fibreglass and plastic to reduce the weight and production costs. Currently they are upgrading components and looking into the logistics of setting up a supply chain.

Aquamarine Power is in the process of developing a 40 MW wave farm off the coast of the Isle of Lewis in Scotland. They have received full consent for the Lewis Wave Farm and have applied for grid connections in this location. The costs associated with using the grid are a key issue and they are working closely with the Scottish Government to achieve this goal. They are also continuing testing and conducting numerous site assessments across the UK and USA. They hope that their product will be available for a full-scale commercial roll out in a large number of locations in the next 2-3 years.

As well as commercial energy production, Aquamarine Power believes this device will be useful for island communities. Where grid connections are unrealistic, the Oyster 800 can generate all the electricity needed to power an island community from the waves. This unique design can also provide fresh water to these island communities. The sea-water is pumped up to the turbine at high pressure by the Oyster device. This pressure is the exact requirement for the reverse osmosis desalination procedure. Once the sea-water has powered the turbines it can then be used to create clean drinking water for the island. It is niche markets and these additional functions that may become the driving force of wave energy technology in an increasingly competitive energy market.

Figure 5.11: Oyster at sea

Source: Aquamarine Power

5.2.1.3 Finance and business strategy

Aquamarine Power is currently in the demonstration stage of its business and is looking for a business partner to help progress the Oyster to a full commercial level. It estimates that approximately £30 million is required. The business partner will not only allow the company to bring the product to the next stage, but will provide potential customers with a surety of the technology's sound basis and reliability. Aquamarine Power stated that wave energy is probably more challenging than many people expected, but they confidently expect, together with their investors, to be part of its future.[76]

In 2011, Aquamarine Power were the first UK marine energy company to secure bank debt finance in the form of a £3.4 million loan with Barclays Corporate. This level of confidence and support is a great boost to the industry reputation and dependability of the product. So far about £70 million has been spent on developing the Oyster, and large investors include ABB and SSE.[77]

Aquamarine Power expressed their conviction that competitive pricing with offshore wind was an important factor in the success of this, or any marine energy source. They also provided forecasts of the capital expenditure necessary for the first arrays.

- Offshore wind is expected to reach £100 per MWh by 2020, by this point Aquamarine Power expect to have overtaken the wind industry
- Early arrays rated at 5-10 MW would cost between £5.5 million and £7 million to deploy
- Later arrays of 20-30 MW should see a fall in costs to between £4.5 million and £5.5 million
- Eventually the deployment cost of arrays >20 MW may fall to £3.5 million

Aquamarine has received considerable support from EMEC, the Scottish Government and other investors throughout the development stages and is very grateful to these funding sources. ABB holds a large proportion of Aquamarine Power's shares through their venture capital arm along with Scottish and Southern Energy, Scottish Enterprise and Scottish Equity Partners. Government ROCs are in place until 2018 but after that the security of this revenue is unsure. With the appropriate backing, the Oyster 800 should be generating revenue in 3-5 years.

5.2.2 Pelamis, Pelamis Wave Power

5.2.2.1 Technological features and competitive advantages

Pelamis is the market leader in the Wave Energy Converters industry. The company manufactures an offshore attenuator device, 180m long and 1,300 tonnes in weight. The second generation model, the P2, is used in various projects around the world and has a total operating time of over 10,000 grid connected hours so far.[78]

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76 Correspondence with Martin McAdam of Aquamarine Power

77 Donald, *Oyster will offer pearl after gritty wave* tests, The Herald, 14/4/13: http://www.heraldscotland.com/business/company-news/oyster-will-offer-a-pearl-after-gritty-wave-energy-tests-independence-will-enhance-scotland.20766578

78 Pelamis Wave Power, *ScottishPower Renewables Pelamis P2 Machine Celebrates One Year of Accelerated Real-Sea Testing*, 21/5/13: http://www.pelamiswave.com/news/news/134/ScottishPower-Renewables-Pelamis-P2-Machine-Celebrates-One-Year-of-Accelerated-Real-Sea-Testing

Figure 5.12: Front section of Pelamis P2

Source: Pelamis

E.ON and Scottish Power Renewable have an agreement whereby data collected from the Pelamis testing is shared so that the technology can be advanced as quickly as possible. E.ON's Pelamis project came to an end in 2013. They have investigated the survivability, output optimization, environmental impact and the wear on each component. New plans to deploy P2s in a small array in the next three years are a good testament to the industry's confidence in the quality of this device.

Table 5.12: P2 testing record at EMEC

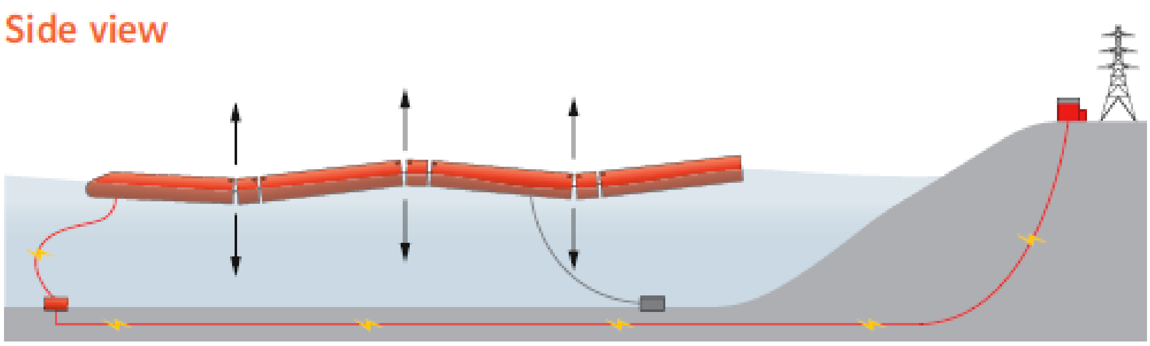
Company	Dates	Performance
Scottish Power Renewables	May 2012-present	Over 7500 grid hours, 160 MWh exported
E.ON	October 2010	Average output of 270 kW and peak of over 400 kW

The P2 floats facing the direction of the oncoming waves. Sections of the body are vertically displaced by the waves and this motion pumps high pressure fluid. The fluid is pumped through an accumulator and a hydraulic motor and a smoothed electricity supply is generated.

The device is one of the earliest types of WEC and it has a high level of design complexity. During extensive testing, the device has shown good survivability and acceptable costs, consequently, this device continues to be a popular choice for offshore wave energy generation. The key component that differentiates this device from many other WECs is the hydraulic motor. This component is readily available and widely used; it is therefore well understood and manufactured to high standards.

The P2 has a rated capacity of 750 kW and can be adjusted to suit different sea states. Deployed in an array, the company predict that this device will give cost effective, commercial outputs.

Figure 5.13: Pelamis set-up



Source: EON, Pelamis wave energy project[79]

Installation costs are a large part of the initial project costs. These are expected to reduce significantly as the relevant developer gains experience with their technology. Pelamis is one of the few companies that have gained enough experience to begin this process: the transportation and installation time for the Scottish Power Renewables device was half that of the device supplied to E.ON.

5.2.2.2 Development Status

The Pelamis device is in its second generation stage. The first generation was a success and was extensively tested and improved upon. Pelamis is demonstrating P2 test machines at EMEC which have reached over 10,000 hours of grid-connected operations and they are commercially available. Three P2 devices are operated in Peniche, Portugal with a combined rated capacity of 2.25 MW, the largest marine project at the time of completion.

Pelamis is currently working on P2e (enhanced), which will be a commercial unit deployed around Scottish waters. Pelamis faces additional problems installing the wave farms as the Scottish Islands require grid connection installations or upgrades. Pelamis are looking at ways to reduce costs without affecting the operation or the longevity of the device. Pelamis Wave Power possesses 170 MW of wave farm sites under active development.[80]

5.2.2.3 Finance and business strategy

The most recent development for Pelamis has been the award of a £1.4 million contract from the Energy Technologies Institute. This was hailed as a re-affirmation of Pelamis' place as the market leader. They are focusing on expanding their capacity and providing a utility-scale electricity supply in the future.

It costs £10,000 for vessels to tow the turbine into place. Installation can be done within 60 minutes as the system does not require a diver or remotely operated underwater vehicle.

The cost per MW installed is expected to decrease significantly as larger arrays are installed. The cost per MW of a 1.5 MW array was £8 million/MW. For a 50 MW and 500 MW array the cost is expected

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[79] http://www.eon-uk.com/Pelamis_demonstration_project_information_sheet.pdf
[80] Pelamis Wave Power, *Pelamis selected for £1.4m ETI wave power project,* 27/2/13: http://www.pelamiswave.com/news/news/127/Pelamis-selected-for-1.4m-ETI-wave-power-project

to be £4million/MW and £2.5million/MW respectively. The levelised cost of electricity is currently £350/MWh. The cost is forecast to drop to £250/MWh by 2018, £150/MWh by 2023 and £100/MWh by 2028-2030.

Pelamis has received a number of grants and a large amount of investment over the years, such as a share of the £13 million Marine Renewables Commercialisation Fund from the Scottish Government. They are one of the few devices expected to be cost competitive with offshore wind and other renewables by 2020. Wave power is pre-commercial. In order to achieve mass deployment, Pelamis needs to get a higher level of funding with more industrial partners.

Table 5.13: Cost breakdown of Pelamis device[81]

	Pelamis (0.75 MW)
First Device	€3.2 million
Installation	€1.6 million
Mooring	€1.38 million
Management	€1.26 million
TPC+cable	€12.6 million

5.2.3 Wave Energy Converter, Offshore Wave Energy Ltd

The Wave Energy Converter (WEC) by Offshore Wave Energy Limited (OWEL) is designed to be deployed in deep water, in highly energetic locations. It consists of a floating horizontal duct, open at one end to catch the oncoming waves. These waves capture and compress air which then drives a turbine. The device was invented in 2000 by Professor John Kemp who has extensive experience in this field.

5.2.3.1 Technological features and competitive advantages

The overall length of the device is 46m with an inlet width of 17m and a draft of 8m. The WEC weighs 650 tonnes and has a power rating of 350 kW.

The incoming waves compress air through a conventional, unidirectional turbine which is then used to generate electricity. The design is easily scalable so that models with different capacities can be made without the need for further design input. This feature will allow OWEL to take orders for devices with a particular capacity rating as required, thus serving small communities and projects in need of a small power supply. The scalability also means that this device can be used for commercial power generation and OWEL is looking to develop in this direction in the future.

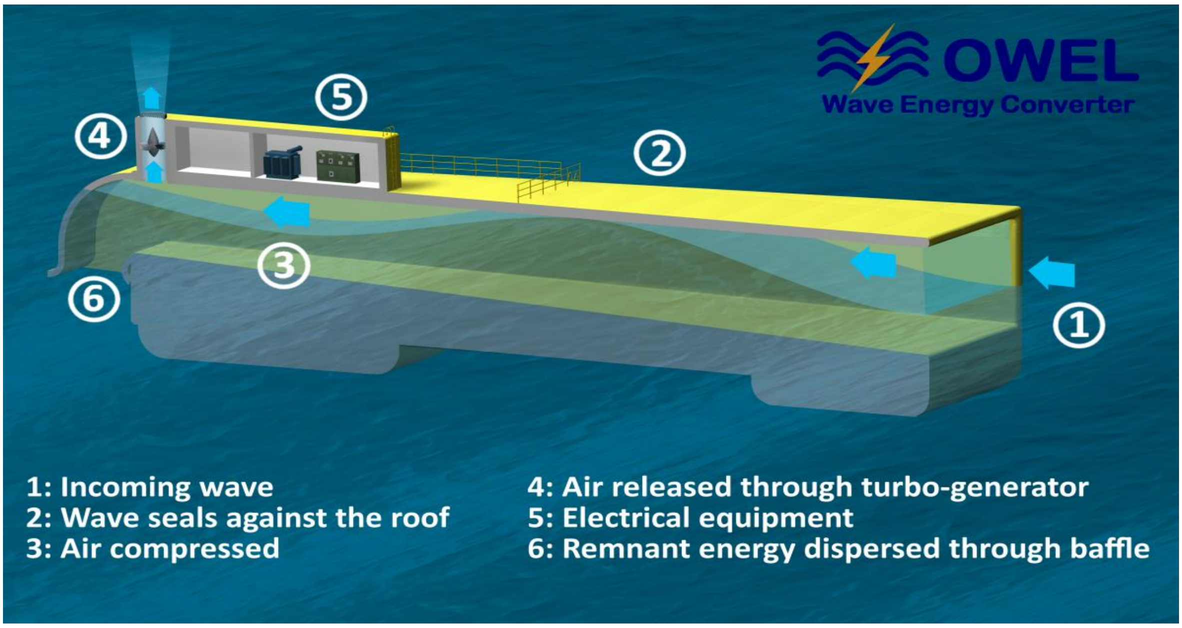
In addition to scalability, the WEC has few moving parts, none of which are in contact with the water. This is achieved by using air to drive the turbine, and therefore the device will be less subject to the increased demands of water damage. The device is still moored in a rough offshore environment but the complex moving parts and the electrical systems are kept dry, thereby increasing the lifetime and lowering maintenance costs.

The use of a conventional unidirectional air turbine is an example of OWELs determination to source parts from existing suppliers. This turbine type is commonly used in wave energy generation and is becoming more easily obtainable. Other parts of the WEC are even more widely available and the

[81] http://www.see.ed.ac.uk/~shs/EWTEC%202011%20full/papers/36.pdf

design is such that the device can be manufactured in any shipyard, which will drive down production costs and make the WEC a more economically viable project.

Figure 5.14: Diagram of OWEL device



Source: OWEL[82]

OWEL believes that their device has a much better potential than its leading competitor in the offshore wave power industry, the Pelamis. OWEL suggests that the Pelamis does not have the same headroom as the WEC for increasing its capacity to the commercial-scale.[83] Pelamis also has a much more complicated design, which may lead to higher O&M costs and increased downtime for the Pelamis. Long-term and commercial-scale tests are yet to be completed for both devices and the lifetime and maintenance costs have not yet been fully discovered.

5.2.3.2 Development Status

The WEC is currently undergoing scale testing at the Corning Wave Hub facility. This machine has proven that the concept works at a large-scale and can survive the ocean environment. The project has been undertaken by a large collaboration of organisations including OWEL, IT Power, Rombol, Narec, NPL, DNV, A&P Shipbuilders, Mojo Maritime, University of Plymouth and PRIMaRe. The main aim of the project is to test and produce a costed and DNV accredited design for a 1st generation product. OWEL intends to then increase the capacity by adding multiple ducts and producing a commercially available platform with a capacity of 2-3 MW, which is expected to be complete by 2016.

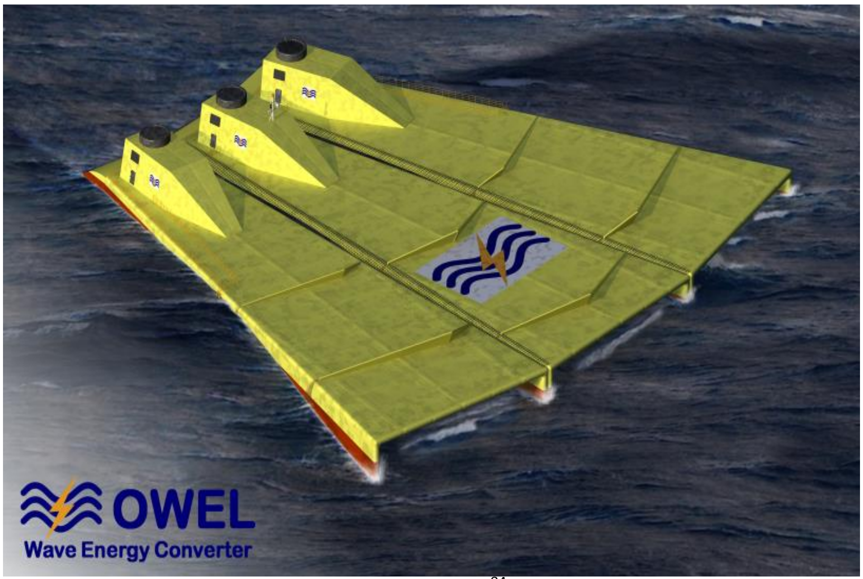
5.2.3.3 Finance and business strategy

OWEL are searching for an investment partner to invest £2.5-4 million in the project. A £2.5 million investment will allow OWEL to complete the demonstration project and assure the commercialisation of the technology on schedule. A £4 million investment would allow OWEL to speed up the commercialisation progress by employing a larger workforce. OWEL suggests that the

[82] http://www.owel.co.uk/owel-technology/
[83] Interview with LRI

business skills and experience that such a partner would bring to the company would be of great service and help to drive the commercial realization of the product.

Figure 5.15: Small array of OWEL WECs

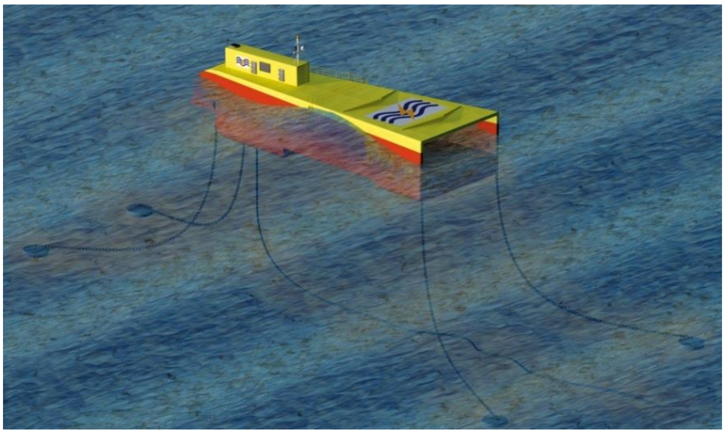


Source: OWEL[84]

OWEL's intention is to remain in the UK wave power industry due to the availability of ROCs. However, this support is not guaranteed for the future and OWEL's long-term revenue forecast estimates a high level of return from 2016 onwards using a conservative estimate of government support. By 2016 small arrays in the range of 6-12 MW should be available and these would offer a high return with a significantly lower level of support than available at present. OWEL bases its business plan on 3 ROCs until 2017 and none thereafter. These predictions forecast a cost per MWh of £150 by 2020, which is comparable with offshore wind today.

OWEL stated that they are primarily interested in licensing project developers to use their technology, as opposed to developing the WEC themselves. They added that the company does have the capability necessary and would be able to continue with the project development if required.

Figure 5.16: Artists impression of WEC



Source: OWEL[85]

[84] http://www.owel.co.uk/owel-technology/

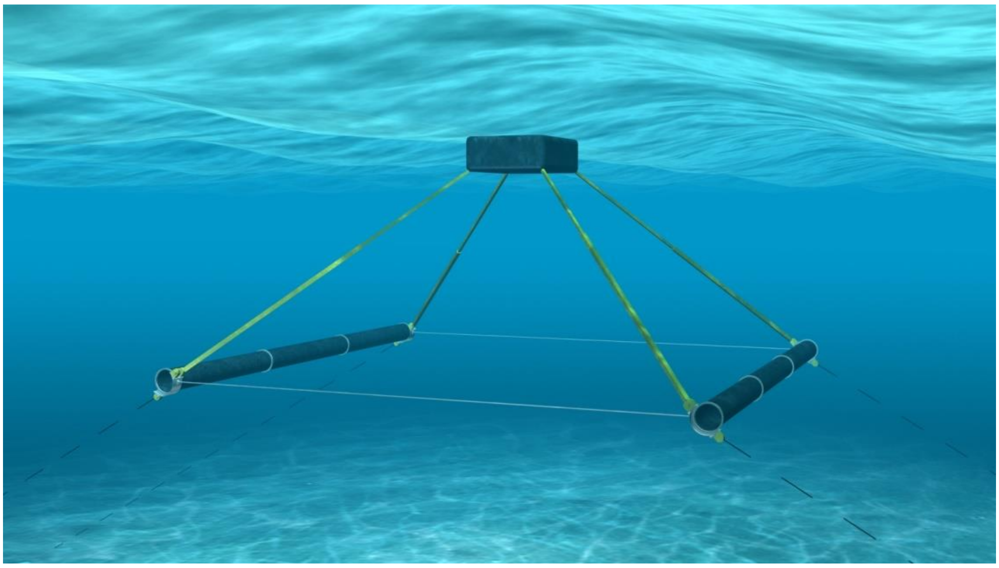
5.2.4 40South Energy

40South Energy is an advanced WEC company currently working in the UK and Italy. They have developed and sold one WEC and are in the process of developing a second, larger model. The company was founded in 2008 by an Italian mathematician with a novel idea. Through their partnership with ABB, 40South Energy is one of the fastest growing companies in this expanding industry. It is also a strong supporter of small- and medium-scale wave energy parks, suitable sites that are developed and ready to host WECs with the backing of the local community.

5.2.4.1 Technological features and competitive advantages

The device consists of two main parts; the upper and lower 'member'. The lower member is submerged at a depth of 15-25 metres and the upper at a depth of 1-12 metres. These depths are varied depending on site, sea usage and sea conditions in real-time. Due to the fact that the WEC is situated below the surface and can vary its depth depending on conditions, it does not have to withstand the extreme forces a normal WEC is subject to. Each device has an onboard control system that varies its depth to optimize production. As the sub-surface environment is much more predictable and constant, the device can be better calibrated to its environment and can protect itself during storms. The device is also therefore not site-specific and can operate in similar conditions with similar outputs all over the world.

Figure 5.17: 40South Energy WEC simulation



Source: 40South Wave Energy[86]

The design was tested using a 100 kW prototype, and details of some of their current models are below.

R115/150 kW:

- 150 kW rated power
- Moored with two gravity bases
- Expected capacity factor 25-35% in the Mediterranean, 45-55% in the Ocean

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[85] http://www.owel.co.uk/owel-technology/marine-demonstrator/

[86] http://www.40southenergy.com/wave-energy-converters/the-technology/

- Lower member consists of two 36m long rails, upper member 115 m^3
- Intended for grid disconnected locations, rated power can be reduced to increase capacity factor to 60-85% and thus provide a more reliable supply
- First model sold to Enel Green Power in 2012 and delivered in 2013
- Device purchase price listed at €300,000

R1300/2 MW

- Commercially available in 2014
- 2 MW rated capacity
- Lower member size unspecified, 1,300m^3 upper member (see Figure 5.17)
- Capable of increasing capacity factor by decreasing rated power to increase reliability
- Suitable for both grid connected and disconnected locations
- Testing of an intermediate model is ongoing

As well as the novel underwater feature of these devices they have the advantage that they are extremely easy to install. In 1-2 days a device can be functional and within a few weeks a whole wave farm could be in operation. The device is towed to its location and attached and the onboard control system then does the rest.

5.2.4.2 Development status

40South was created in 2008 and has been testing devices since 2010. Both devices are fully commercial on project sites with both single units and arrays. They have an array of units 3 x 15 kW and 2 x 2 MW. The first WEC was sold to Enel Green Power in 2012 and launched from Pisa on 19th June 2013. This device was operational until the end of the summer when it was retrieved, checked, and then used for prime time grid supply.

40South Energy published a case study of a small-scale installation with the following information:[87]

- 900 kW rated capacity
- Located 2 nautical miles offshore: nearshore installation
- Size of installation is roughly 100 x 600m
- Maintenance can be carried out locally with no bespoke vessels
- CAPEX excluding cabling costs estimated at £4.05 million
- Project development costs estimated at 3% CAPEX
- O&M casts £182,000 per year
- LCOE estimated at £107/MWh, lower than that of offshore wind
- Capacity factor is highly dependent on location but estimated at 50%
- Lifetime of 25 years

5.2.4.3 Finance and business strategy

Four main markets have been identified for the WECs:

1. Wave Parks supplying electricity through the grid on a commercial-scale. This will require a price similar to that of other renewables such as offshore wind.
2. In harbours which implement cold ironing.
3. In the desalination of water, this commodity can be stored much more readily than electricity.

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[87] 40 South Energy. *Case study for a small scale installation in UK waters:* http://www.40southenergy.com/wp-content/Case-study-for-a-small-scale-installation-in-UK-waters3.pdf

4. For isolated communities, which will require some backup sources. The high capacity factor modes makes the devices some of the most reliable in wave energy generation.

40South Energy strongly supports Wave Energy Parks. These are locations with the capability of hosting WECs either for community or utility-scale generation. 40South Energy have played a large role in the set-up of various Wave Energy Parks, notably the Punta Righini, Elba, Gorgona and Lavagna parks in Italy and the Scilly Airport park in the UK. These parks then encourage the local community to support wave power and increase investment in that region. The Wave Energy Parks even have the option of becoming a supplier of 40South Energy devices. Such a strategy progresses the industry as a whole while improving the 40South Energy position within that industry.

A single small machine costs €3 per watt and a large machine costs €2 per watt. A 2 MW unit costs €4 million with an additional 10-20% for site development, which amounts to €400,000-800,000. The O&M cost can be between 2-4% annually of the initial capital expenditure.

40South Energy signed a technology partnership with ABB in May 2013. The agreement is for the sale of drives for electrical power conversion. ABB will also work with 40South Energy in the optimisation of both models of WEC.

Spa Technical Services Pvt Ltd is a Gujarat-based partner of 40South Energy. They promote the technology and especially use of Wave Energy Parks as a hub for the technical, social and financial aspects of WEC projects.

The R280/500 kW model, an intermediate step in the progression towards larger WECs, was given funding from the Regional Government of Tuscany in December 2012, which shows Italy's growing interest in the industry and the increased confidence in 40South Energy's capabilities.

One of the engineers from 40South Energy is stationed in Plymouth University in the new Marine Energy Building. This link is intended to support interaction with current research and provide access to resources for both parties.

5.2.5 WaveNET, Albatern

5.2.5.1 Technological features and competitive advantages

Albatern are the creators of the WaveNET device. The WEC consists of a number of Squids, each with six pumping modules which move in response to the circular pressure field within the wave. These squids are connected together in an array called the WaveNet, which generates electricity using a hydraulic generator system. Each of the squids can be thought of as acting like a point absorber, however the fact that they are interconnected demonstrates similarities with the attenuators.

The currently available squid has the following specification:

- 7.5 kW rated capacity
- Dry weight of 8.4 tonnes
- Installed in depth of 10-30m
- Standard hydraulic generation system, readily obtainable
- Onboard device for rectifying AC to DC
- Floating system attached to the seabed with a catenary mooring system
- Can be attached in a WaveNet array with a rated capacity of up to 300 kW

Figure 5.18: Albatern WaveNET under testing

Source: Albatern

The device is easily transported to its location; it can be towed behind any normal vessel. Once it has reached the intended site it must be anchored in place and attached in the WaveNET. If one squid fails the array continues to produce electricity, and the broken squid can be replaced in one journey and taken to the shore for repair.

The device is designed with a minimum lifetime of 20 years. There is no end stop or similar attachments which experience wear and could reduce the lifetime of the device. The mooring system moves with the device; this also decreases O&M costs and increases the lifetime of the device.

Due to the small-scale of the operation, the technology has not been expensive to develop and therefore it is a cost effective way of generating electricity with a LCOE similar to that of a diesel generator. Most of the components can be sourced from other industries and assembled at standard shipyards, therefore the WaveNET is a cost-effective and easily available source of electricity for small communities.

5.2.5.2 Development Status

The smallest squids have been deployed and tested at a number of sites including EMEC. They are commercially ready and are intended for small communities without grid access.

Albatern views the largest market for the wave industry to be commercial-scale generation. 6 units were used for the first small-scale demonstrator project which has a capacity of 45 kW. The second production run of 6 more units is underway and will generate electricity from late 2014 onwards. Any array which is over 300 kW will require the modular unit to be increased. Currently they are in the process of developing a 75 kW squid for WaveNET arrays of up to 10 MW. These arrays will be a viable option for a utility-scale project. Testing for the Squids and WaveNETs is ongoing and expected to last until late 2014.

Larger squids and higher capacity WaveNET devices are foreseen for about 2020, possibly reaching 750 kW and 100 MW respectively, although these have not been developed yet.

5.2.5.3 Finance and business strategy

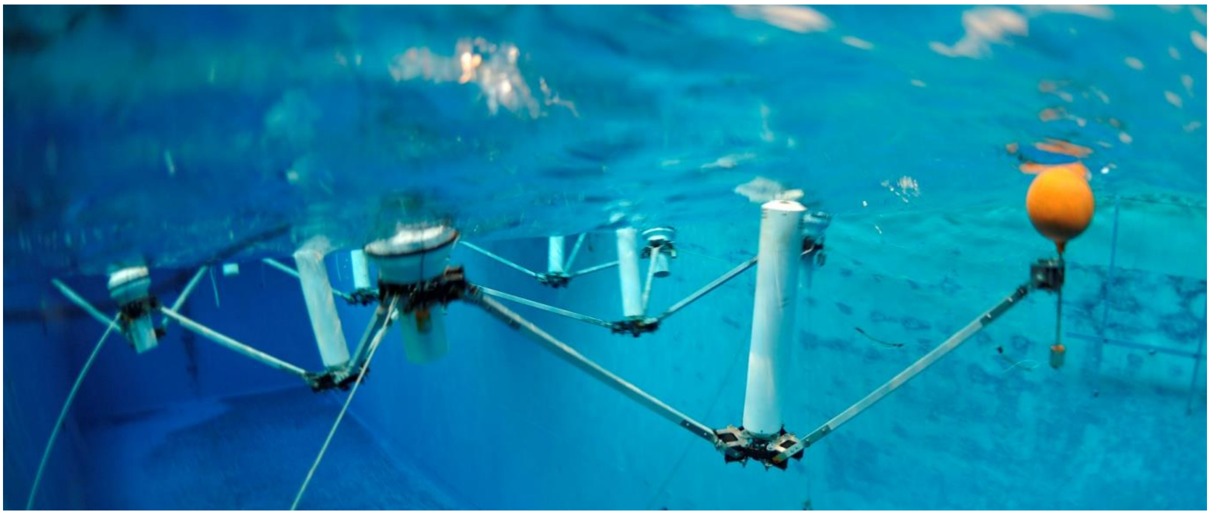
In August 2012, Albatern received an award of £617,000 from the WATERS2 programme to aid the development of the first WaveNET device. Other funding comes from grant money, personal investment by the senior management and investment from high-net-worth individuals.

Albatern is currently seeking funding by the end of 2014 to scale their devices to the next size. £2-3 million would be required for a period of 18 months to 2 years. Albatern is looking for partners in hydraulics, electrical systems for grid connectivity and marine operations.

Deployed capital was £2-3 million as of 2014, which is spread between two sites. The majority was spent on an operating fish farm site in the west coast of Scotland.

Their target market consists of users of off-grid diesel generators used in offshore aquaculture and island communities. The current price of £0.64-0.70 is competitive with diesel generators and they are aiming for levelised generation costs of £0.45/kWh through engineering cost reductions. Manufacturing costs are predicted to decrease as the volume of units produced increases.

Figure 5.19: Albatern device during tank testing



Source: Albatern

CHAPTER 6: CONCLUSIONS

6.1 Technology Conclusions

- Tidal power potential is large and often conveniently located for commercial production.
- Offshore wave power potential is large but difficult to access; a few novel concepts may soon help mitigate this issue.
- Array optimization is expected to be quicker for tidal devices due to their similarity to wind turbines. Wave device arrays will be slower to develop to utility-scale arrays.
- Investor confidence and levels of investment are key; these need to increase so that the industry can fully develop. This can best be achieved by continuing to lower the LCOE of marine energy based electricity.
- A LCOE competitive with that of offshore wind is achievable in the short to medium term and will boost investment in the sector.
- Initial investors must accept the current risk to allow the industry to reach this stage. Developers must seek to reduce this risk to stimulate investment.
- Government confidence and support will also play a large part in this goal. In the UK, the EMR's CfD strike price should boost the marine energy industry by making it a more attractive investment.

The marine energy sector is gaining momentum rapidly, though confidence in the industry is relatively low and investment scarce. Aside from one or two large-scale investments, such as the Siemens subsidiary MCT, there have been very few investments to date despite the promise the industry shows. The most important factor in driving the industry's confidence levels is the LCOE of the technology.

The UK is the country with the most abundant potential globally, and is currently host to substantially more technology developers than any other country. This is supported by the 5 ROCs on offer for projects made operational by 2017.

There are a number of countries, besides the UK, with high potential: notably Australia, New Zealand, USA, Canada, Chile, South Africa, Portugal and China. To realize these potentials, government incentives and support must be put in place in the near future.

6.2 Commercial Viability

- Marine energy could provide over 10 GW of power by 2030; 2.1 GW of this is expected to be generated in the UK.
- There are still many technical issues to be overcome with both wave and tidal technology, and these problems have been greater than originally envisaged by developers. The cost of production is still high.
- In the tidal division there are more companies at an advanced stage of development.

- Many devices will soon reach the highest point of development in terms of their efficiency and capacity factor.

- Some companies have begun to enter the commercial production stage. Economies of scale and infrastructure efficiencies from large arrays are the main sources of savings for the future of the industry.

- High capital expenditure is necessarily associated with the infant technologies. Companies with functioning commercial units have witnessed this decrease significantly over time.
    - Once design costs have been reduced, manufacturing and installation are the highest costs technology developers will face.

- Combining technologies and economies of scale may yield a massive increase in profitability which should be evident in the first medium-sized arrays.

The path to commercialisation has been difficult in many cases and there is a need for technological confidence. Developers must work to establish the actual production cost for their technology, and only then can they make a commercial plan. With many companies, the technology is not yet fully developed, so they cannot know this cost. Once the cost of production is known, there will be significant scope to identify savings.

6.3 Investment Conclusions

- Marine energy technology developers have struggled to find financing, though some have found backing from larger engineering companies.

- Investment and expenditure has favoured commercial-scale generation over niche applications such as seawater desalination.

- Tidal power technologies are considerably lower risk for investors than wave power technologies at present.

- Offshore wave has the highest potential and there are a number of promising companies working to access this. The technology required is at least 10 years from utility-scale generation and requires strong investment at this stage.

- The goal for marine energy developers is to have a LCOE which is comparable to that of offshore wind. Both wave and tidal industry leaders believe their LCOE will be competitive with offshore wind by 2020.

- Electricity Market Reform in the UK is likely to significantly decrease the risk for investors in the UK. Other developed countries are expected to show similar government support in the near future.

With the gradual deployment of arrays and the introduction of the Electricity Market Reforms, the marine energy industry in the UK is expected to accelerate its growth significantly up to 2020. By 2030, a sizeable proportion of the renewable energy generation mix is anticipated to come from wave and tidal power. This will have global consequences as other countries seek to emulate the success of the UK industry, In the short to medium term, both public sector support and private sector investment is required to continue to develop technologies to a level where they are competitive with the LCOE for offshore wind. The industry is close to achieving this, but investors must be patient.

GLOSSARY

Capacity	The rated output of a power generation unit.
Carbon Price Floor	A tax on fossil fuels used to generate electricity.
Contracts for Difference (CfD)	The new method of support that will be given to low carbon electricity-generating businesses after the Electricity Market Reforms in the UK.
Degression	Successively lower rates or amounts. In this report, it is applied to electricity tariffs that decrease at a set amount every year.
Feed-in tariff (FIT)	A primary support mechanism used by governments to promote renewable electricity development. It generally offers price guarantees for a set period of time and a system of obligatory purchase of all power by a network operator. See premium and tradable green certificates for comparison.
Generation	In this report, it refers to the production of electricity.
Incentives	Government programmes to promote the development of renewable energy for power.
Installed capacity	Power-generating capacity measured in Watts. See also generation.
Levelised Cost of Electricity (LCOE)	A quantity often used to compare the cost of generating electricity from different sources. It is calculated from the expected lifetime costs and total supply.
Off-peak hours	The period of day when demand for power is at the lowest (generally at night).
Peak hours	The period of day when demand for power is the highest.
Power Purchase Agreements (PPA)	Contracts for the purchase of electricity from suppliers.
Practical Potential	This takes into account competing sea uses: shipping, fishing etc. This represents the energy a developer can extract from a given area.
Renewable electricity	Electricity generated from a renewable energy source.
Renewable energy	Renewable energy is any form of energy (electricity, heat, transportation fuels, etc.) produced by renewable energy sources such as hydro, wind, biomass, wave and tidal, solar, and geothermal.
Renewables Obligation Certificate (ROC)	A form of support issued by the UK Government for developers of renewable technology. The support is given per MWh supplied to the grid.

Suppliers	Those who sell electricity to end users.
Technical Potential	A further reduction from the theoretical potential which takes into account device characteristics. Efficiency and capacity factor are included as are average weather conditions.
Theoretical Potential	A reduction from the total potential which accounts for the difficulties of access to the resource due to natural barriers; waves in the Antarctica are not included.
Tidal Stream Generator	A device that generates electricity from the tidal stream, usually using a turbine. Separate from those devices which use a barrage to capture tidal energy.
Total Potential	The total resource available. Taking wave energy as an example, this would be the total energy available across the globe, including inaccessible areas.
Tradable green certificates	A primary support mechanism in which renewable electricity generators are awarded certificates for their power generation from renewable sources. Suppliers or distributors have a quota obligation for renewable energy and need to buy the certificates to prove they have met their quota.
Utility/Commercial-scale array	An array of marine energy converters providing energy to the national grid. The capacity of the array is comparable to other suppliers such as power stations.
Variable premium	A premium system in which the generation compensation is capped at a set amount. The variable premium fills in the gap between the market price of electricity and the set amount and hence the variable premium will change with the market price of electricity.
Wave Energy Converter	A device that converts wave energy into electricity; there are many types of these devices described in Chapter 2.
Wholesale electricity market	The purchase and sale of electricity from generators to resellers on the open market.

