IRENA
International Renewable Energy Agency

OCEAN ENERGY

TECHNOLOGY READINESS, PATENTS, DEPLOYMENT STATUS AND OUTLOOK

REPORT

AUGUST 2014

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

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Ocean Energy

Technology Readiness, Patents, Deployment Status and Outlook

REPORT

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FOREWORD

In the transition to a clean energy future, we need to explore ways for all forms of renewable energy to be developed and deployed fully, competitively and in a sustainable way. Over the last few years we have witnessed tremendous growth and cost reductions with some renewables, particularly wind power and solar photovoltaics. The deployment outlook for these technologies remains strong.

However, this is still not the case with all forms of renewable energy. Ocean energy is a striking example of a renewable resource with tremendous potential but only a very small share in the global energy mix to date. The sheer potential of the world's oceans to meet our future energy needs is huge. The challenge of harnessing this vast reservoir of clean, renewable energy has piqued the curiosity, as well as the ambition, of humanity for millennia. This continues to be the case today, amid remarkable innovation and advances in research and development related to ocean energy technologies.

As REmap 2030, the global roadmap from the International Renewable Energy Agency (IRENA), shows, the world can more than double the share of renewables in the global energy mix by 2030, sufficient to keep the rise of global temperatures within two degrees Celsius, at no extra cost compared to conventional energy solutions. Even so, we need to step up efforts to ensure that all renewable sources contribute to the clean energy revolution and sustainable economic development.

We therefore need to better understand the complex barriers to ocean energy technology deployment and work together to create the enabling conditions to unleash its potential. Ensuring policy clarity, along with developing roadmaps for technology rollout with realistic commercialisation timescales, will accelerate cost and risk reduction. In order to evaluate the merits of support measures to nurture the market for such technologies, we must also take on board the socio-economic benefits of ocean energy. In this regard, policy makers need to be more aware of niche applications - such as cooling, water desalination, sustainable tourism and aquaculture, as long-term market opportunities for ocean energy deployment.

This report is complemented by a set of technology briefs on the main forms of ocean energy, from tidal currents and waves to temperature and salinity gradients. I hope that this contribution from IRENA encourages informed policy-making and international collaboration in order to help overcome barriers to tapping the huge potential of the oceans.

In the effort to commercialise ocean energy applications, we need to be realistic about what is possible over any given time scale. With a strong vision, broad cooperation and pragmatic planning, however, we can increasingly tap into the abundant, clean, secure energy that is stored in the oceans of the world. By taking the right steps today, we can ensure that ocean energy contributes to the sustainable energy future to which we all aspire.

Adnan Z. Amin
Director-General
International Renewable Energy Agency

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List of Abbreviations

ADFD	Abu Dhabi Fund for Development
DNV GL	Det Norske Veritas and Germanischer Lloyd
EDF	Électricité de France
EMEC	European Marine Energy Centre
FiT	Feed-in tariff
IEA-OES	International Energy Agency's Ocean Energy Systems Implementing Agreement
GREIN	Global Renewable Energy Islands Network
kW / kWh	Kilowatt / Kilowatt-hour
LCOE	Levelised cost of energy
MW / MWh / MWe	Megawatt / Megawatt-hour / Megawattelectric
NREAP	National Renewable Energy Action Plan
O&M	Operations and maintenance
OEM	Original equipment manufacturers
OTEC	Ocean thermal energy conversion
PCT	Patent Cooperation Treaty
PTO	Power take-off
SI Ocean	European Strategic Initiative for Ocean Energy
TRL	Technology readiness level
TW/TWh	Terawatt / Terawatt-hours
WEC	Wave energy converter

EXECUTIVE SUMMARY

The contribution of ocean energy to the global energy mix now and in the next five years remains very small, with technologies still in the development and demonstration phases. Member states of the International Renewable Energy Agency (IRENA) have mandated the agency to make the credible case for the widespread adoption and sustainable use of all forms of renewable energy. Over the years the agency has received several requests on ocean energy from policy makers in member states on a range of issues including: resource availability; the status and outlook for the various forms of ocean energy conversion technologies; deployment viability of each technology type; capital and operational costs and cost reduction potential; operation and maintenance aspect, particularly in the case of island states; which policies and support mechanisms to apply in support of ocean energy technology development and deployment; what sources of funding and finance models exist; barriers to ocean energy deployment; and opportunities for cooperation on ocean energy. Similarly, the agency receives on a regular basis requests from ocean energy technology developers and potential project developers seeking current information on ocean energy and opportunities worldwide.

This report aims to accelerate and promote the widespread sustainable deployment of ocean energy technologies worldwide by providing a robust, accurate and up to date analysis of ocean energy, focussing on the readiness of the various technologies involved, their deployment status and trends, patent activities in the sector, and market outlook as well as the barriers to ocean energy deployment. The objective is to provide information that can (i) help to identify emerging technologies approaching commercialisation, and (ii) assist policy makers in their medium- and long-term energy technology planning and strategic options.

The report builds on analysis of current understanding of ocean energy using (i) information and data published in the literature, (ii) data compiled from public sources by Det Norske Veritas and Germanischer Lloyd (DNV GL) of ocean energy technologies and projects, and (iii) ocean energy technology related international Patent Cooperation Treaty (PCT) publications.

The power of the ocean: abundant clean energy

The ocean energy resource is vast. The theoretical resource potential of ocean energy is more than sufficient to meet present and projected global electricity demand well into the future. Estimates for this potential range from 20 000 terawatt-hours (TWh) to 80 000 TWh of electricity a year, which is 100% to 400% of current global demand for electricity. Furthermore, successful deployment of ocean energy technologies offers substantive opportunities and benefits, including:

- **Energy independence:** tapping into an indigenous resource
- **Decarbonisation:** delivering CO_2-free power
- **Job creation:** building a low-carbon industry, including providing employment opportunities for coastal and island communities
- **Complement to other renewables:** attractive in combination with other renewable energy options: *e.g.*, improved predictability, decreased variability, spatial concentration, and socio-economic benefits.

Technology review: a sector characterised by diversity

Ocean surface waves, tidal currents, tidal range, deep ocean currents, thermal gradients, and changes in salinity are all ocean energy resources. Ocean energy technologies seek to convert these renewable energy resources into a useful form – typically electricity.

Ocean energy converters are far from a homogenous set of technologies. There are a number of technology

Ocean Energy Technologies

Wave energy converters

Tidal stream converters

Deep ocean current devices

Tidal range technology

Ocean thermal energy conversion (OTEC) devices

Salinity gradient technology

Technology trends

Most leading **tidal stream** developers are currently pursuing seabed-mounted, horizontal-axis, axial flow turbines.

Wave energy converters exhibit less design convergence – albeit that there is a tendency towards designing floating point absorber systems for offshore applications.

variants, largely defined by the ocean resource that they seek to harness. Each technology variant is distinctive in terms of technical design, operation, and commercial maturity.

For most ocean energy technologies the main challenge is to reduce costs and improve the reliability and performance of systems, in order to demonstrate a sustained commercially competitive cost of energy. Most ocean energy technologies are significantly behind other renewables – such as wind and solar – in technical maturity. This is largely due to challenges of working in an offshore environment.

Levelised costs of ocean energy technologies are currently substantially higher than those of other renewable energy technologies; the long-term pathway to cost reduction is difficult to predict: The uncertain costs, usually high, is a consequence of limited available empirical cost data and wide variability in project cost strategies as a result of the diversity of device designs, and limited understanding – with regards to ocean energy – of key costs of energy drivers such as capacity factor and design life.

Tidal stream and wave energy converters are the technologies of greatest medium-term relevance. With the exception of tidal range, they are the most advanced ocean energy technologies available – albeit that they are still of pre-commercial status. Tidal range is a mature technology, but the very limited site availability, high capital investment and the potentially significant ecological impacts have previously ruled this out for large scale utility projects in all but a couple locations. Other ocean energy technologies may become increasingly relevant over longer time horizons.

Commercial maturity is expected from the 2020s onwards. Deployment rates of ocean energy technologies to date have been slower than expected. Technology and market trends indicate that ocean energy technologies are unlikely to be cost competitive with other forms of renewable energy generation before 2020. However, as has occurred with other renewable energy technologies such as wind power and solar PV, such cost reduction depends largely on deployment, investment, learning and innovation rather than just on time.

Patents and announced projects are truly global. Analysis of patent publications and announced projects demonstrates that there is substantial activity on ocean energy across the globe – with the UK, France, USA, Canada, Japan, South Korea and Australia being some of the hotspots of activity. However, deployment of ocean energy technologies is slow, with the potential cumulative installed capacity by 2020 being in the order of only a few hundreds of megawatts (MW). Patent activity provides an initial indication of interest in ocean energy technologies globally. The average annual registrations of patents related to ocean energy technology between 2009 and 2013 was well over 150, mostly related to wave energy and tidal stream systems.

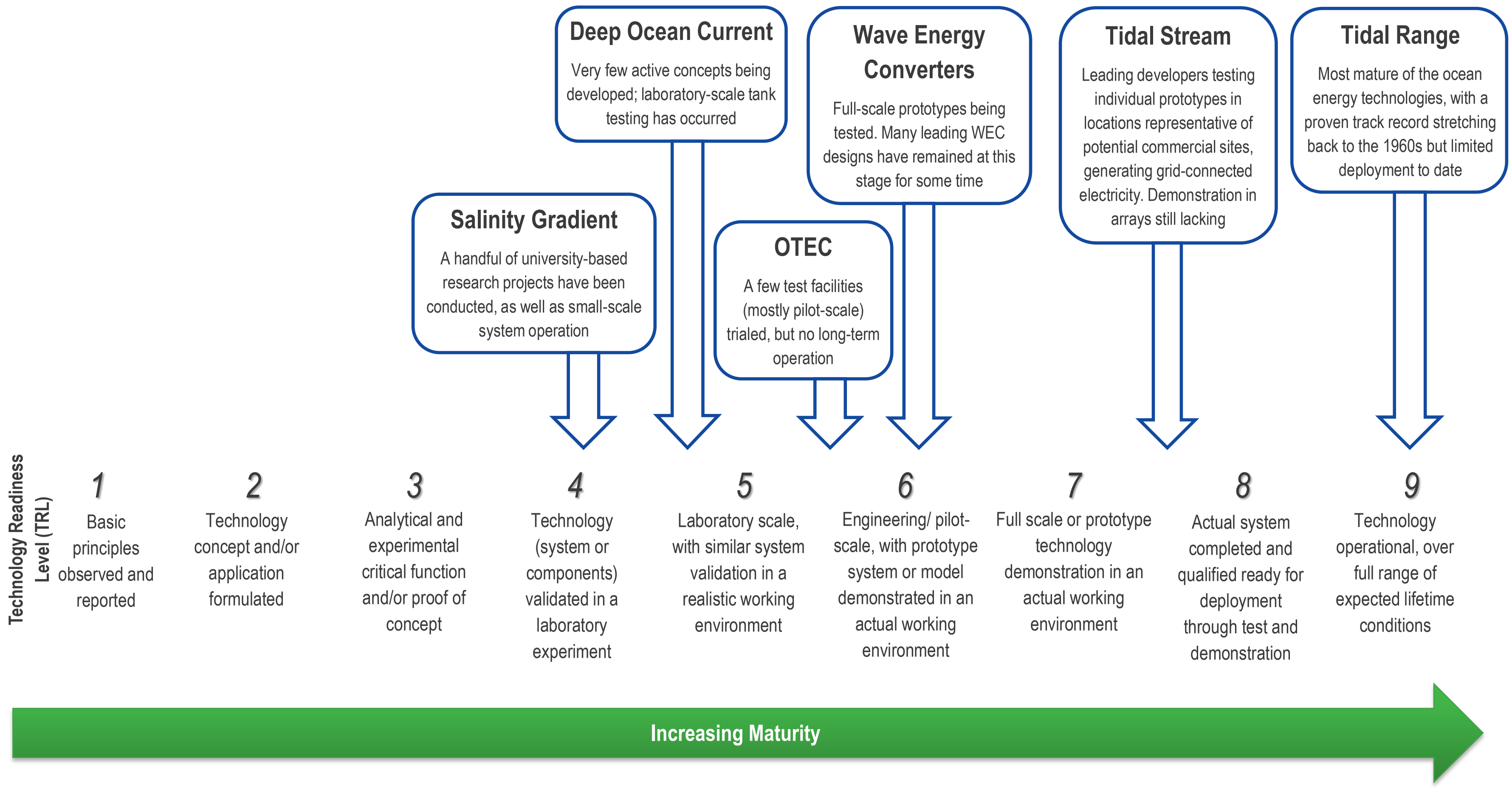
Fulfilling the potential: overcoming barriers

Fulfilling the potential of ocean energy requires that technical, economic, environmental, social and infrastructural hurdles are overcome.

Tidal stream PCT publications in 2013

Wave energy PCT publications in 2013

Ocean energy technology readiness



Deep Ocean Current

Very few active concepts being developed; laboratory-scale tank testing has occurred

Wave Energy Converters

Full-scale prototypes being tested. Many leading WEC designs have remained at this stage for some time

Tidal Stream

Leading developers testing individual prototypes in locations representative of potential commercial sites, generating grid-connected electricity. Demonstration in arrays still lacking

Tidal Range

Most mature of the ocean energy technologies, with a proven track record stretching back to the 1960s but limited deployment to date

Salinity Gradient

A handful of university-based research projects have been conducted, as well as small-scale system operation

OTEC

A few test facilities (mostly pilot-scale) trialed, but no long-term operation

Technology Readiness Level (TRL)

1 Basic principles observed and reported

2 Technology concept and/or application formulated

3 Analytical and experimental critical function and/or proof of concept

4 Technology (system or components) validated in a laboratory experiment

5 Laboratory scale, with similar system validation in a realistic working environment

6 Engineering/ pilot-scale, with prototype system or model demonstrated in an actual working environment

7 Full scale or prototype technology demonstration in an actual working environment

8 Actual system completed and qualified ready for deployment through test and demonstration

9 Technology operational, over full range of expected lifetime conditions

Increasing Maturity

Recommendations to address technical challenges

Technical challenges relate to the resource, device and array configuration. Addressing technical barriers should be a priority for Ocean thermal energy conversion (OTEC), salinity gradient and ocean current technologies, since these are the least technically mature of the ocean energy technologies. Although approaching commercial deployment, wave and tidal stream technologies also have a number of technical challenges to overcome before commercialisation is realised. Policy makers are encouraged to:

- Conduct a **resource-mapping** exercise to identify the most suitable ocean energy technologies for each location
- Make **capital grant funding** available for research and demonstration of prototypes and the first small arrays, and incubator opportunities to encourage next generation systems and step-changes in innovation.
- Promote **sharing of best practice**
- Encourage the **spreading of risk** amongst all stakeholders who stand to benefit from a successful ocean energy industry
- Support **test centres** to accelerate learning from practical experience
- Promote **international collaboration, technology transfer and collaborative research, development and demonstration** of ocean energy technologies

Recommendations to address economic challenges

Policy makers and utilities are often under pressure to adopt least-cost and least-risk decarbonisation technologies. Therefore, the next step, once technical concepts have been proven, is to reduce the cost and risk profile of the ocean energy technologies when compared with other renewable energy technologies in the market. The most significant barrier, at present, is the comparatively high cost of energy produced by ocean energy technologies relative to other renewables. Policy makers are encouraged to:

- Provide **capital support** for technologies at demonstration stage and the first small arrays
- Provide a **premium price per unit of energy generated** to give a clear signal of a long-term market. This is necessary to attract the attention of Original Equipment Manufacturers (OEMs) and catalyse activity
- Promote **niche applications areas** such as aquaculture, cooling, water desalination, defence, and sustainable tourism, which may provide market entry opportunities where ocean energy technologies would otherwise struggle to compete with other grid-connected renewables
- Quantify **additional benefits,** so that the full added value of ocean energy technologies is recognised
- Accelerate cost and risk reduction through **roadmapping**

Recommendations to address environmental and social issues

At the prototype stage, test centres tend to minimise the environmental/social burden on device developers through centralised studies and testing. However, once developers reach transition to commercial-scale deployment, environmental and social issues can come to the fore – particularly for tidal range systems. Policy makers are encouraged to:

- **Remove bottlenecks** in the process of granting **consent** for ocean energy technology deployment applications
- Improve **access to baseline data.** The provision of baseline data through centrally-funded studies brings significant efficiencies, avoiding the need for developers to duplicate activities
- Incorporate ocean energy development in national **maritime spatial plans**
- **Consult and engage** with the public early on

Recommendations to address infrastructural barriers

At a high-level, the infrastructural challenge for ocean energy technologies is twofold, relating to grid issues and the supply chain.

Policy makers are encouraged to:

- Ensure that ocean energy technologies are taken into account in **network planning** in a fair and transparent manner
- Use national/regional development agencies to ensure that **supply chain opportunities** related ocean energy deployment are well disseminated, and to **build capacity** amongst local companies

Above all, policy makers need to apply different approaches to ocean energy technologies. Ocean energy technologies are diverse in both technical characteristics and commercial readiness. Informed policy makers will examine their local resource, understand the technical maturity of each technology, and then tailor their ocean energy technology strategy accordingly. It will be the resulting policies targeted at selected ocean energy technologies that deliver their deployment success. A 'one size fits all' approach is unlikely to be ideal.

IRENA can assist member states in the development and deployment of ocean energy technologies through various aspects of the thematic areas of its work programme. For example:

- In the **islands: lighthouses for renewable energy deployment** thematic area, **ocean energy provides an opportunity for niche applications** to support the various Global Renewable Energy Islands Network (GREIN) clusters, including **water desalination**
- Under the thematic area of **planning for the global energy transition**, IRENA's REmap 2030 renewable energy roadmap provides the framework for assessing the contribution of ocean energy in the global energy mix. Furthermore, IRENA's country-led **renewables readiness assessments** (RRA) provide an opportunity for countries with ocean energy resources to consider **supply chain and job creation opportunities and the benefits of ocean energy technology investment** when reviewing their renewable energy options
- IRENA's **gateway to knowledge on renewable energy** thematic work programme area provides the framework, in collaboration with other organisations, to continually improve knowledge on ocean energy technology **deployment costs, best policy practices, and global resource potentials and distribution**
- The **enabling renewable energy investment and growth** work programme activities, with a focus on renewable energy policy assessment, energy pricing analysis, quality assurance and standardisation, and innovation and collaborative research, development and demonstration, can contribute to increasing understanding of enablers for commercialisation of ocean energy technologies. Furthermore, the **IRENA and Abu Dhabi Fund for Development (ADFD) Project Facility** helps to meet the challenge of financing renewable energy projects, including **niche applications of ocean energy technologies**

1 INTRODUCTION

The ocean has been an integral part of human civilisation and development since ancient times, and although its potential use in generating power has been the subject of patents dating back to the 18 century, technologies capable of harnessing this vast resource have only been deployed recently. Ocean energy resources are vast, with the theoretical potential to generate between 20 000 terawatt-hours (TWh) and 80 000 TWh of electricity each year – enough to meet between 100 and 400% of the present global demand for electricity (International Energy Agency (IEA), 2013). In recognition of this energy resource, various initiatives are being promoted worldwide to harness the potential of the ocean, an example of which is the IEA-Ocean Energy Systems Implementing Agreement (IEA-OES), which has an international vision for ocean energy that includes a goal of installing 337 gigawatts (GW) of capacity worldwide by 2050.[1]

Along with other renewables, ocean energy technologies generate carbon dioxide (CO_2) emission-free power and as an indigenous resource can promote energy independence. Ocean energy technologies can also contribute to a balanced, diversified energy portfolio, with generation profiles that complement those of other renewables – such as solar and wind – thus helping to balance the variable generation of different renewable energy sources. Furthermore, ocean energy technologies can extend the range of options for densely populated coastal nations with limited land space, to increase their use of renewables. The issue of competing land use is often a significant advantage for many ocean energy technologies, as they provide the opportunity to put renewable generation plants "under the surface" or "over the horizon".

Member states of the International Renewable Energy Agency (IRENA) have mandated the agency to make the credible case for the widespread adoption and sustainable use of all forms of renewable energy. Over the years the agency has received several requests on ocean energy from policy makers in various member states on a range of issues including: resource availability; the status and outlook for the various forms of ocean energy conversion technologies; deployment viability of each technology type; capital and operational costs and cost reduction potential of different technologies; operation and maintenance aspects, particularly in the case of island states; which policies and support mechanisms to apply in support of ocean energy technology development and deployment; what sources of funding and finance models exist; barriers to ocean energy deployment; and opportunities for cooperation on ocean energy. Similarly, the agency receives on a regular basis requests from ocean energy technology developers and potential project developers seeking current information on ocean energy and opportunities worldwide.

Realising the potential of ocean energy requires a concerted effort by policy makers, and industry and academia alike to commercialise the technology and remove barriers. This report aims to summarise current market and technology status, and to tease out the implications for policy makers. In doing so, it addresses a number of key questions that are answered sequentially in the following sections of this report.

- **Section 2: Review of ocean energy**
  - What are the different types of ocean energy sources, their characteristics and conversion mechanisms?
  - What is the development and deployment status of ocean energy technologies?
  - What is the high-level market outlook and who are the key players?
- **Sections 3: Classification of ocean energy technologies and development trends**
  - What are the main technology types and patent classifications within the key ocean energy technologies?
  - What is the global nature of patent publications and how are they related to ocean energy technologies?
  - What are the leading technologies and who are the main developers?
  - What are the trends in design and innovation?
- **Section 4: Barriers to ocean energy technology development and deployment**
  - What are the technical, economic, environmental and social, and infrastructural barriers to deployment of ocean energy technologies?
  - What should policy makers do to mitigate barriers?
- **Section 5: Conclusions and summary of recommendations**
  - What are the technology trends and market outlook?
  - What are the main focus areas for policy makers?
  - How does IRENA's work programme support ocean energy development?

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[1] *See www.iea.org/techinitiatives/renewableenergy/oceanenergysystems/*

2 REVIEW OF OCEAN ENERGY

2.1 Resource and technology characteristics

Ocean energy, often referred to as marine renewable energy, is a term encompassing all of the renewable energy resources found in the oceans; that is, those that use the kinetic, potential, chemical or thermal properties of seawater. Ocean surface waves, tidal currents, tidal range, ocean currents, thermal gradients, and changes in salinity all represent energy resources that can be harnessed using a variety of different technologies. Ocean energy technologies convert these renewable energy resources into a useful form – typically electricity.[2]

Certain renewable resources found in and around the ocean are excluded from the above definition. For example, the production of biofuels from marine biomass is generally considered a form of bioenergy rather than ocean energy. Similarly, concepts for harnessing energy from submarine vents are considered a form of geothermal energy and offshore wind (fixed or floating) is considered a particular application for wind energy technology; in the same vein, floating photovoltaic technology is not normally included in the definition of ocean energy technology.

Considering the above, ocean energy technologies are most broadly classified by the resource they are seeking to capture. The most typical technical options are reviewed in the following subsections.

Tidal range

Solar and lunar gravitational forces, combined with the rotation of the Earth, generate periodic changes in sea level known as the tides. This rise and fall of ocean waters can be amplified by basin resonances and coastline bathymetry to create large surface elevation changes at specific geographic locations. High and low tides occur twice a day at most coastal sites throughout the world (semi-diurnal tides), although some places experience just one high and low tide per day (diurnal tides). Other places are characterised by a combination of diurnal and semi-diurnal oscillations (mixed tides). The difference in sea level height between high and low tide at a given location is called the tidal range, and it can vary each day depending on the location of the sun and moon, and globally depending on the coastal location. Tides have been well studied for centuries, and can be accurately predicted years in advance. As tides are caused by the aforementioned gravitational interactions, they are considered a renewable energy resource.

There are two general approaches to tidal energy conversion. The first seeks to capture the potential energy created by the difference in sea level between high and low tides, *i.e.*, tidal range, and is described here. The second is a hydrokinetic approach that seeks to capture the kinetic energy from the horizontal flow of tidal currents that can occur at certain locations, and is described in the following section on tidal stream.

Tidal range technology is based on conventional hydropower principles and requires a natural or a man-made structure (*e.g.*, a dam or barrier) to impound a large body of water. As the tidal height varies outside of the impounded area during the tidal cycle, water is discharged either in or out of the enclosed area through conventional hydro turbines (typically of the low-head type, *i.e.,* propeller turbines) housed in the dam or barrier. This is commonly achieved by placing a tidal barrage across the mouth of an estuary, creating a reservoir (basin) behind it. More recent proposed projects have included multiple-basin schemes and enclosed basins located offshore (single or multiple) away from estuaries called tidal lagoons.

Figure 2-1 illustrates the tidal range found globally in one of the primary tidal constituents, which demonstrates that there are certain areas around the world where the resource is likely to be sufficient for tidal projects (both range and stream). For a particular project to be feasible, however, certain other site conditions must also be met, *e.g.,* an estuary suitable for a tidal barrage.

Tidal range is the only technology discussed in this report that has proven its technical viability and can be considered a mature technology. The world's first large-scale tidal range power plant, the 240 megawatts (MW) Rance Tidal Power Station, became operational in 1966 in Brittany, France and is still operated today by Électricité de France (EDF). The 254 MW Sihwa Lake Tidal Power Station in South Korea, became the world's largest (and newest) tidal barrage when it was opened in 2011. Both of these tidal barrages employ conventional bulb turbines. Only a few other much smaller sites have been developed around the world, resulting in a total installed tidal range capacity world-wide of about 498 MW.

Aside from the fact that tidal range projects have substantial capital costs and are only feasible in specific project locations, the inevitable environmental consequences of such schemes result in significant planning constraints. Most governments to date have encouraged the development of other renewable energy projects

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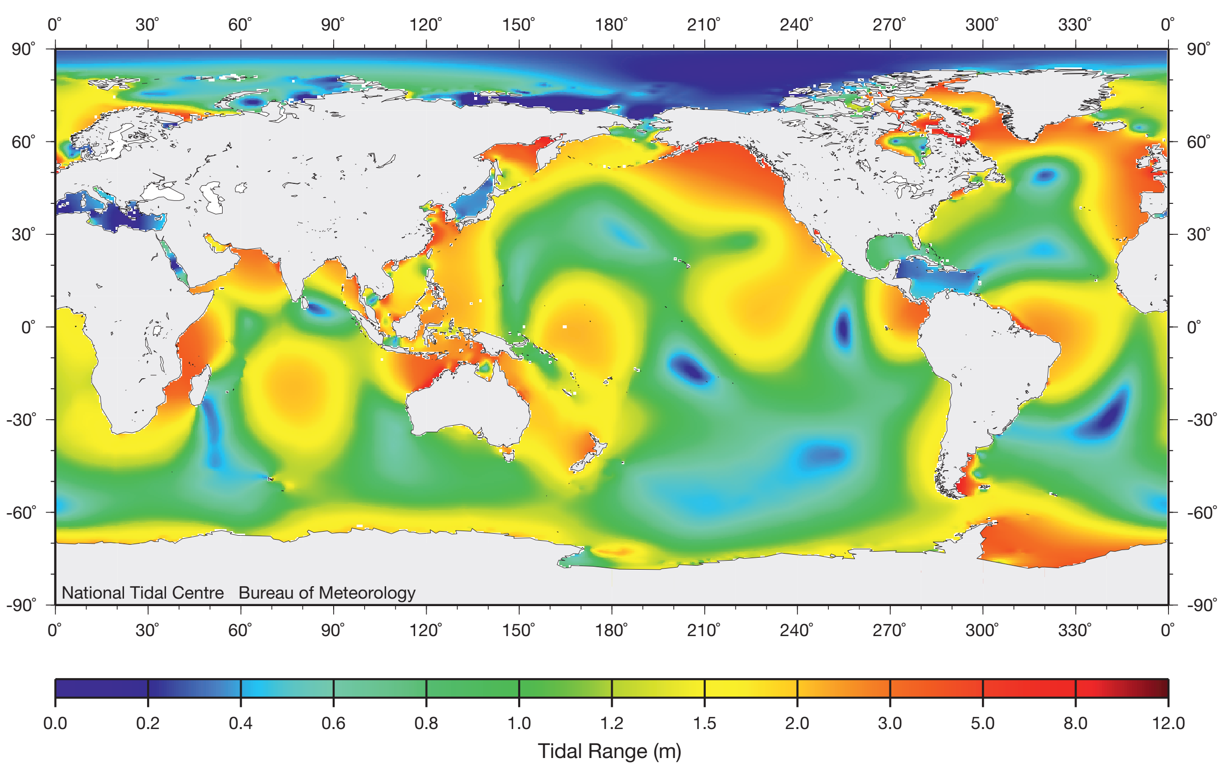
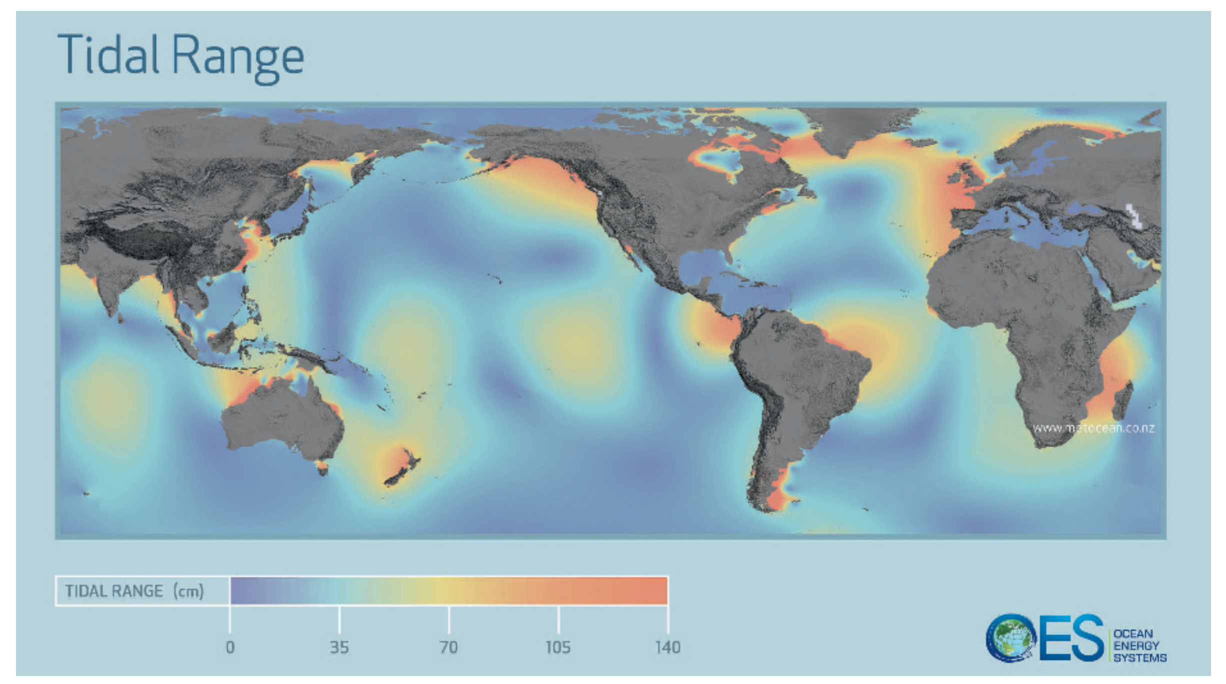
[2] *Examples of other potential uses include: freshwater production via desalination, thermal energy, compressed air supply for aquaculture and hydrogen production by electrolysis.*

Figure 2-1: World map of average tidal range

a. Range = approximately Mean High Water Springs – Mean Low Water Springs[3]



b. Semidiurnal lunar (M2) tidal constituent



Note: Map provided with print permission by (a) James Chittleborough, National Tidal Centre, Bureaux of Meteorology, Australia, and (b) Huckerby *et al.* (2011), provided with print permission by IEA-OES

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[3] Estimated as twice the sum of the amplitudes of the four main tidal constituents, approximately equal to the difference in Mean High Water Springs (MHWS) and the Mean Low Water Springs (MLWS). The main four tidal constituents are M2 (semidiurnal lunar), O1 (diurnal lunar), S2 (semidiurnal solar) and K1 (diurnal solar).

and technologies over tidal range. Although this may explain why only one major project has been developed in the world over the past couple of decades, as global calls for more renewable energy generation increase there may be some renewed interest in tidal range. The fact is that out of all the ocean energy technologies, tidal range remains the only one that has proven reliability in existing commercial projects, the example being the two large-scale utility projects mentioned previously. Particularly in combined applications (*e.g.*, for flood control and water quality management) or where existing impoundment structures are required for other reasons, the net benefits of a project may warrant future tidal range power plant development.

It should also be noted that, since the tidal range approach is based on conventional hydropower technology and commercial operation has occurred for decades at a handful of selected sites around the world, tidal range technology is often omitted from consideration when discussing emerging marine renewable energy. The remainder of the ocean energy technologies discussed in this section are all still undergoing research and development, or are at the pre-commercial prototyping and development stages.

Tidal stream

The vertical rise and fall of water, known as tides as described in the section on tidal range above, is accompanied by an incoming (flood) or outgoing (ebb) horizontal flow of water in bays, harbours, estuaries and straits. This flow is called a tidal current or tidal stream. Tidal currents can be exceptionally strong in areas where large tidal ranges are further constrained by local topography. There will also be periods of time when there is little or no horizontal flow of water (*i.e.*, slack water – the short time before the tide changes between ebb and flood and vice versa).

Hydrokinetic turbines convert the kinetic (moving) energy of free flowing water into electricity using the same principles that wind turbines use to convert the kinetic energy of flowing air (wind). When hydrokinetic systems are used in a tidal environment they are often referred to as tidal stream turbines, tidal in-stream energy converters, or tidal/marine/hydrokinetic current turbines. Most designs of tidal stream energy converters are representative of modified wind turbines made to suit the higher density and different characteristics of the surrounding environment, since the principles of energy conversion are the same. Although the wind industry has converged on the standard lift-based, 3-bladed, horizontal-axis turbine predominantly seen throughout the world today, in the early years of wind energy many different designs were tested and tried. As discussed in Section 3.2 below, many of these designs, including cross-flow turbines, ducted turbines, and drag turbines, are now being re-examined for hydrokinetic applications. In this way, the maturity of the tidal stream industry can be compared to the early stages of the wind energy sector a few decades ago.

The most advanced tidal stream turbine developers are at a stage where they are testing and demonstrating individual prototypes in tidal streams representative of potential commercial sites. It is anticipated that commercial projects will operate in arrays of turbines as tidal farms, similar to how commercial utility scale wind farms are developed. The next stage for leading industry developers is to demonstrate their systems in small pilot arrays. After proving the reliability of such schemes, bringing costs down through learning, operational experience, and economies of scale, it may be possible to secure finance for commercial projects. One recent trend that may help the sector develop such early arrays is the increasing interest expressed by large Original Equipment Manufacturers (OEMs) such as Alstom, Andritz Hydro, DCNS, Hyundai Heavy Industries, Kawasaki Heavy Industries, Lockheed Martin, Siemens, and Voith Hydro.

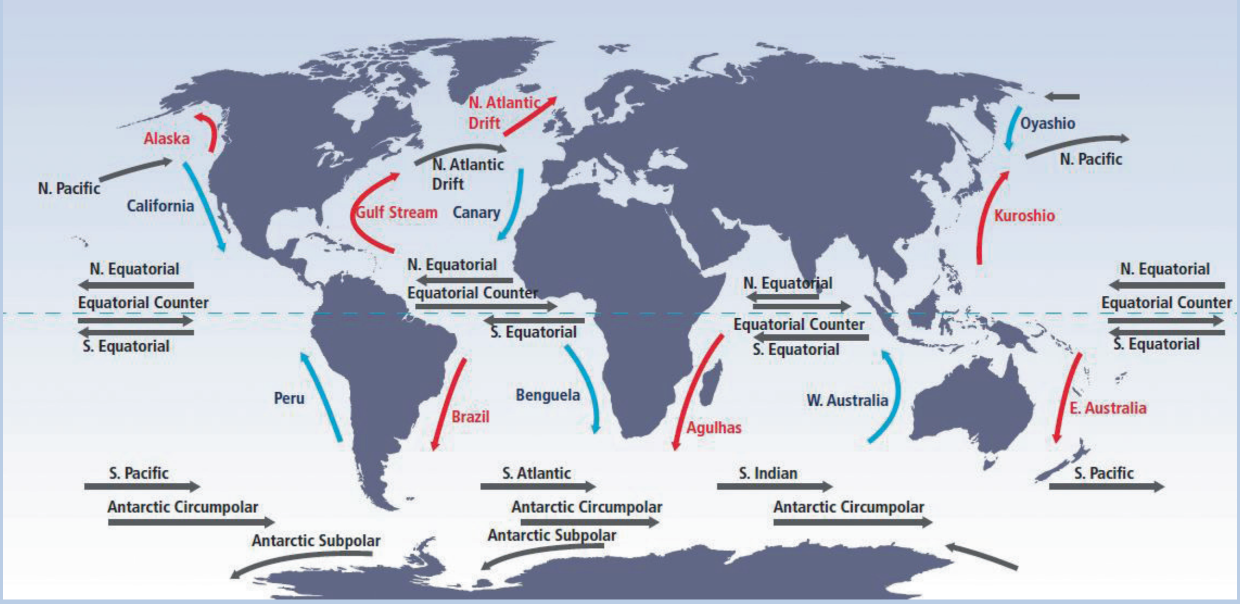
Generally, high tidal ranges are a prerequisite for fast tidal currents in addition to certain geographic features to create the tidal stream, and therefore Figure 2.1 also demonstrates the general regions where high potential tidal stream sites may be located. Generally, tidal streams must reach flow speeds of at least 1.5-2 metres per second (m/s) for tidal current turbines to operate effectively. Major tidal streams have been identified along the coastlines of every continent, making it a global, albeit site specific, resource.

Ocean current

Open ocean currents are driven by latitudinal distributions of winds and thermohaline ocean circulation. They are generally slower, but more continuous than tidal currents and although often located at deep ocean sites, they tend to operate most strongly near the surface. Another difference from tidal currents is that the flows are unidirectional, whereas tidal current reverse direction with each flood and ebb cycle. Some proponents have suggested the potential to generate baseload power from these technologies, due to the steady nature of some ocean currents. Although these currents are distributed globally (see Figure 2-2), it remains unclear how many may prove enticing enough to draw interest for project development. However, if technologies can be developed to harness these lower velocity currents, the scale of projects at those locations could potentially be much larger given the large volumes of water and scale of oceanic currents in comparison to tidal streams.

The same hydrokinetic approach and operating principles behind the turbines described in the subsection

Figure 2-2: Ocean surface currents showing both warm (red) and cold (blue) systems.



Source: Lewis *et al.*, 2011

on tidal stream can be applied to the flow of water in oceanic currents. Owing to the ocean depth at suitable locations for ocean currents, turbines would need to be held in location with moored floating or typically submerged systems. Research in this area is being conducted by several universities and companies with commercial interest in the technologies; however, this technology area remains at an even more nascent stage of development than hydrokinetic turbines designed for tidal and river applications. Although there are technology developers working on concepts from the USA, Japan, Italy and Spain, they are much fewer in number than those developing tidal stream turbine concepts. There also have not been any full-scale, individual prototypes tested or demonstrated anywhere in the world.

In the United States, the Southeast National Marine Renewable Energy Center (SNMREC) at Florida Atlantic University, seeks to advance the science and technology of recovering energy from ocean currents – specifically from the Florida Current that is part of the Gulf Stream system – found offshore from the centre. While several test centres have been established for wave and tidal stream energy around the world, SNMREC is seeking to install the first for ocean current energy.

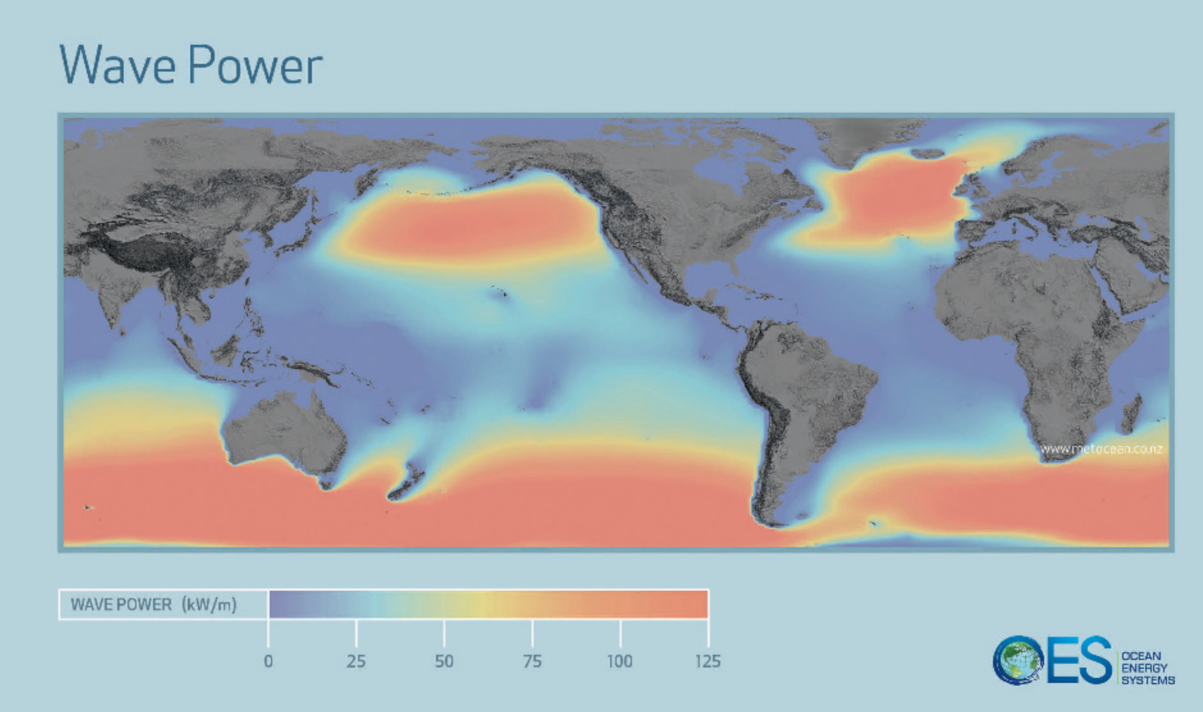
Wave energy

Wave Energy Converters (WECs) transform energy from the kinetic and potential energy of ocean surface waves into another form of energy (*e.g.*, electricity). These waves, generated primarily by wind blowing across the ocean surface (ripples), can propagate over deep water with minimal energy loss and will combine and continue to gain energy from the wind over long open ocean stretches (leading to swells). Although the air-sea interactions and energy transfer mechanisms are complex, ocean surface wave formation is primarily influenced by the speed of the wind, its duration and the fetch (distance of open water over which the wind blows). As it is solar energy that creates the differences in air temperature that cause wind, wave energy can be considered a concentrated form of solar energy. The spatial concentration of energy is one key advantage of wave energy in comparison to other renewable energy resources.

The most energetic wave conditions can be found primarily between latitudes of 30° to 60°, as can be seen in Figure 2-3, with the largest power levels occurring off the west coasts of continents. As a resource, wave energy has the advantage of relatively good predictability for sea state conditions (utilising methods and measurement networks developed for the benefit of existing offshore industries). Although there is seasonality, with higher wave conditions experienced in the winter than in the summer at most locations, waves arrive day and night, 24 hours a day, and sea states have more inertia than solar/wind conditions, with less potential for sudden changes in the resource potential.

Although ideas for wave energy conversion have been around for some time, with serious academic attention beginning in the early 1970s, extraction of wave energy at useful scales and costs has proven challenging. It is only recently that a proliferation of technology developers have started to produce full-scale prototypes and

Figure 2-3: Global annual mean wave power distribution



Source: Huckerby *et al.* (2011). Note: Provided with print permission by IEA-OES

therefore truly demonstrating the potential utility of this form of power production (Cruz, 2007). At present there are a number of grid-connected devices installed in high-energy environments, representing the pre-commercial prototypes of devices that are targeted for build-out into utility scale arrays in the next decade.

Ocean thermal energy

A significant portion of solar energy incident on the ocean surface is retained as thermal energy stored as heat in the upper layers of the ocean. The temperature gradient between the sea surface water and the colder, deep seawater – generally at depths below 1000 metres (m) – can be harnessed using different ocean thermal energy conversion (OTEC) processes. OTEC requires practical temperature differences of at least about 20 degrees Celsius (°C). Thus, as can be seen in Figure 2-4, the resource is principally distributed in the tropics (latitudes 0 to 35 degrees) on either side of the equator. As can be expected, in those tropical latitudes the ocean surface temperatures are highest and there is often stable stratification of the oceanic water column.

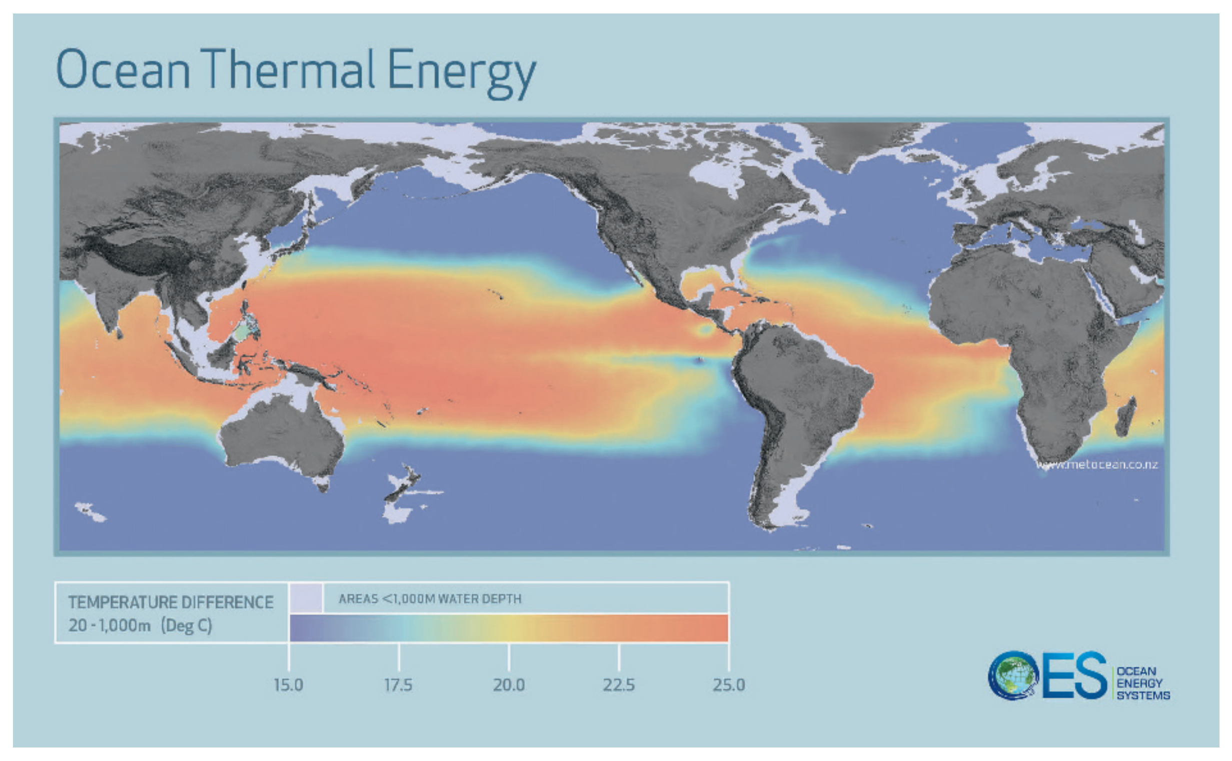
Although there is a slight seasonal variation in temperature gradients, the resource can be considered continuously available, and as such OTEC represents an ocean energy technology with the potential to generate baseload power. The theoretical global total resource potential for ocean thermal energy is the highest among the ocean energy resources. However, compared to other ocean energy technologies such as wave and tidal stream energy converters, the energy density of the OTEC systems is quite low. This represents one of the ongoing challenges towards a cost-effective OTEC operation.

The concept of operating a heat engine between the warm surface water reservoir and a cold reservoir of deep seawater is not new (first suggested by French physicist Dr. J. A. d'Arsonval in 1881), with the first ocean test conducted by French Professor G. Claude occurring at a site off Cuba in 1930 (Takahashi, 1991).

Open-cycle, closed-cycle and hybrid OTEC schemes have all been proposed. The open-cycle systems use a vacuum chamber to 'flash evaporate' some of the warm surface seawater. The steam generated, which is the working fluid for the system, passes through a turbine generator before being condensed by the cold deep seawater. It may also be possible to use such open-cycle plants for desalination applications. Closed-cycle systems have more efficient thermal performance, and pump the warm surface water through heat exchangers to vaporise a secondary working fluid (such as ammonia which has a low boiling point). The resulting

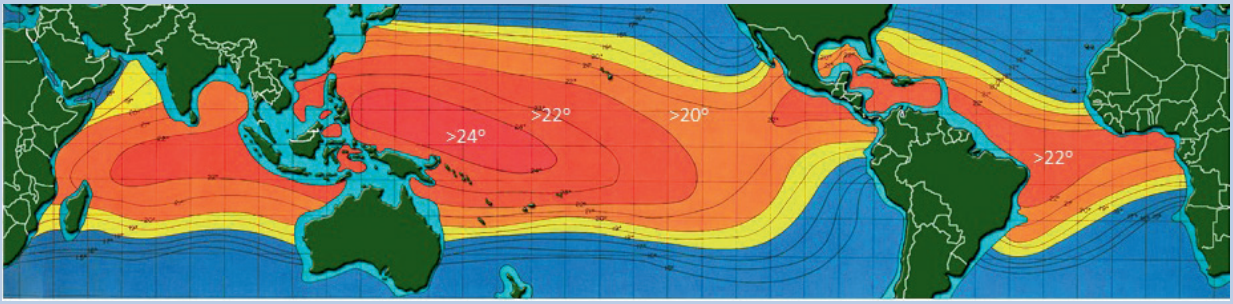
Figure 2-4: Global ocean thermal energy resource distribution

(a) Global mean ocean temperature difference between 20 m and 1000 m depths



Source: Huckerby et al. (2011). Note: Provided with print permission by IEA-OES

(b) High resolution contours of annual average temperature difference,[4] from 20°C (yellow) to 24°C (red), between warm surface seawater and cold seawater at a depth of 1000 m.



Map courtesy of U.S. Department of Energy[5]

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[4] *A temperature difference of at least 20°C is required for the operational reliability of a commercial-scale ocean thermal power plant.*

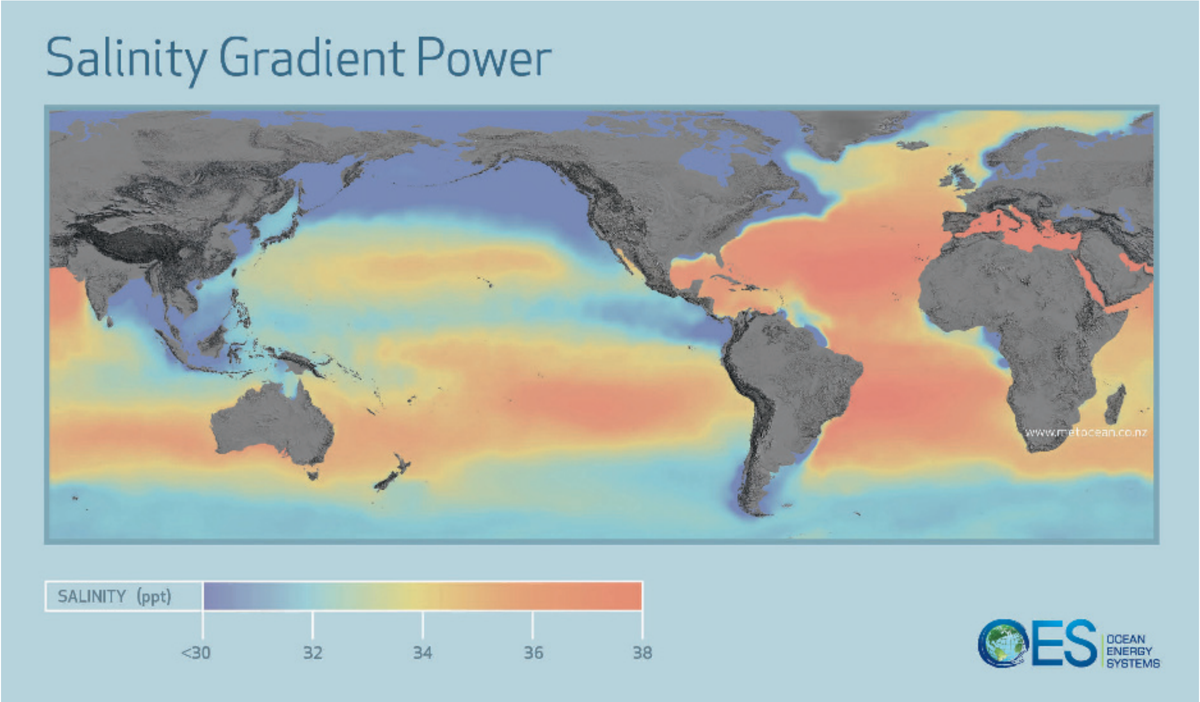
[5] *Based on oceanographic data analysed by Ocean Data Systems under contract for the U.S. Department of Energy, and adapted from the printed map by Lockheed Martin*

high-pressure vapour drives the turbine, before being subsequently cooled by the deeper seawater to return to a liquid phase. Because the secondary working fluid operates at a higher pressure in closed-cycled conversion, the systems can typically be smaller than open-cycle plants. There are also hybrid conversion cycles where steam from flash evaporation is used as the heat source for a closed Rankine cycle that uses a secondary working fluid.

Salinity gradient

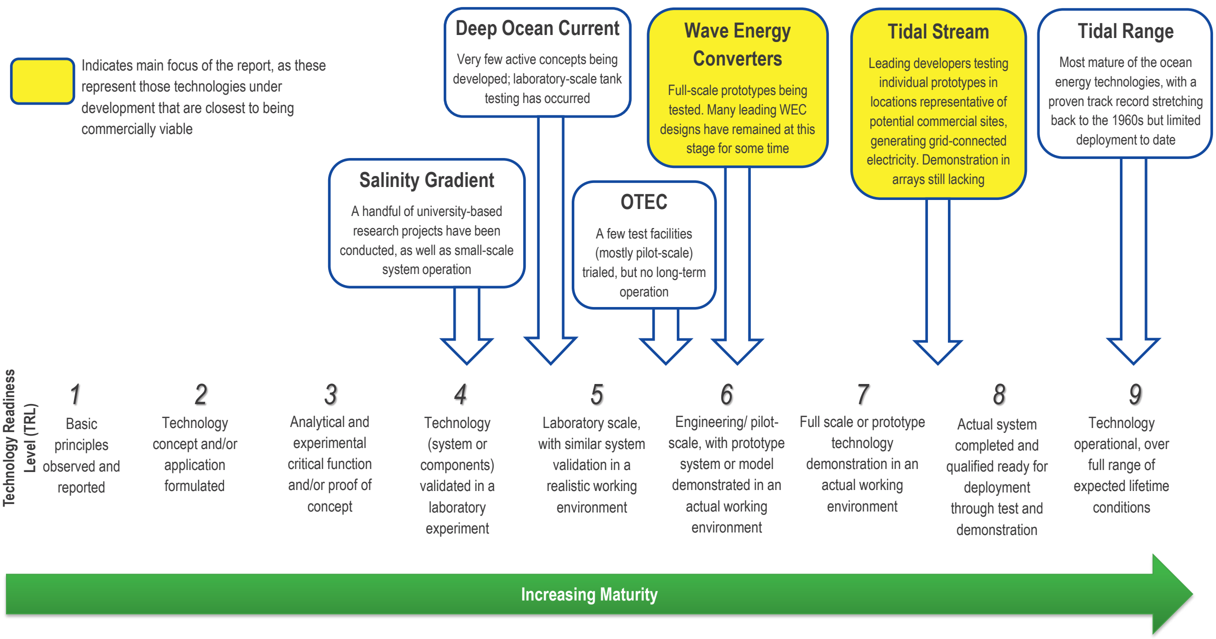
Energy associated with a salinity gradient can be harnessed using concepts such as pressure-retarded osmosis (PRO), reversed electro dialysis (RED) processes and associated conversion technologies. Also called osmotic power, such technologies seek to harness the chemical potential between freshwater and seawater, captured as pressure across a semi-permeable membrane.

Figure 2-5: Global salinity gradient resource distribution



Source: Huckerby *et al.* (2011). Note: Provided with print permission by IEA-OES

Figure 2-6: Ocean energy technology readiness



Indicates main focus of the report, as these represent those technologies under development that are closest to being commercially viable

Deep Ocean Current

Very few active concepts being developed; laboratory-scale tank testing has occurred

Wave Energy Converters

Full-scale prototypes being tested. Many leading WEC designs have remained at this stage for some time

Tidal Stream

Leading developers testing individual prototypes in locations representative of potential commercial sites, generating grid-connected electricity. Demonstration in arrays still lacking

Tidal Range

Most mature of the ocean energy technologies, with a proven track record stretching back to the 1960s but limited deployment to date

Salinity Gradient

A handful of university-based research projects have been conducted, as well as small-scale system operation

OTEC

A few test facilities (mostly pilot-scale) trialed, but no long-term operation

Technology Readiness Level (TRL)

1 Basic principles observed and reported

2 Technology concept and/or application formulated

3 Analytical and experimental critical function and/or proof of concept

4 Technology (system or components) validated in a laboratory experiment

5 Laboratory scale, with similar system validation in a realistic working environment

6 Engineering/ pilot-scale, with prototype system or model demonstrated in an actual working environment

7 Full scale or prototype technology demonstration in an actual working environment

8 Actual system completed and qualified ready for deployment through test and demonstration

9 Technology operational, over full range of expected lifetime conditions

Increasing Maturity

Based on analysis of data from DNV GL (2014)

Salinity gradient resources are distributed globally (as shown in Figure 2-5) and located where freshwater from rivers discharges into saline seawater. River mouths are the most obvious locations where there is the potential for large adjacent volumes of fresh and salt water. As the salinity gradient resource is continuous there is the potential to generate baseload power, if cost-effective technologies can be developed. Currently the cost of membranes compared to generation capacity has prevented commercial development of salinity gradient power plants.

Although the first concepts were invented decades ago, salinity gradient technology remains at mostly a conceptual and early research and development stage. There are a few developers interested in the technology and a number of university-based research projects have been conducted around the world, with the majority of studies at a laboratory scale. One small 4 kW pilot plant was opened by Statkraft in Norway in 2009[6], but no large-scale demonstrations or commercial projects are operating anywhere in the world.

2.2 Technology development and deployment status

At the end of 2013 the global installed capacity of ocean energy technologies was just over 530 MW (REN21, 2014) with most of this capacity attributable to the La Rance (France) and Sihwa (Republic of Korea) tidal range plants. All of the technologies discussed in Section 2.1 fall under the broader ocean energy technology classification; however, wave and tidal stream energy are largely viewed to have the highest potential for significant commercial applications globally in the near to medium terms. This is demonstrated by the global interest and number of prototype deployments and sea trials that have recently occurred at significant scale (100 kW nameplate power capacity or greater) for these two ocean energy technologies in comparison to the others. As mentioned previously, the only tidal range project to occur since the turn of the 21 century is the 254 MW Sihwa Lake Tidal Power Station in South Korea. While the capacity of that single station dwarfs the cumulative capacity of both wave and tidal stream prototypes combined to date, the fact that there has only been a single large project since the technology was first commercially operated in the 1960s, illustrates that the tidal range technology is not drawing as much serious developmental interest as the other emerging, pre-commercial ocean energy technologies. Furthermore, there have not yet been any prototype demonstrations of ocean current or salinity gradient projects of significant scale, nor new large-scale OTEC demonstrations since the turn of the 21 century. However, OTEC has seen a handful of pilot plants (ranging from 10s to 100s of kW in capacity) over the previous three decades in the USA, Republic of Nauru, India, and most recently, Japan.

Figure 2-6 provides a visual representation of the relative measure of each ocean energy technology's level of technological maturity, using the so-called Technology Readiness Level (TRL) scale. The TRL assess the maturity of evolving technologies during their development and early operations. It should be noted that although TRL scaling has some limitations, it is useful nonetheless in providing an indicative value of maturity for various technologies.[7]

Looking at other aspects beyond the TRLs of the various ocean energy technologies, it is important to note that there are other parameters that influence short-term development prospects, such as manufacturability and economic performance. Table 2-1 provides a relative rating for the various ocean energy technologies mentioned so far.

As can be seen from Table 2-1, of the ocean energy technologies described in this report, wave and tidal stream energy converters are often considered the options with best global reach and potential, and have attracted the most commercial interest, with many national governments significantly supporting innovation in the wave and tidal sectors during recent years. The remaining sections of this report will focus mainly on the ocean energy technologies related to wave and tidal energy conversion (TRL 6-8 range, as shown previously in Figure 2-6).

Tidal stream deployments

To date, nearly all tidal stream deployments have been single machine prototype testing, often at designated test centres, such as the European Marine Energy Centre (EMEC) in the Orkney Islands, UK. There were still no commercial tidal stream arrays operating anywhere in the world in early 2014. Figure 2-7 provides an illustration of the geographic distribution of tidal stream

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[6] www.statkraft.com/about-statkraft/innovation/osmotic-power/history.aspx

[7] *Another scale sometimes referred to is the 'Manufacturing Readiness Level' (MRL). One challenge facing ocean energy technologies is that even when the TRL might be high (suggesting increasing technical maturity), often the MRL is relatively low – indicative of high manufacturing costs. For instance, MRLs are referred to in the European Commission's Draft Horizon 2020 Work Programme 2014-15, in the areas of Secure, Clean and Efficient Energy: http://ec.europa.eu/research/horizon2020/pdf/work-programmes/secure_clean_and_efficient_energy_draft_work_programme.pdf*
A further scale which has been used in relation to ocean energy technologies is 'Technology Performance Level', a metric used to assess and quantify the techno-economic performance of devices. For instance, see Weber, Costello and Ringwood (n.d.) 'WEC Technology Performance Levels (TPLs) – Metric for Successful Development of Economic WEC Technology. www.eeng.nuim.ie/coer/doc/PUB0051_851-Jochem%20Weber.pdf

turbine deployments at significant scale (100 kW or higher capacity) since the turn of the century, when tidal stream technology development and testing began to ramp up. The United Kingdom (UK) has largely been the hub of activity throughout this period, and certainly the most consistent in terms of having attracted demonstration deployments. Although other significant locations have included Norway, South Korea, and the USA, with Canada proposing significant plans going forward.

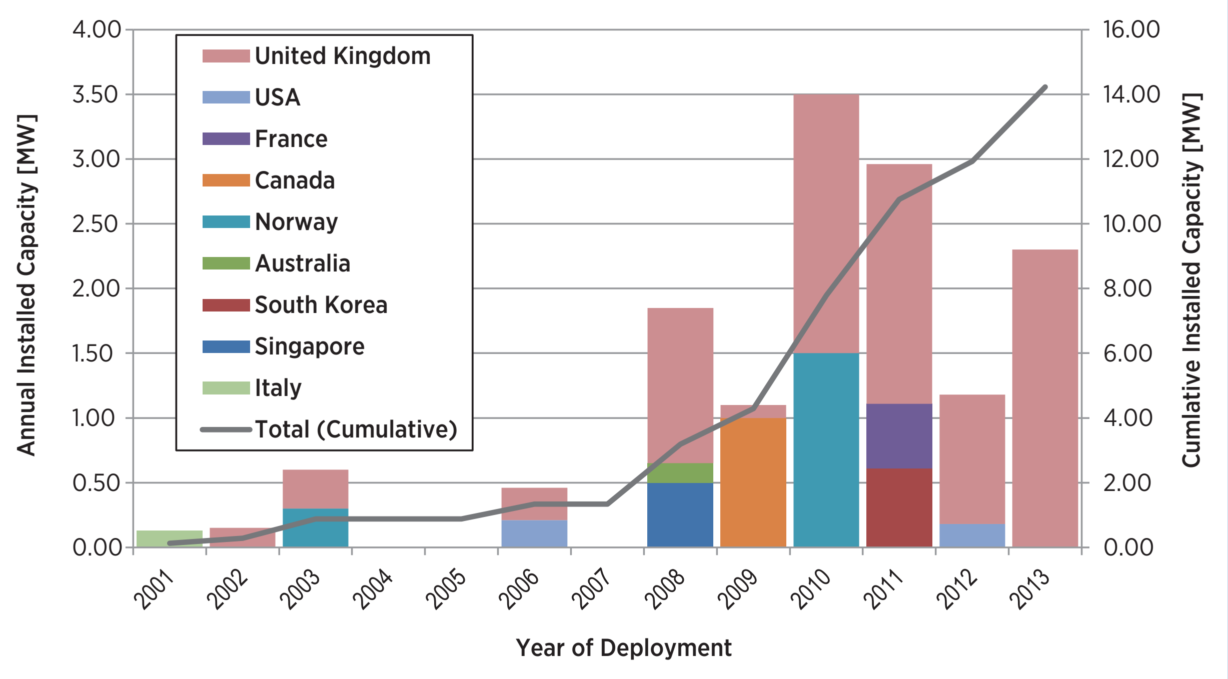
Table 2-1: Short-term development attractiveness of ocean energy technologies[8]

	Technology readiness levels	Global site/ resource availability	Level of industrial involvement	Financial investment interest	Relative attractiveness
Salinity gradient	□	▨	□	□	□
Ocean current	□	▨	□	□	□
OTEC	▨	■	□	□	▨
Wave	▨	■	■	■	■
Tidal stream	▨	▨	■	■	■
Tidal range	■	□	▨	□	▨

Key

■ High	▨ Moderate	□ Low

Figure 2-7: Summary of large-scale tidal stream prototype deployments to date



Based on analysis of data from DNV GL (2014)

Note: Includes any new, large-scale (*i.e.*, greater than 100 kW) deployment as of February 2014, regardless of grid-connection and time deployed (although most large-scale prototypes were grid connected). As some units were removed after testing periods, cumulative capacity deployed does not represent total installed capacity today.

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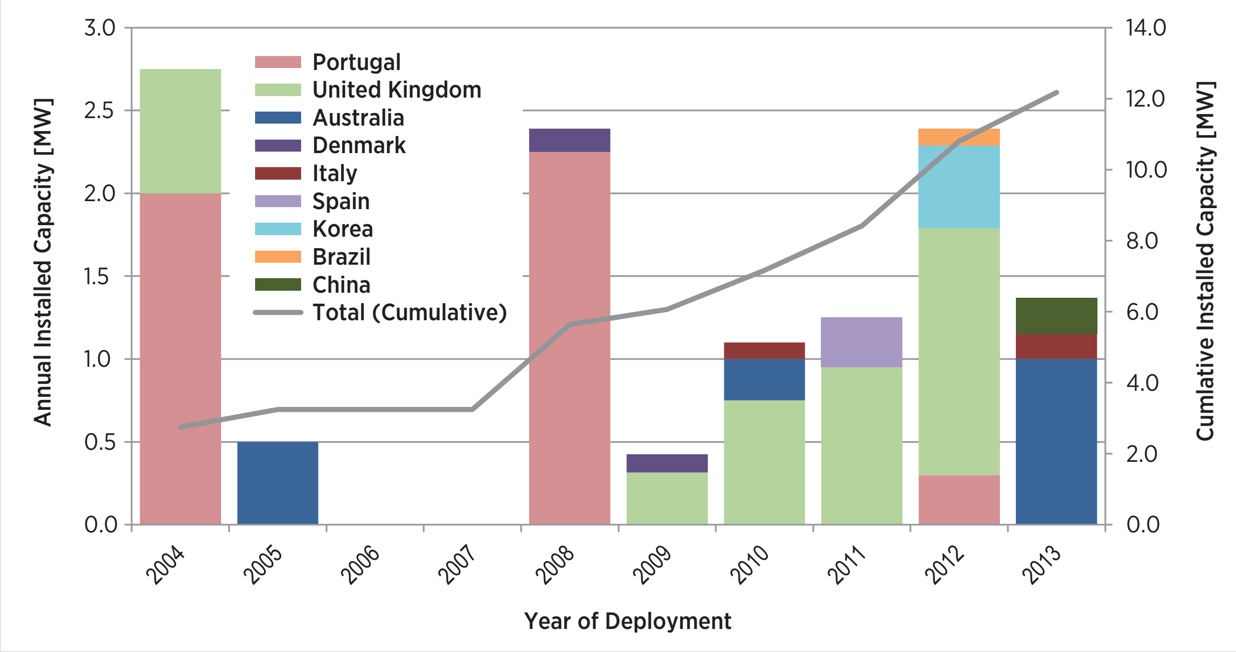
[8] *Based on analysis of data from DNV GL (2014)*

Figure 2-8: Summary of large-scale wave energy prototype deployments to date



Based on analysis of data from DNV GL (2014)

Note: Includes any new, large-scale (i.e., greater than 100 kW) deployment as of February 2014, regardless of grid-connection and time deployed (although most large-scale prototypes were grid connected). As some units were removed after testing periods or failed during the trial effort, cumulative capacity deployed does not represent total installed capacity today.

Wave energy deployments

Similar to tidal stream, the vast majority of wave energy deployments have been single machine prototype testing, often at designated test centres like EMEC. At the start of 2014, there were no commercial WEC arrays in operation anywhere in the world. Figure 2-8 provides an illustration of the geographic distribution of large-scale (100 kW or higher capacity) WEC prototype deployments since the turn of the century. As can be seen in that figure, Portugal and the UK have historically been the main hubs of activity. The Pelamis prototype became the first full-scale offshore WEC to generate electricity into the UK national grid in 2004, soon followed by a 2 MW Archimedes Wave Swing (AWS) prototype later installed in Portugal during the same year. Further deployments and test campaigns have followed for a variety of concepts. A first pre-commercial array was tested in 2008 to 2009 at the same Portuguese site, again featuring Pelamis technology. The majority of additional large-scale prototype deployments have occurred at EMEC in Scotland, although there have also been others in Australia, Denmark, Italy, Spain, Brazil, China and Korea.

Ocean thermal energy deployments

Despite knowledge of the resource and the theory behind OTEC, the challenges and costs associated with deployment, operation and maintenance in deepwater marine environments and the large flow rates required for OTEC cycles with typical temperature differences of only around 20°C, have prevented the commercial implementation of an OTEC plant anywhere in the world to date. A handful of test facilities have been trialled globally since the first two prototype plants (after Professor Claude's early efforts) were tested in the USA in 1979 and 1981, yet none have sustained long-term operation. However, during the last couple of years there has been some renewed interest in OTEC development. The newest pilot demonstration is a 50 kilowatt (kW) plant which began operation in Japan in 2013[9], and it is the only OTEC plant currently operating.

Ocean thermal technology has been demonstrated at sub-MW levels, and technology is currently available for making ocean thermal power systems of up to 10 megawatt$_{\text{electric}}$ (MWe) capacity. Such systems are not yet commercially viable. However, scaling up manufacturing techniques so as to enable the commercial production of large subsystem components, such as the cold water pipes could contribute to the commercial viability of such systems.

The need to be durable in the marine environment for periods of up to 30 years or more is a key requirement

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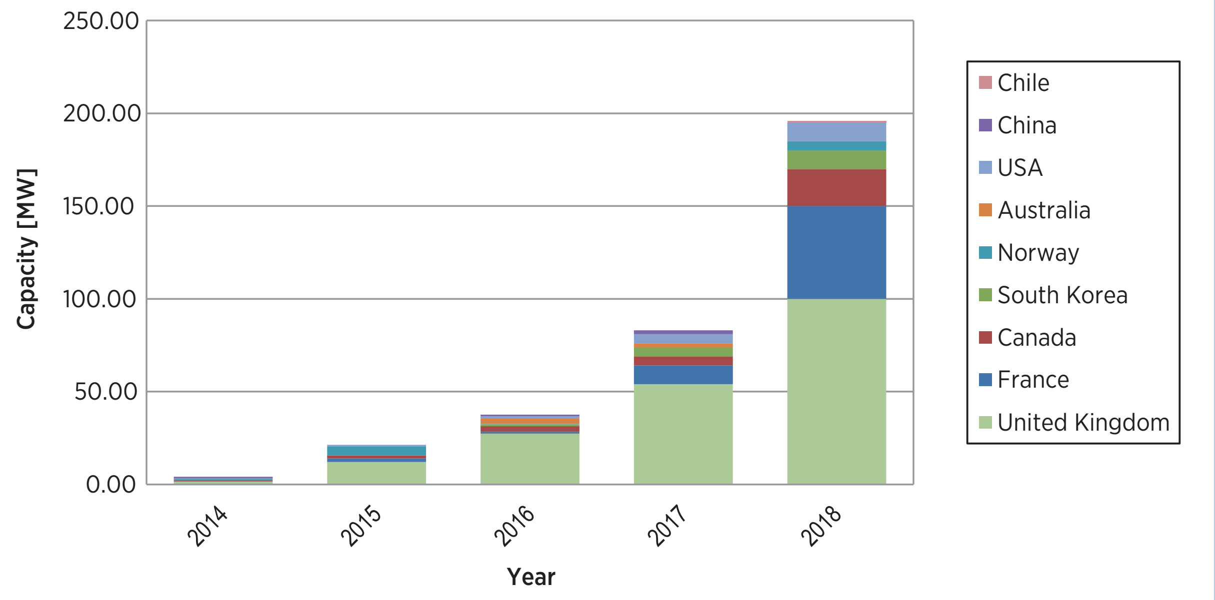
[9] www.otecnews.org/2013/05/otec-testing-in-okinawa/

Figure 2-9: Tidal stream potential project deployment pipeline



Based on analysis of data from DNV GL (2014)

for achieving economically viable ocean thermal power plant systems (*i.e.*, having low capital, as well as operation and maintenance costs). Fortunately, the offshore industry has already acquired extensive long-term experience with offshore subsystems and components that can operate over long periods of time in the harsh marine environment. Much of this experience will be applicable for satisfying similar requirements for ocean thermal plants deployment. A specific requirement for ocean thermal plants is large quantities of durable (*i.e.*, corrosion-resistant), low-cost metallic heat exchangers. Accordingly, in designing such heat exchangers, ocean thermal researchers are focusing on substituting durable, but low-cost, aluminium alloys for durable, but more expensive, titanium ones.

The continuing research and development efforts by companies such as DCNS, Lockheed Martin, Makai Ocean Engineering, Bluerise, among others, are lending credibility to the potential for commercial viability of ocean thermal energy plants in the medium term. A major technology barrier to offshore commercial ocean thermal plants is the need to install mammoth, stable, reliable, and survivable ocean platforms and the mooring systems. The experiences and technologies of the offshore oil industry, gained from 1978 to the present, in investing, building and successfully operating ocean platforms and mooring systems are similar to those required to launch a commercial ocean thermal industry sector and so could contribute to the removal of this barrier and add to the credibility of the potential to realise commercial-scale ocean thermal plants in the 2020s.

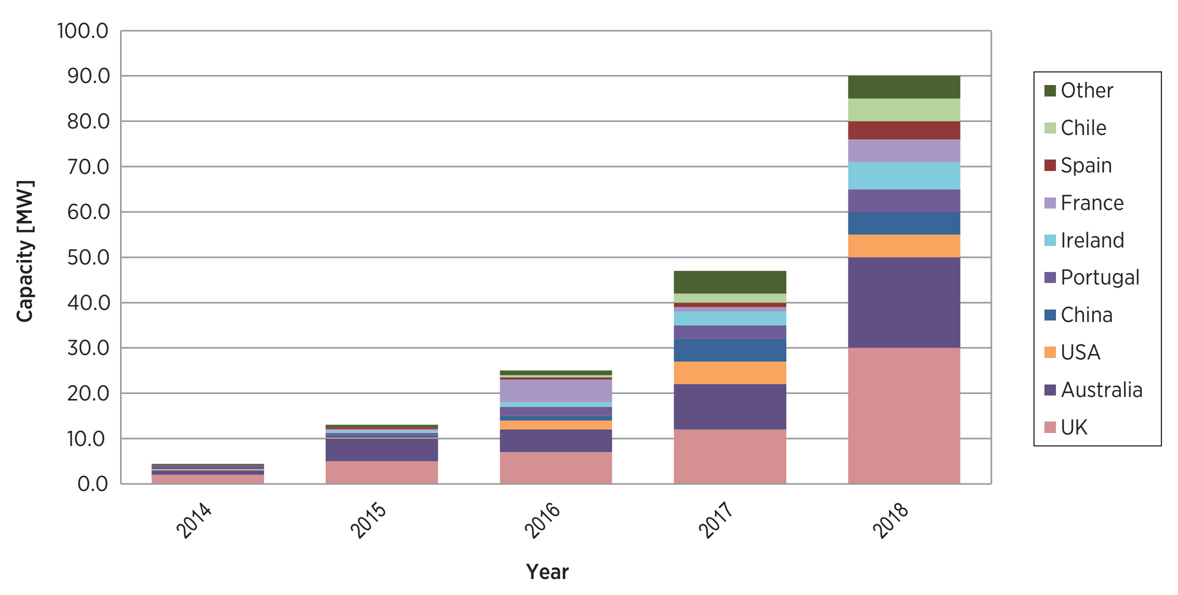
Research and development activities should continue providing and maturing the key technologies that will be required for commercial ocean thermal systems. For example, through research funding support from U.S. Navy and the U.S. Department of Energy from 2009 to 2011, Lockheed Martin has developed key technologies, such as heat exchangers and a large-diameter cold water pipe, required for ocean thermal plants. Those research and development studies included detailed design studies of an offshore, utility-scale, 10 MWe ocean thermal pilot plant.

However, two key hurdles remain to be overcome to achieve commercial ocean thermal power plants, which need to be sized at 100 MWe or larger to achieve the requisite economies-of-scale, namely: (i) successful demonstration of a utility-scale ocean thermal pilot plant, probably at the 10MWe level, and (ii) successful development of commercial-diameter (10 m or greater) cold water pipes, in parallel with the pilot plant demonstration.

2.3 Future deployment

As mentioned throughout the previous sections, there has been increased commercial interest in wave and tidal technologies. This interest is expected to continue going forward as can be seen from the overview of the market outlook for wave and tidal stream projects over the next five years. Timescales beyond this period are subject to substantial uncertainty and highly depend-

Figure 2-10: Wave energy potential project deployment pipeline



Based on analysis of data from DNV GL (2014)

ent on the success of short-term projects, given the pre-commercial status of these technologies. The projections presented here are informed by both a 'bottom-up' analysis of announced projects in the pipeline and a 'top-down' view of government targets for ocean energy globally. These two approaches are described analytically as follows:

"Bottom-up" pipeline

Figure 2-9 and Figure 2-10 below[10] consider key developer project announcements and development activity in each of the various countries. The pipeline of announced projects is most likely substantially greater than what can be realistically expected to be deployed in this timeframe since funding is likely to be secured for only a fraction of announced projects, and the natural 'developer optimism bias' in the time taken to develop projects needs to be accounted for. The challenges of operating in the marine environment and grid connection difficulties are further reasons why the 'bottom-up' pipeline is unlikely to be realised according to developer announcements.

"Top-down" government targets

Another way to project future deployment growth of ocean energy technologies is to refer to government targets. Of particular note are the European Union's ambitious deployment targets for ocean energy technologies via National Renewable Energy Action Plans (NREAPs). Member States were required to submit NREAPs in 2010 outlining their plans for achieving their 2020 renewable energy targets. The January 2014 European Union Communication on Ocean Energy indicates that the European Union is targeting around 2.2 GW of ocean energy technologies by 2020. A number of other countries have also announced targets; for instance, Thailand is targeting 2 MW of ocean energy deployment by 2020.

However, as with the bottom-up pipeline, top-down targets have a natural upward bias, and based on the track records to date, are of limited value when forming deployment projections for ocean energy technologies. This is because targets are often aspirational rather than predictive: targets are sometimes set particularly high as an aspirational "stretch" to motivate the industry, showing what could be achieved, rather than as a realistic prediction of what will be achieved. Targets are also subject to substantial revision. For instance, the UK government aspirations in 2010 for 1-2 GW of marine energy by 2020 were downgraded to 200-300 MW the following year. More recently the emerging industry consensus appears to be that a more realistic figure of approximately 150 MW in the UK by 2020 is to be expected.

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[10] *Notes: Based on details provided in most recent public domain developer announcements. Planned installation years are based on developer announcements and country activity. Consideration given to both demonstration/prototype projects and planned commercial arrays, including potential expansions on existing sites. Excludes projects which have been terminated or cancelled. Excludes devices that have been removed from earlier projects and will be reinstalled. Records projects >100 kW only. Considers both grid and non-grid connected projects.*

Deployment: technology to flourish in 2020s

The deployment projections quoted in this report are based on a pessimistic reflection of activity to date having fallen short of past expectations. As the European Strategic Initiative for Ocean Energy (SI Ocean) report of 2013 noted, 'progress has been much slower than anticipated, with a significant risk of being unable to meet deployment targets' (MacGillivray, *et al.*, 2013)

There are a number of reasons why real-life deployment has been slower than has historically been projected, including:

- Slower technology development than hoped
- Natural technology optimism by device developers
- Pressure to exaggerate technical maturity in order to secure the attention of policy makers and investors
- Challenging macroeconomic environment – particularly significant in some European countries such as Portugal and Ireland, and leading to reduced risk appetite amongst investors (European Commission, 2014)
- Targets often not being backed up by the financial support needed to deliver deployment

The ocean energy industry is now undergoing a period of introspection where deployment projections are being reassessed, with the result that ocean energy deployment will likely ramp up to multi-GW scale deployment in the 2020s rather than in the 2010s (European Commission, 2014).

Projections

The limitations of both the "bottom-up" and "top-down" methodologies for projecting future growth of ocean energy technologies indicate the importance of expressing deployment figures as a wide range. Taking into account the current "bottom-up" potential pipeline, and government aspirations, as well as considering barriers (see Section 3.4), new commissioned capacity in wave energy deployment is expected to be in the range of 5-90 MW globally from 2014-2018, and tidal stream deployment in the range of 10-200 MW globally from 2014-2018. It should be stressed that even these wide ranges are subject to significant uncertainty. In general, the deployment of ocean energy technologies is expected to ramp up to multi-GW scale in the 2020s rather than this decade, as indicated in the box below.

2.4 Key players in the ocean energy sector

Due to their pre-commercial status, much of the research, demonstration and development of ocean energy technologies is being led by universities and start-ups.[11] However, in recent years major OEMs and utilities have entered the sector. This is a vital step towards commercialisation since only the larger players have the capabilities and resources to deliver utility-scale, bankable projects. In addition, OEMs are the players who are best-placed to deliver the benefits of mass production and equipped with the value engineering expertise required to drive down costs. An overview of the engagement of large manufacturers into the sector is summarised in Table 2-2.

Due to the early stage nature of ocean energy technologies, it is notable that many device developers have become proactively engaged in project development, in order to ensure a market for their machines. An example of such vertical integration is Atlantis Resources Limited, which is both a turbine supplier and project owner operating in the emerging tidal stream sector. Nonetheless, device developers also often work closely with utilities to help ensure a long-term market for their products. For forward-thinking utilities, the opportunity to support research projects and demonstrations involves them early and encourages the development of new clean energy technology which they recognise holds the potential to one day join their energy generation portfolios in significant quantities.

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[11] *Tidal range technologies are a notable exception to this.*

Table 2-2: Industry engagement in ocean energy technologies

Technology	Engagement of large manufacturers[12]
Wave energy converters: Ongoing market consolidation	Although the wave sector has succeeded in initially attracting the interest of OEMs and utilities, it has struggled to retain it, with 2013 in particular being a year of market consolidation. The German OEM Voith Hydro decided to close down its WaveGen operations in Scotland, while French multinational Alstom announced it would not be investing further in wave energy device developer AWS (it acquired 40% of the developer in 2011). The Swiss-Swedish multinational ABB, however, remains a shareholder in Aquamarine Power through its venture capital arm, ABB Technology Ventures. French naval defence company DCNS is also pushing forward – currently progressing plans for a project in France using AW-Energy's WaveRoller™ technology. American defence and technology giant Lockheed Martin has also retained interest in the sector via a partnership with Ocean Power Technologies. In Asia, both Mitsubishi Heavy Industries and Mitsui Engineering and Shipbuilding Co. have had some recent supporting roles related to wave energy development. Some early utility backers have also recently shown some hesitancy: German utility E.ON has pulled out of the Pelamis wave energy research project, and Scottish Utility SSE has announced that it is reviewing its involvement in both wave and tidal projects. On the other hand, Finnish energy company Fortum, Spanish utility Iberdrola (including subsidiary ScottishPower Renewables), French utility EDF, and Swedish energy giant Vattenfall remain committed to the sector.
Tidal stream converters: Substantial OEM engagement	The tidal stream industry is the most developed of the emerging ocean energy technologies. Recent years have seen the entry of major OEMs into the sector – notably Alstom, Andritz, DCNS, Hyundai Heavy Industries (HHI), Kawasaki Heavy Industries (KHI), Siemens, and Voith Hydro. All of the above are European except for Japanese KHI and Korean HHI. American multinational General Electric (GE) has also recently shown interest in the sector, and GE Energy is supplying the electrical power system for an upcoming prototype deployment in the UK. Nonetheless, these OEMs remain cautious, and generally seek co-funding from public sources to minimise their risk exposure in early array projects. Utilities engaged in tidal projects include Bord Gais of Ireland, EDF and GDF Suez of France, and Iberdrola (including subsidiary ScottishPower Renewables). Scottish utility SSE is currently reviewing its engagement in the sector.
Deep ocean currents devices: Start-ups and universities	To date, there has been much less notable interest from large industry players in deep ocean currents. Some interest has come from Asia, where IHI Corp., Toshiba Corp., and Mitsui & Co. have joined forces in a consortium with the University of Tokyo to investigate and develop systems capable of harnessing energy from the Kuroshio current off Japan. The large American domestic oil & gas company Anadarko Petroleum Corporation has also pursued early-stage development of an ocean current turbine system.
Tidal range technology: Consortium approach or government co-ordination	Due to the large scale and civil engineering emphasis of tidal range technology, the players involved with tidal range are quite distinct from those for tidal stream. Generalisation is challenging due to the limited number of tidal plants built. The high risk associated with developing a large tidal range project can promote a consortium approach, or else requires a strong co-ordinated government approach. The UK is an example of the consortium approach. For instance, Hafren Power, which seeks to develop the Severn Barrage, is a private limited company, owned and controlled by a group of British entrepreneurs and investors, but it has a delivery team spanning Arup, Bechtel, DHL, Mott MacDonald and URS. To take another UK example, Tidal Lagoon (Swansea Bay) plc. is a Special Purpose Vehicle which draws upon expertise from a consortium of engineering firms including Atkins Global, Van Oord, TenCate, Costain and KGAL.

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[12] *Not an exhaustive review. As of early 2014.*

OTEC devices: Two large defence players; otherwise limited engagement	Two notable industry heavyweights in the sector are the French naval and defence player, DCNS, and American defence, aerospace and technology company, Lockheed Martin. DCNS commissioned a land-based OTEC prototype plant in La Réunion in early 2012. In July 2014 Akuo Energy and DCNS received funding to the level of EUR 72.1 million from the European Union's NER300 programme[13] to support the development of a 16 MW ocean thermal energy plant as part of the NEMO[14] project in Martinique. Lockheed Martin has commenced design of a utility-scale 10 MWe ocean thermal pilot plant, in a project sponsored by the Reignwood Group, headquartered in Beijing, China.
Salinity gradient technology: Limited involvement of major industry players	Industry involvement to date has been limited, but is diverse insofar as it has spanned both companies with specialist membrane capabilities and more traditional renewable power companies. With regards to the former, Fujifilm, the imaging company headquartered in Japan, is developing membrane technology. Japanese company Nitto has also sought to apply its membrane manufacturing expertise to salinity gradient technology. However, industry engagement remains shaky. In December 2013, Norwegian energy company Statkraft announced that it was discontinuing its developments in osmotic power after 10 years of involvement. The stated reason was that the technology is unlikely to become competitive within the foreseeable future.

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[13] *The European Union's NER300 Programme, funded from the sale of 300 million emission allowances from the New Entrants' Reserve (NER300) of the EU emissions trading system, supports innovative low-carbon energy demonstration projects in the EU.*

[14] *New Energy for Martinique and Overseas*

3 CLASSIFICATION OF OCEAN ENERGY TECHNOLOGIES AND DEVELOPMENT TRENDS

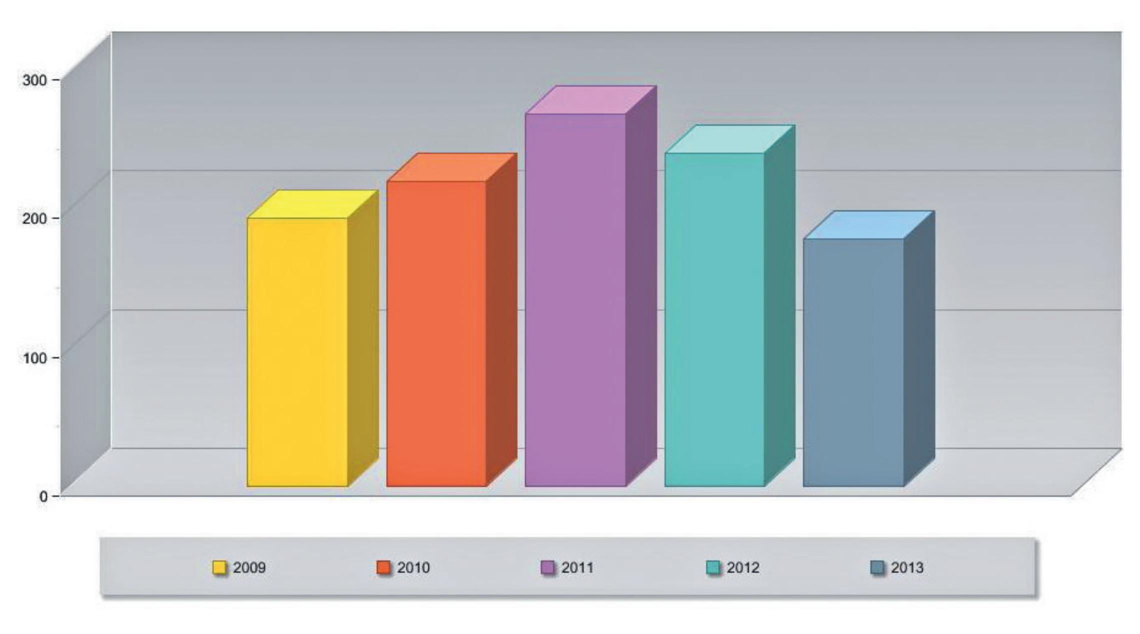
3.1 Review of international patent activity on ocean energy technologies

In order to support the development of ocean energy technologies and provide the enabling environment for their deployment, policy makers need to have access to relevant, reliable and up to date information on technology developments. Patent activity is one of the sources of such information. Making patent information more accessible can help to catalyse further innovation in ocean energy technologies. Activities in intellectual property rights originations and registrations could give an indication of possible break through and game-changing technologies or application areas, as well as an insights on potential market activity and interest in the development and deployment of technologies in the medium-term. It provides an opportunity to identify trends in technology transfer from one country to another; as well as international collaboration on research and development of technologies as indicated by registrations of co-invention and co-ownership patents.

The global level of patent activity with regards to ocean energy technologies is significant, with the number of annual international Patent Cooperation Treaty (PCT) publications for these technologies averaging well over 150 for the period 2009 to 2013, as shown in Figure 3-1. This report focussed on these international PCT publications, numbered beginning with "WO" (for "world"), in order to avoid the risk of duplication with the same technology filing for patents in various different countries and issues with language barriers that would arise from analysing individual national patent publications.

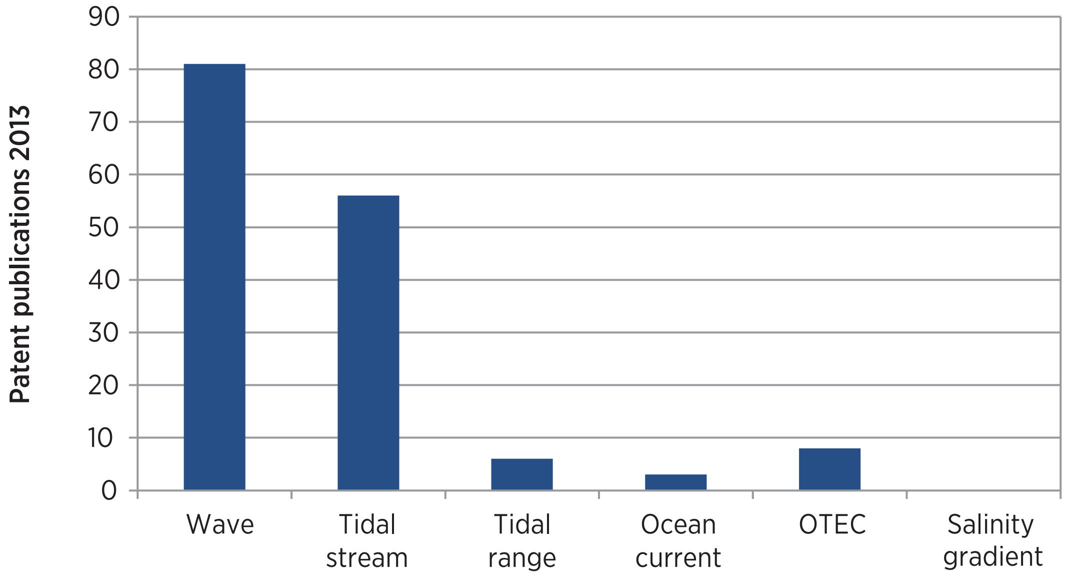
Online patent databases and search interfaces such as the European Patent Office's Espacenet patent search

Figure 3-1: Ocean energy technology international Patent Cooperation Treaty publications between 2009 and 2013



Source: Thomson Innovation (as cited in INPI and OEPM, 2014)

Figure 3-2: Number of international Patent Cooperation Treaty publications by ocean energy technology type in 2013



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

portal[15] provide free access to more than 80 million patent documents worldwide. Such databases can be a good place to start, and there are various classifications and patent families established that can be used to look for various technology types, including classifications designated for renewable energy produced from the sea (classification Y02E 10/30) and the new classification of Y02E 10/28 for tidal stream. The Y02E 10/30 include sub-categories of Y02E 10/32 for oscillating water column, Y02E 10/34 for OTEC, Y02E 10/36 for salinity gradient, and Y02E 10/38 for wave energy and tidal swell. However, in patent databases many ocean energy technologies are often misclassified. For example, wave energy technologies frequently show up in lists generated by tidal stream classification searches. As such, high level classification searches provide a starting point but additional filtering of results must be undertaken to gain a clear picture of ocean energy technology patents and trends. This is particularly true for less widely understood and novel technologies such as those for ocean energy conversion.

In this report a more refined system was followed where international PCT data, including the list of 2013 ocean energy PCT publications was adapted from technology watch bulletins[16] for ocean energy produced by the Portuguese and Spanish patent authorities, *i.e.*, Instituto Nacional de Propriedade Industrial (INPI) & Oficina Espanola de Patentes y Marcas (OEPM) and supplemented by keyword searches on Espacenet[17]. In the referenced technology watch bulletins, which are posted on the INPI's website on a quarterly basis, INPI and OEPM collate patents pertaining to ocean energy. All PCT publications considered for analysis in this report were confirmed to be ocean energy technology patents and then classified by the technology types covered herein.

In 2013, wave and tidal stream patents dominated those of other ocean energy technologies based on international PCT publications, as shown in Figure 3-2. Due to this comparatively high level of global technology development activity, trends in wave and tidal stream technologies are considered in more detail below (see Section 3.2 and Section 3.3). Other ocean energy technologies are considered at a more general level, due to the limitations of a small sample size of patents publications (Section 3.4). The international PCT patent publications analysed in this report are listed in Appendix 1.

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[15] http://worldwide.espacenet.com/

[16] *Available at http://www.marcasepatentes.pt/index.php?section=725 [last accessed 29 July 2014]*

[17] *http://worldwide.espacenet.com/ [using the Y02 classification: climate change mitigation and adaptation technologies. Last accessed 29 July 2014]*

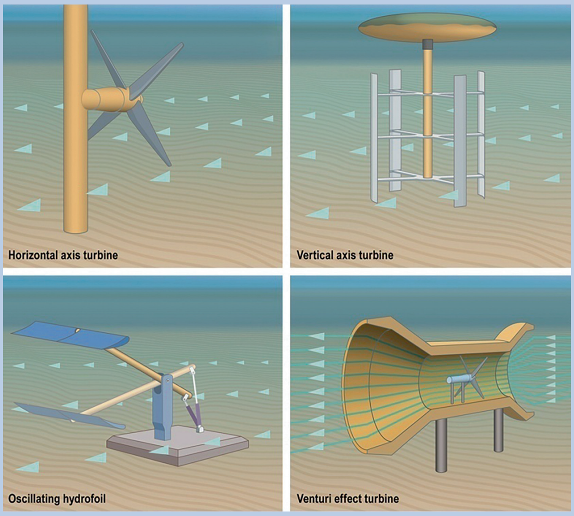
3.2 Tidal stream conversion systems

Hydrokinetic turbines are generally classified as one of several typical turbine-types shown in Figure 3-3 as follows:

- Horizontal-axis axial flow turbines (upper left). They may have any number of blades per rotor
- Vertical-axis cross flow turbines (upper right). They can also be rotated 90 degrees to form a horizontal-axis cross flow turbine.
- Reciprocating devices, such as oscillating hydrofoils (bottom left)
- Ducted, shrouded, or Venturi-effect turbines (bottom right). These additions can be applied to either axial or cross flow turbines

Horizontal-axis, axial flow turbines are the type most comparable to modern conventional wind turbines. The incoming flow passes the turbine in parallel with the axis of rotation, and multiple hydrofoil blades generate lift that creates a torque to spin the rotor. The rotor is then used to mechanically drive an electric generator. Axial flow turbines must be oriented into the direction of the flow, which is an important consideration in bi-directional tidal streams. As the underlying physics behind open rotor horizontal axis turbines is the same as for modern wind turbines, developers can benefit from a range of advanced numerical modelling tools developed for the more mature wind energy sector. These tools can be applied to horizontal axis turbines with appropriate adaptation for tidal-specific considerations like buoyancy, added mass effects, and cavitation inception. Some devices yaw into the changing tidal stream directions, although many are fixed to simplify the designs for operation in an aquatic environment. Blades can be fixed or variable pitch. Some developers pitch the blades a full 180° to extract energy from both ebb and flood tidal flows, while others use bi-directional blades to allow the turbine to spin in both tidal directions without requiring yaw or pitch systems. Both shrouded/ducted and open rotor devices have been developed.

Figure 3-3: Major types of hydrokinetic energy conversion device



Source: Augustine et al., 2012

A vertical-axis cross flow turbine has an axis of rotation which is perpendicular to the incoming flow. Cross flow turbines can also be oriented with a horizontal axis perpendicular to the flow direction, which may prove more useful in depth constrained locations. Vertical axis turbine designs could prove advantageous in narrow, deep channels that often seek the benefit of housing power take-off (PTO) equipment above the water surface. A vertical axis cross-flow turbine incorporates blades which use lift forces to generate the torque required to spin the rotor; however, there are also cross flow turbines that use drag forces from the flow to generate the driving torque. Cross flow turbines can often operate in flow from multiple directions (*e.g.*, ebb and flood tides) without reorientation. Cross flow turbines with both ducted and open rotors have been developed.

As mentioned, hydrokinetic turbines may be ducted or shrouded, often in order to utilise what is known as the "Venturi effect." This effect is the increase in velocity of a fluid that occurs through a constricted section of a pipe. Turbine shrouds can take many forms, and in some cases the primary purpose serves to house a rim-mounted generator, while in other cases the purpose is to capture and accelerate more flow through the device.

In another type of hydrokinetic device the flow is used to generate forces, which cause an oscillating component to transverse the flow direction. The behaviour can be induced by lift and drag on a hydrofoil, vortex shedding, the Magnus effect, or flow flutter. Mechanical energy from the oscillating component is then used to drive a power conversion system. A common example that has been developed is an oscillating hydrofoil device. Here a hydrofoil blade similar to a wing, is placed in the flow. A control system adjusts the relative angle of attack between the flow and the blade causing the lift and drag forces generated to force it into oscillation.

Finally, there are a few select developers pursing designs that do not fit clearly into any of these major categories, some of which are even testing large-scale prototypes. Examples include systems which incorporate screw-shaped rotors, tidal kites, and tidal sails.

Different developers are pursuing a range of control techniques for the various turbine designs, which including pitch, stall, and overspeed regulation. PTO systems also vary widely with the individual technologies and include more conventional gearbox and generator systems, variable speed generators, direct-drive permanent magnet systems, direct-drive hydraulic systems, and others.

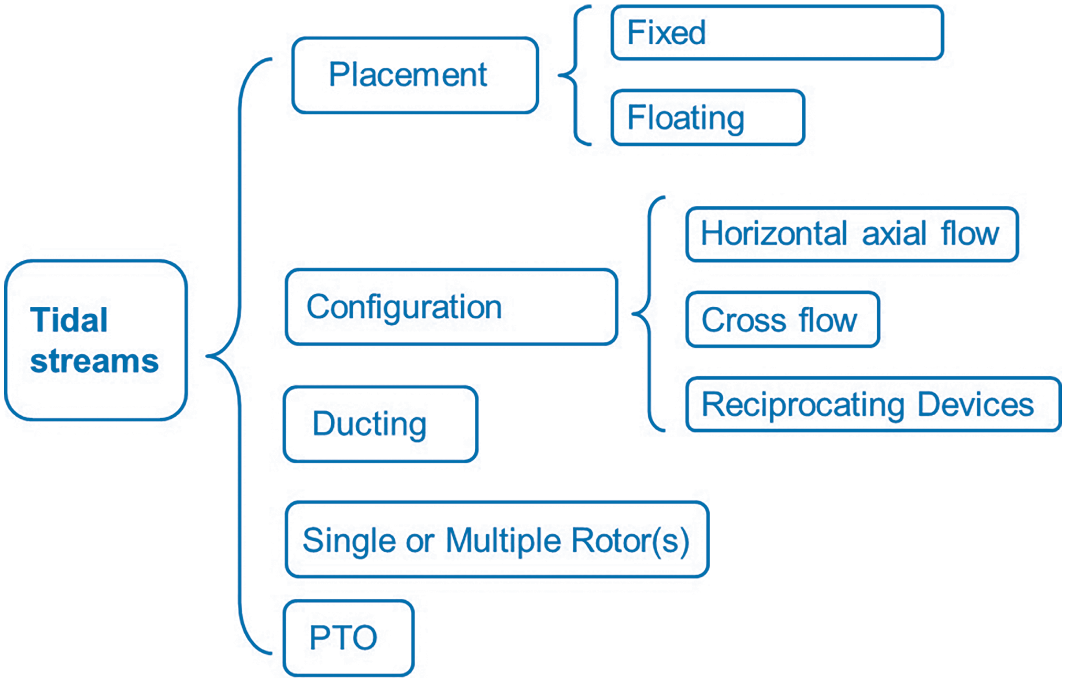
All hydrokinetic systems must be kept in position in the tidal current. Methods for station-keeping also vary with the designs. Generally tidal stream systems can either be floating and held in position by a flexible mooring system, or bottom-mounted and rigidly connected to a foundation. Bottom foundations could include gravity bases, suction caissons or piles that are drilled or pounded into the seabed. Additionally devices can either be designed to be fully submerged during operation, so they are out of sight and even permit boat traffic overhead, or they can be surface piercing for easy access. Many developers are also looking to place multiple (two or more) rotors or turbine generators on a single foundation or floating platform.

Figure 3-4 illustrates the breakdown of typical tidal stream turbine classifications discussed above.

Hydrokinetic energy converters are generally designed to be modular systems, which can then be scaled up into multi-megawatt arrays. Developers of systems for tidal applications tend to be seeking individual turbines for commercial applications with rated power capacities of over 1 MW. Arrays of dozens to hundreds of such turbines are then envisioned to be capable of utility-scale tidal stream generation. Although currently the first small array projects are being planned, there are still no utility-scale commercial tidal stream arrays operating anywhere in the world as of June 2014. Major technology developers are at a stage where they are testing full-scale concepts and are seeking ways to drive down the levelised cost of energy (LCOE) for their systems.

For this reason, there is not considered to be any 'best' or 'winning' hydrokinetic turbine design at this point in time. It can be noted that the majority of developers focusing on tidal stream applications that also already have prototypes of 500 kW or more capacity at sea are pursuing designs in the form of horizontal axis axial flow turbines, similar to the modern wind turbine. In that sense, it may appear that there is more convergence amongst technology developers and fewer types of devices in tidal stream energy than in wave energy. However, the apparently rapid advancement of these concepts may be due in part to the availability of machinery and design tools from the mature wind sector. There are still a significant number of technology developers pursuing cross-flow turbines and other designs, and as the constraints of tidal sites differ from wind (particularly with spatially constrained channels and depth-limited flows) other devices may prove suitable for tidal stream energy conversion and retain a portion of the market.

Figure 3-4: Summary of typical tidal stream turbine classifications



Tidal stream patent activities

In 2013, at least 56 tidal stream international PCT applications were published, with applicants coming from 18 different countries (Figure 3-5). See tables in Appendix 1 to see all patents considered. Exploring the patents in the table shows that there are a wide range of technologies described by the patents, with no clear trend in terms of technology type. It is important to note that patent registrations and publications do not necessarily indicate the likelihood of technologies that get developed into widespread commercial use, and as such it would not make sense to draw conclusions regarding technology convergence from patent activity. The following sub-section looking at technologies that are demonstrating clear development activity, shows a more useful approach for analysing trends in the types of tidal stream turbines being pursued. However, an examination of who is submitting patent applications can provide some insight into the status of the sector. For example, among the 2013 international PCT publications for tidal stream energy, 36% were submitted by individuals, with only 3.5% coming from universities, and the majority (60%) coming from companies (Figure 3-6). In fact, many the companies who submitted patent applications are large, multinational OEMs: Alstom (owner of Tidal Generation Ltd.), Andritz, Boeing, DCNS (owner of OpenHydro), GE, and Hyundai. This could be indicative of a movement toward maturity when compared to sectors where the vast majority of patent applications are coming from individual inventors and small start-up companies.

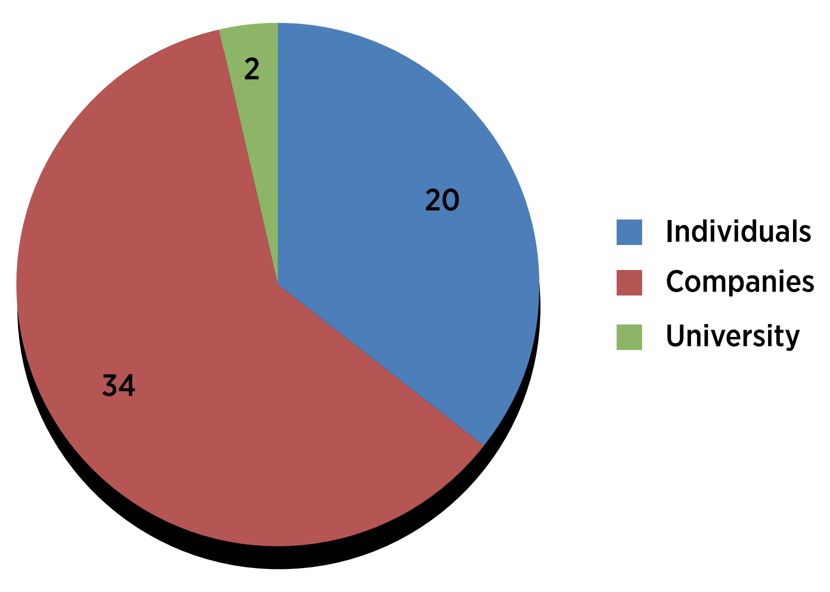
Analysis of the DNV GL data compilation on tidal stream technology

Patent searches alone provide a limited understanding regarding the type of technologies being pursued toward commercialisation. A very large number of patents in the ocean energy sector do not accurately represent the design concepts being actually developed. This is also true for those approaching commercial readiness for use in real electricity generation projects. In order to more accurately identify current development trends and the market status of ocean energy technologies, it is more useful to assess and analyse those technologies that have progressed significantly along the design development path. DNV GL has developed an internal compilation of known tidal stream turbine developers. This data is updated regularly as new information is released in the public domain regarding the various technology developers and their projects. As of February 2014, the database lists 110 tidal stream concepts. The

Figure 3-5: Tidal stream international Patent Cooperation Treaty publications by country in 2013

Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

Figure 3-6: Number of tidal stream Patent Cooperation Treaty publications by owner type in 2013



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

data is a useful tool for understanding the technologies under development and progression of the tidal stream sector, and some trends from this are analysed here.

Each tidal stream developer and their technology is classified in their profile summary by home country, status (active, inactive, or unknown), application (some tidal stream developers are also perusing river hydrokinetic and ocean current system developments), device type (horizontal axis axial flow, vertical axis cross flow, horizontal axis cross flow, oscillating, venturi, or other), configuration details (whether or not it utilises multiple rotors and/or ducting) and regulation (pitch, stall, overspeed, or no regulation), PTO (variable speed or not, gearbox and generator, direct-drive permanent magnet, direct-drive hydraulic, or undefined/other), and support structure (whether device is fully submerged, rigid connection, monopile, tether/moorings, or undefined). These categories align with the description of tidal stream turbine classifications provided at the beginning of Section 3-2. The developers were considered to be "active" if there was awareness of relatively recent evidence that the developers are actively pursuing development of the technology concept.

In addition to the technical overview of each tidal stream design concept, information related to the device developer's progress is compiled in the DNV GL data set under four main categories: project development, technology classification, evidence of a modelling program and full-scale design. Progress is recorded incrementally through a set of criteria defined under each category, given below:

- Project development
    - Company history (>5 years)
    - Staff (>10 full-time)
    - Investment (>£1m)
    - Investment (>£10m)

- Technology classification
    - PTO development
    - Deployment strategy development
    - Operations and maintenance (O&M) strategy development

- Evidence of a modelling program
    - Numerical modelling
    - Experimental modelling
    - Prototype deployed at sea
- Full-scale design
    - Independent verification
    - Full-scale prototype (FSP) deployed

Based on expert judgment, each concept is given a point for each of the above 12 criteria that it meets (0.5 points for an unconfirmed "yes") giving a total score of between 0-12 points. This helps to establish a shortlist of concepts for those which score above 5 out of 12 and are considered to be actively under development.

It is noted that, while useful, this methodology only helps to demonstrate what aspects of the development process each concept has undergone, and not necessarily whether or not they are credible technologies that will significantly and cost effectively convert ocean energy into a useable form. Assessing the latter requires detailed technical assessments, and knowledge of information not available in the public domain. Even then, due to the early-stage of the sector, it is really time and investment – and the learning, innovation, and operational experience that comes with it – that will demonstrate which technologies prove ultimately successful.

Furthermore, although the resulting shortlist and score comparisons may help in determining which developers have progressed along the path toward commercialisation and have achieved higher TRLs for their concepts, it should be noted that the methodology does not fully consider individual differences between device concepts and development programmes and the degree to which each criterion is met. For example, a "prototype deployed at sea" could mean a larger-scale device tested in deep ocean waters in a more extreme environment for a longer period of time, or it could mean a small-scale prototype deployed in more sheltered seas for a short period of time. In this example, there is some inherent upward bias to scoring for concepts easier to deploy or which have had shorter term, smaller-scale sea trials than otherwise. It should also be noted that prototype and full-scale deployments do not require that the systems be grid-connected. With the current status of the tidal stream sector, prototypes are often put in place for predetermined testing periods and/or removed as needed to make adjustments or avoid extreme conditions, and although a deployment has occurred, the unit may not still be installed today.

The information contained in the DNV GL data compilation also lends itself readily to statistical analysis of trends amongst the technologies being actively developed. Following the methodology described, Table 3-1 presents 25 known active, commercial (*i.e.*, non-university) tidal stream technology developers from 13 differ-

Table 3-1: Shortlisted tidal stream technology developers

Developer	**Country**	**Website**
Andritz Hydro Hammerfest	Norway/Austria	www.hammerfeststrom.com
Alstom	France/UK	www.alstom.com/power/renewables/ocean-energy/tidal-energy
Atlantis Resources Corporation	Singapore/UK	www.atlantisresourcesltd.com
Clean Current Power Systems	Canada	www.cleancurrent.com
Elemental Energy Technologies	Australia	www.eetmarine.com
Flumill	Norway	www.flumill.com
Hydra Tidal (Straum AS)	Norway	www.hydratidal.info
Hyundai Heavy Industries	South Korea	www.hyundaiheavy.com/news/view?idx=332
Kawasaki Heavy Indutries	South Korea	www.khi.co.jp/english/news/detail/20111019_1
Marine Current Turbines (Siemens)	UK/Germany	www.marineturbines.com
Minesto	Sweden	www.minesto.com
Nautricity	UK	www.nautricity.com
New Energy Corporation	Canada	www.newenergycorp.ca
Ocean Renewable Power Company	USA	www.orpc.co
Oceanflow Energy	UK	www.oceanflowenergy.com
OpenHydro (DCNS)	Ireland/France	www.openhydro.com
Pulse Tidal	UK	www.pulsetidal.com
Sabella	France	www.sabella.fr
Schottel	Germany	www.schottel.de
Scotrenewables Tidal Power	UK	www.scotrenewables.com
Swanturbines	UK	www.swanturbines.co.uk
Tidal Energy Limited	UK	www.tidalenergyltd.com
Tocardo	Netherlands	www.tocardo.com
Verdant Power	USA	www.verdantpower.com
Voith Hydro	Germany	www.voith.com/en/products-services/hydro-power-377.html

Based on analysis of data from DNV GL (2014) ent countries around the world that scored greater than 5 points out of a maximum 12. The criteria (greater than a score of 5 points) provides a preliminary shortlist from the 82 known active tidal stream turbine developers, to give a more useful basis for the statistical analysis that follows, focusing on those active developers furthest along the pathway to higher TRLs.

Several observations can be summarised about the trends among these 25 shortlisted developers:

- 76% of the technologies involved are horizontal axis, axial flow technologies, 12% are cross flow turbines, 4% are reciprocating systems, and 8% are classified as "other" (Figure 3-7a)
- 68% of the technologies are designed to be fully-submerged while operational
- 68% of the concepts utilise a single turbine per structure, while the other 32% of the technologies are seeking to use multiple rotors on each foundation or floating platform
- 64% of the tidal stream turbines have a variable speed power train
- 56% are rigidly connected to the seabed using a non-monopile foundation system, 36% are floating systems tethered in position via moorings, while 4% are designed to be placed on a monopile foundation, and the remaining 4% unspecified (Figure 3-7b)
- 48% are known to utilise a gearbox and generator system, with 44% utilising a direct-drive permanent magnet generator, and the other 8% unspecified
- 44% are designed to yaw around into the incoming flows, with the others designed to avoid the need for yawing or unspecified. Tethered devices that freely yaw into the flow are considered to be yawing systems
- 16% are pursuing a ducted concept
- 28% use pitch regulation, 16% use overspeed regulation, 16% have no regulation, and 8% use stall regulation, with 32% unspecified or unannounced publically

Table 3-2 provides the percentage of shortlisted developers with 'yes' (including an unconfirmed yes) in each development category described previously. The table can be used to identify trends among development priorities.

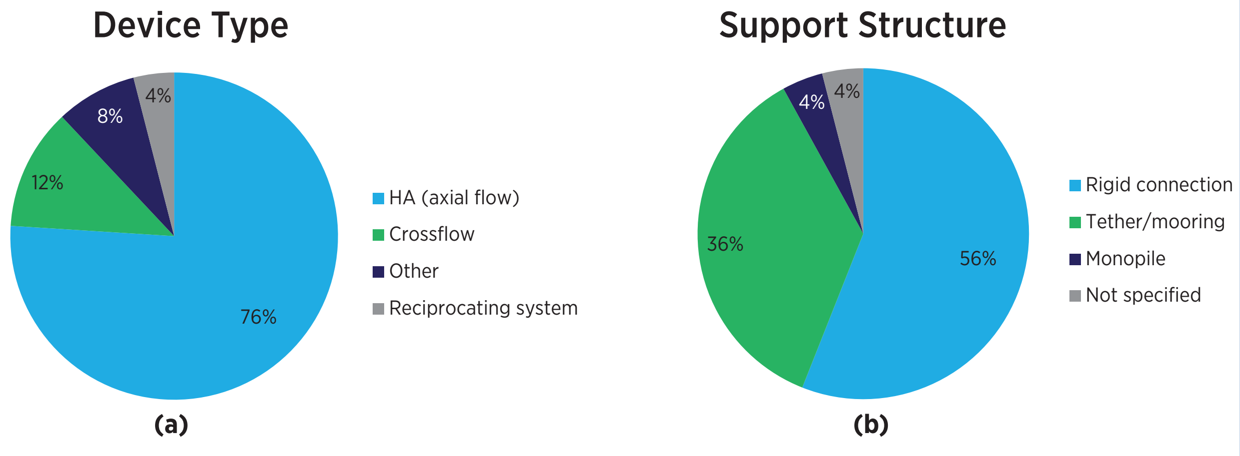
Summary of tidal stream technology trends

Patent activity published in 2013 included patent applications from 18 different countries, while the shortlisted technology developers come from 13 countries. The correlation between the leading countries in each is clear (Figure 3.8).

The UK, followed by France and Germany dominate both international patent activity and the location of the shortlisted tidal stream developers. The UK and France are considered to have the best tidal stream resource in Europe, and it is clear that domestic developers and technologies have arisen to exploit that resource. Meanwhile Germany's technology companies and OEMs seek involvement in their European neighbours' markets. Korea and Canada are both notable secondary players in the development of tidal stream technologies today.

In terms of technology, the clearest trend is that the majority of the leading developers (about three quarters) today are pursuing horizontal-axis axial flow concepts. It is also clear that only 16% of developers are pursu-

Figure 3-7: Breakdown of device types and support structures being pursued by shortlisted tidal stream developers



Based on analysis of data from DNV GL (2014)

Table 3-2: Statistical summary – shortlisted tidal stream technologies

Total number of developers	25
Nationalities	13
Average number of sub-categories fulfilled	9.1 (out of 12)
Standard deviation	2.1
Company history (> 5y)	96%
Staff (>10 full time)	68%
Investment	100% (>£1m); 60% (>£10m)
PTO strategy	100%
Deployment strategy	100%
O&M strategy	64%
Numerical modelling	100%
Experimental modelling	100%
Prototype deployed at sea	88%
Independent verification	60%
Full-scale prototype (FSP)	48%

ing a ducted or shrouded system, with most preferring open rotors. A little over two-thirds of the shortlisted developers are pursuing fully-submerged concepts. This approach would lead to an 'invisible' turbine for coastal residents that may also be more protected from storms at any site that can receive significant wave activity; however, it may also be more costly and difficult to access for O&M than a surface piercing system that can be accessed on site. Just over two-thirds of the developers are planning to only place a single turbine/rotor on each foundation or platform. Nearly two-thirds of the systems will use a variable speed generator in their power trains. The remainder of PTO characteristics, foundation/station-keeping methods, and control/regulation techniques are much more diverse among the shortlisted tidal turbine developers.

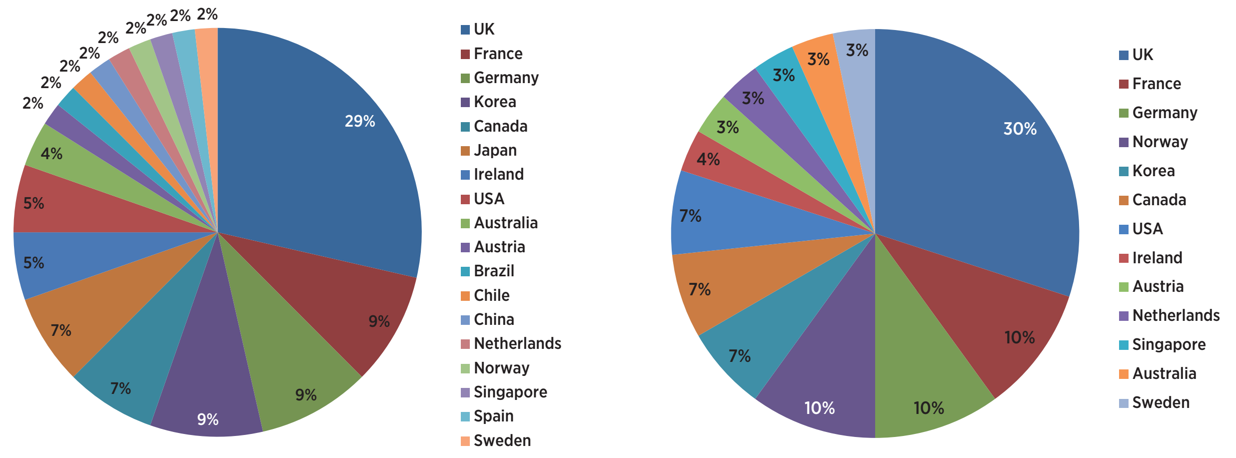
3.3 Wave energy conversion systems

The types of wave energy conversion systems may be categorised in different ways. Figure 3-9 illustrates some examples of the primary types of WEC devices. The point absorber, attenuator, and inverted pendulum (or 'oscillating surge') systems in the figure are all examples oscillating body WECs.

Oscillating body WECs involve the transfer of power from the waves to the motion of a structure or structures. A PTO arrangement is then connected between structures (self-referenced) or between a structure and the seabed (seabed referenced). This type of WEC sometimes operates on the surface (floating) or is completely submerged.

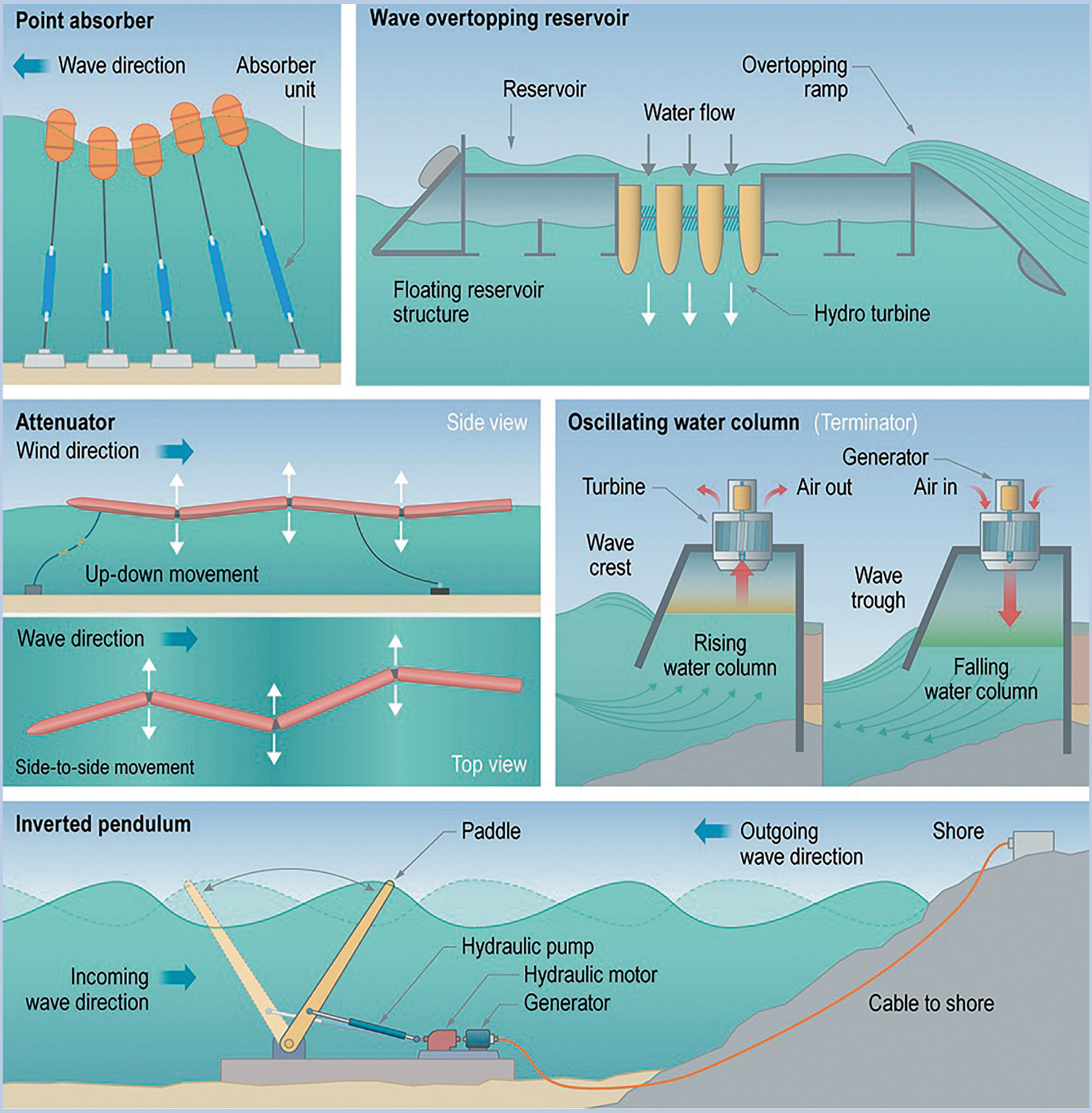
The first, top-level, category of WEC – oscillating water column devices – consist of an air chamber with its lower end open to the ocean and its top connected to the surrounding atmosphere via an air turbine. As the waves oscillate within the chamber, air is pushed through the turbine forcing it to spin and drive an electric generator. This arrangement may be fixed (to the seabed or shore)

Figure 3-8: Tidal stream 2013 international Patent Cooperation Treaty publications by country (left) and shortlisted developer countries (right)



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

Figure 3-9: Examples of major types of wave energy devices



Source: Augustine et al., 2012

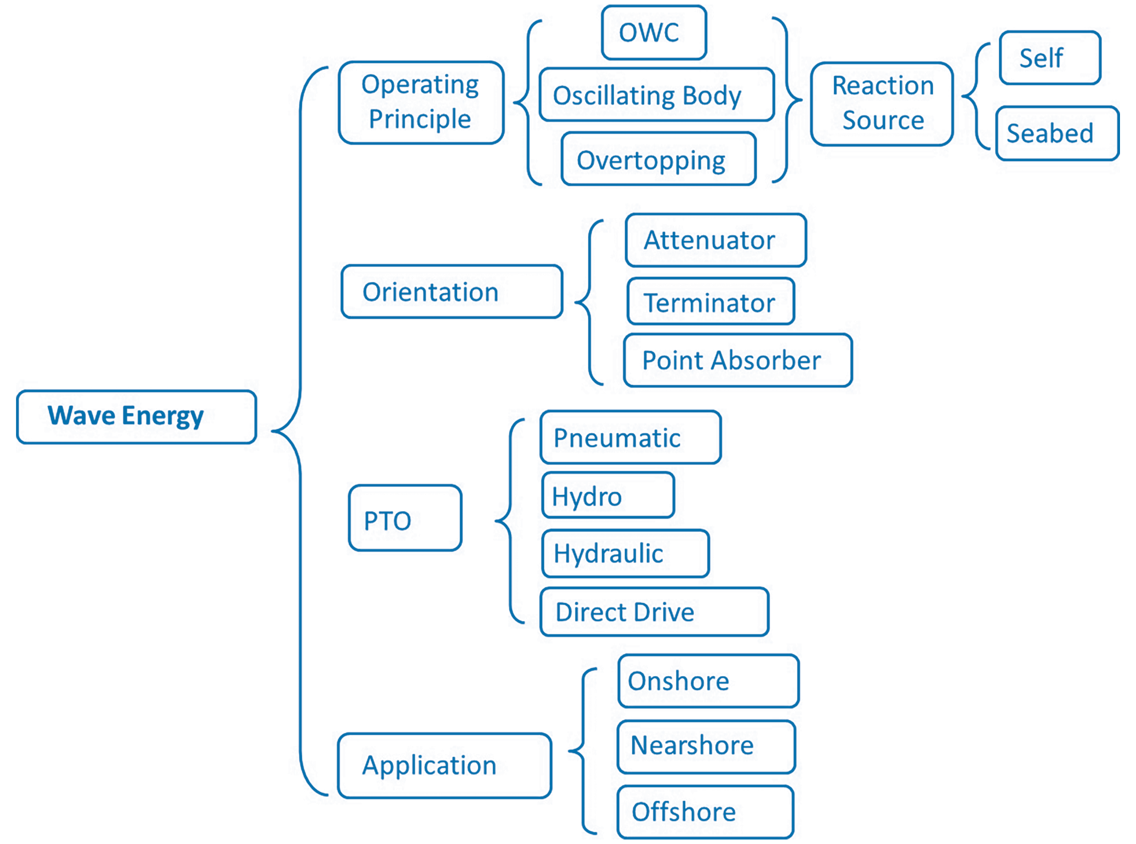
or floating (in which case it is the oscillations in sea surface elevation relative to the motion of the structure from which power is derived).

Overtopping devices use the action of the waves to deposit water into a reservoir (sometimes via a concentrating collector) above the mean water level. This is then returned to the sea via a low head turbine which converts the potential energy to electricity.

WECs are sometimes also categorised based on their dimensions and orientation as either point absorbers, attenuators or terminators. Attenuators extend more in the down-wave direction than parallel to the wave front and progressively absorb energy as the wave travels down the length of the WEC. Terminator WECs, on the other hand, are those in which the converter predominantly extends in the cross-wave direction. Point absorbers are small in both cross-wave and down-wave horizontal dimensions in comparison to dominant incident wave lengths.

The terms 'onshore', 'nearshore' and 'offshore' refer to the depth in which the WEC is situated, with the lat-

Figure 3-10: Summary of typical classification for wave energy converters



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

ter offering the greatest potential in terms of energy resource, but also generally being associated with the largest installation and O&M costs.

Figure 3-10 shows one such arrangement of the most common technology types.

WECs, like both wind and tidal stream turbines, are generally designed to be modular systems, which can then be scaled up into multi-megawatt arrays. Developers of systems for utility-scale electricity generation applications tend to be seeking individual WECs with rated power capacities of at least several hundred kilowatts. Arrays of dozens to hundreds of such WECs are then envisioned to be capable of significant generation capacity. Although currently the first small array projects are being planned, as of June 2014 there were no utility-scale commercial WEC arrays operating anywhere in the world. Major technology developers are at a stage where they are testing full-scale concepts and are seeking ways to drive down the LCOE for their systems.

For this reason, there is not considered to be any 'best' or 'winning' WEC design at this point in time. Due to the range of different wave energy climates found around the world and interest in applications offshore, nearshore and onshore, there may not be convergence on a single technology type in the wave energy sector. Different styles of devices may prove most suitable for differing uses.

Analysis of WEC patent activities

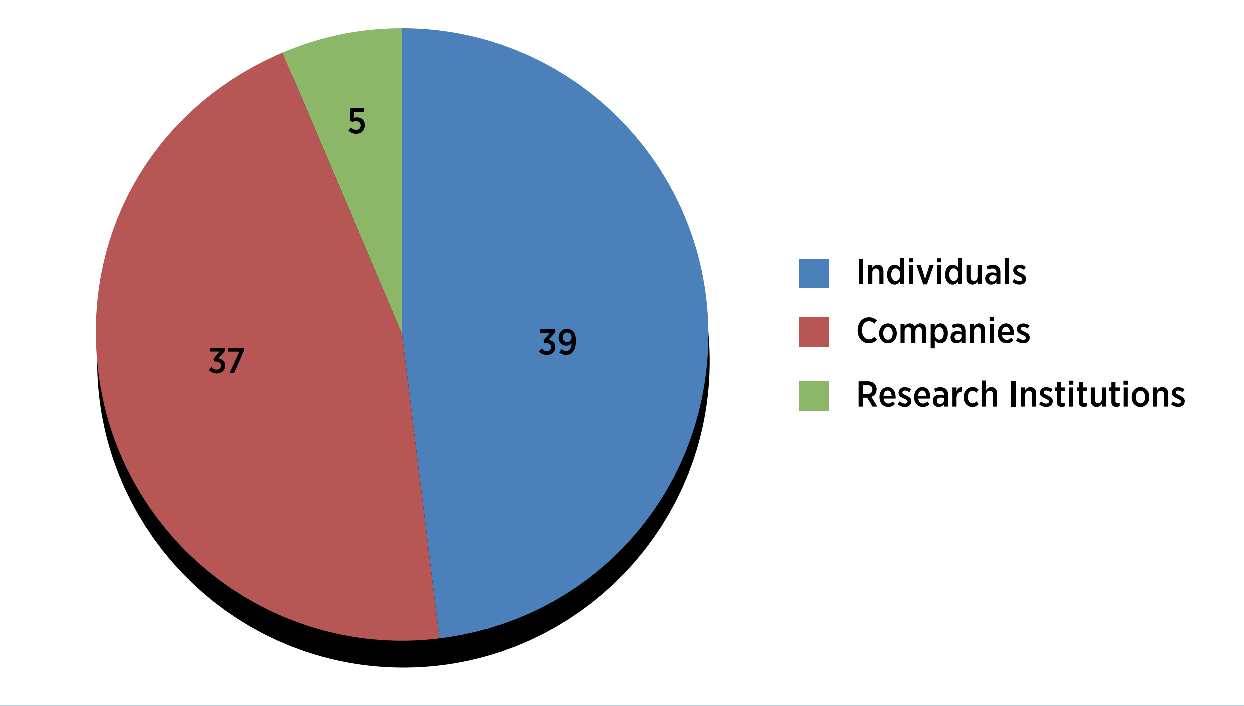
In 2013, at least 81 international PCT publications were published for wave energy with applicants coming from 26 different countries (Figure 3-11 – Wave international PCT applications in 2013). See Appendix 1 for a list of patents considered.

As was the case for tidal stream energy described earlier, there are no clear trends of value that can be derived from the many types of technologies described

Figure 3-11: Wave energy international Patent Cooperation Treaty publications by country in 2013

Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

Figure 3-12: Number of wave energy international Patent Cooperation Treaty publications by type in 2013



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

in the 2013 PCT publications for wave energy. Compared to the tidal stream sector, 2013 had significantly more international patent publications for wave energy, from more countries around the world and with perhaps even more variety in technology type. Once again, these patents do not necessarily reflect designs which will secure investment to develop the technology, validate the proposed design, and progress toward commercial use. The following section will analyse trends among developers, which have progressed WEC designs and are on the path to commercialisation. While looking at patents is not helpful for determining any trends among technologies under development, looking at who submitted the patents shows some interesting results. Among the 2013 international PCT publications for wave energy, nearly half (48%) came from individuals, 6% came from universities, and 46% came from companies. In comparison to tidal stream (see the review of international patent activity), this implies a sector that is slightly less mature with more early university research and development and individual inventor activity. A number of the companies involved are smaller WEC developers as compared to the number of OEMs submitting patent applications for tidal stream technology. Nevertheless, wave energy did see some larger multinational organisations submit patents in 2013, *e.g.*, Chevron and Bosch.

Analysis of the DNV GL data compilation on WEC technology

As for tidal stream energy, patent-searches alone provide a limited understanding regarding which WEC types are being pursued toward commercialisation. As stated previously, a very large number of patents in the ocean energy sector do not accurately represent the design concepts being actually pursued. As in the case of tidal stream technologies, the DNV GL data compilation also covers WEC turbine developers. As of February 2014, the database listed 176 WEC concepts. The data set is a useful tool for understanding the technologies under development and progression of the WEC sector, and some trends from the data are analysed here.

Each WEC developer and their technology is classified in their profile summary by status (active, inactive, or unknown), application (nearshore, onshore, or offshore), output (electrical/desalination), installation (bottom-standing, floating, or submerged), orientation (attenuator, terminator, or point absorber), reaction source (seabed or self-referenced), and PTO (pneumatic, hydro, hydraulic, or direct drive). Many of these categories were touched on earlier in Section 3-2, and they are further defined below.

- *Status*
    - Active – Relatively recent evidence that the developers are actively pursuing development of the WEC concept.
    - Inactive – It has been determined that the developer is no longer actively pursuing development of the WEC concept.
    - Unknown – It is unknown if the developer is still actively pursuing their WEC concept. This status often means that no significant news of development activity in the public domain has recently been publicised.
- *Application*
    - Nearshore – The device is designed to be installed in shallow, nearshore wave environments that are typically close to the shoreline and where bottom friction has begun to dissipate some of the energy in the incoming ocean waves.
    - Onshore – The device is designed to be located onshore (often built into an existing structure like a breakwater).
    - Offshore – The device is meant to be located in deep, offshore wave environments, typically further from the shoreline and where bottom friction has a negligible effect in the incoming wave energy. This corresponds roughly to a site where the depth is greater than about half the wavelength of the ocean waves.
- *Output*
    - Electrical – The WEC is meant to produce electricity for either distributed generation or utility grid applications.
    - Desalination – The WEC is meant to produce pressurised seawater for direct use in desalination systems.
- *Installation*
    - Bottom-standing – The WEC is meant to be installed on a foundation fixed to the seabed or a shoreline structure.
    - Floating – Mooring systems are used to maintain the system floating in an offshore (or less commonly, nearshore) location.
    - Submerged – The WEC concept is meant to be fully submerged – whether tethered to the seabed or fixed to the bottom.
- *Orientation*
    - Attenuator – The device has its principal axis perpendicular to the incident wave front, so that energy is captured as the wave moves along the WEC.
    - Terminator – The device has its principal axis parallel to the incident wave front, so that it physically intercepts the wave.
    - Point Absorber – Point absorbers typically have small dimensions relative to the incident wavelength, and absorb wave energy from water from all directions.
- *Reaction Source*
    - Seabed – The relative motion of the WEC compared to the stationary seabed provides

  the reaction source utilised by the PTO. This is most common in WECs rigidly connected to the seabed.

  - Self-referenced – The relative motion of one feature (typically a body) of the WEC device to another provides the reaction source utilised by the PTO. This is most common in moored, floating concepts where one component's hydrodynamic response is designed to be different than the other component in the floating system (*e.g.*, a donut buoy around a spar or a point absorber buoy on a relatively stable floating platform).

- *Power Take-Off*
  - Pneumatic – Wave action causes the movement of air that drives a turbine. This PTO method is common to the oscillating water column group of devices.
  - Hydro – Water is used to drive conventional hydro turbo-machinery, *e.g.*, a low head hydro

Table 3-3: Shortlisted active wave energy technology developers

Developer	**Country**	**Website**
40South Energy	Italy/UK	www.40southenergy.com
AquaGen Technologies	Australia	www.aquagen.com.au
Aquamarine Power	UK	www.aquamarinepower.com
Atargis Energy	USA	www.atargis.com
AW-Energy	Finland	www.aw-energy.com
AWS Ocean Energy	UK	www.awsocean.com
BioPower Systems	Australia	www.biopowersystems.com
Carnegie Wave Energy	Australia	www.carnegiewave.com
Columbia Power Technologies	USA	www.columbiapwr.com
COPPE Subsea Technology Laboratory	Brazil	www.coppenario20.coppe.ufrj.br/?p=805
Crestwing	Denmark	www.crestwing.dk/
DEXAWAVE	Denmark	www.dexawave.com
Eco Wave Power	Israel	www.ecowavepower.com
Ecomerit Technologies	USA	www.ecomerittech.com/centipod.php
Floating Power Plant	Denmark	www.floatingpowerplant.com
Fred Olsen	Norway	www.fredolsen-renewables.com
Industrial Technology Research Institute	Chinese Taipei	www.itri.org/eng/econtent/research/research05.aspx
Langlee Wave Power	Norway	www.langlee.no
Ocean Energy Ltd.	Ireland	www.oceanenergy.ie
Ocean Power Technologies	USA	www.oceanpowertechnologies.com
Oceanlinx	Australia	www.oceanlinx.com
Oceantec Energias Marinas	Spain	www.oceantecenergy.com
Offshore Wave Energy Ltd. (OWEL)	UK	www.owel.co.uk
Oscilla Power, Inc.	USA	www.oscillapower.com
Pelamis Wave Power	UK	www.pelamiswave.com
PIPO Systems	Spain	www.piposystems.com
Resolute Marine Energy	USA	www.resolute-marine-energy.com
Seabased	Sweden	www.seabased.com
Seatricity	UK	www.seatricity.net
Trident Energy	UK	www.tridentenergy.co.uk
Wave Rider Energy	Australia	www.waveriderenergy.com.au
Wave Star Energy	Denmark	www.wavestarenergy.com
Wedge Global	Spain	www.wedgeglobal.com
Wello	Finland	www.wello.fi
Weptos	Denmark	www.weptos.com
WET-NZ	New Zealand	www.waveenergy.co.nz

Based on analysis of data from DNV GL (2014) turbine in overtopping devices or a Pelton turbine for systems that pump pressurised water.

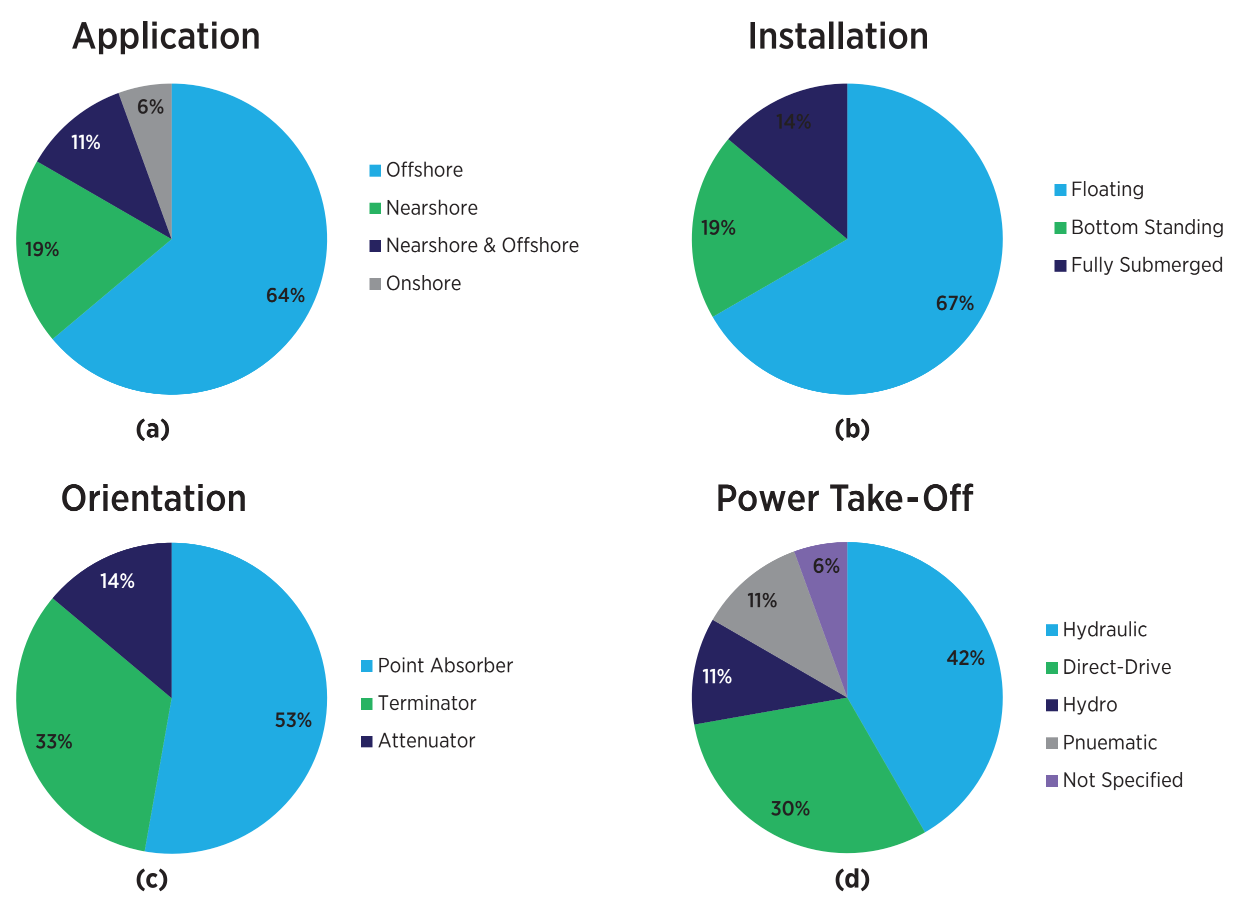
- Hydraulic – High pressure hydraulic oils are transmitted between pumps, motors, and accumulators to drive a generator.
- Direct drive – Most often this specifies linear generators, but also directly coupled mechanical systems (*e.g.*, flywheels, ratchet systems, etc.)

The same scoring methodology as described under tidal stream converters above was applied to the analysis of the wave energy converters data from the DNV GL data set to derive the data in Table 3-3. The table presents 36 known active, commercial (*i.e.*, non-university) WEC technology developers, from 13 different countries around the world, that scored greater than 5 out of a maximum of 12 points. The criterion (greater than a score of 5 points) provides a preliminary shortlist from the list of known active WEC developers, to give a more useful basis for the statistical analysis that follows, focusing on those active developers furthest along the pathway to higher TRLs.

Several observations can also be summarised about the trends among these 36 shortlisted developers.

- 64% of these technologies are designed specifically for use offshore, 19% for shallow nearshore use only, roughly 11% could be used in both nearshore and offshore applications, and only 6% are meant for use on shoreline structures (Figure 3-13a)
- 67% of the technologies are floating, 19% are bottom-standing and surface-piercing, and 14% are fully submerged (Figure 3-13b)
- 64% are self-referenced, while the other 36% use the seabed as the reaction source
- 53% are point absorbers, 33% are terminators, and 14% are attenuators (Figure 3-13c)
- 42% of the technologies use a hydraulic PTO, 30% use a direct-drive PTO, 11% use hydro machinery, 11% use a pneumatic PTO, with 5.6% unspecified (Figure 3-13d)

Figure 3-13: Breakdown of device types being pursued by shortlisted wave energy technology developers



Based on analysis of data from DNV GL (2014)

Table 3-4 provides the percentage of shortlisted developers with 'yes' (including an unconfirmed yes) in each development category described previously. The table can be used to identify trends among development priorities.

Summary of WEC technology trends

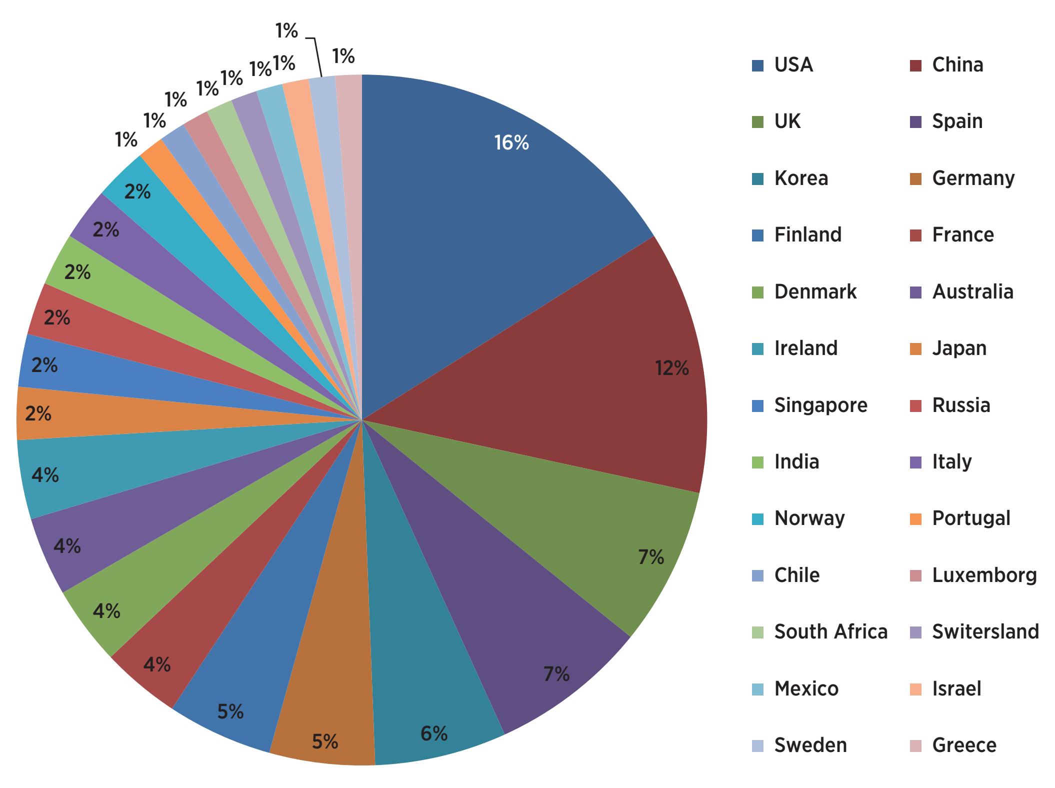
Patent activity in 2013 included patent publications from 26 different countries (significantly more than for tidal stream technology), while the shortlisted technology developers come from 13 countries (Figure 3-15). As can be seen in Figure 3-14, the activity is much more diverse and from many more countries. While the USA and China had the most publications, the UK and Spain also had significant activity.

The breakdown of shortlisted developers' countries in Figure 3-15 shows a slightly different story. It is clear that fewer countries to date have yielded developers that are actively advancing their technologies toward commercialisation and have achieved a significant number of milestones along that path. The UK, the USA, Denmark

Table 3-4: Statistical summary – shortlisted wave energy technologies

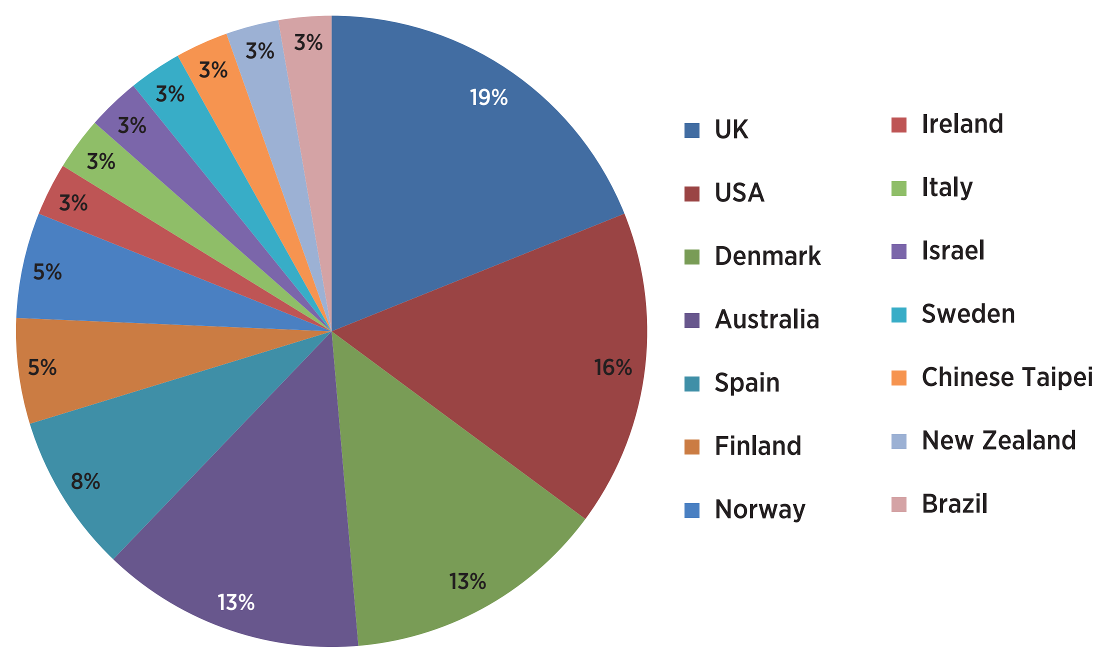
Total number of developers	36
Nationalities	13
Average number of sub-categories fulfilled	8 (out of 12)
Standard deviation	2.34
Company history (> 5y)	86.1%
Staff (>10 full time)	52.8%
Investment	100% (>£1m); 38.9% (>£10m)
PTO strategy	100%
Deployment strategy	86.1%
O&M strategy	47.2%
Numerical modelling	100%
Experimental modelling	100%
Prototype deployed at sea	83.3%
Independent verification	55.6%
Full-Scale Prototype (FSP)	30.6%

Figure 3-14: Wave energy international Patent Cooperation Treaty publications in 2013, by country



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

Figure 3-15: Active wave energy technology developers, by country



Based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM, and the European Patent Office's Espacenet patent search portal

and Australia lead in this area. Due to the diverse interests in wave energy, in the future it is possible that many other countries will catch-up, but for the time being, it appears likely that the first wave energy projects will be carried out largely with British, American, Australian or Danish technology.

As may be expected from the quantity and diversity of patent applications, the WEC technologies themselves vary greatly. That said, it can be noted that a majority of the shortlisted WEC developers are pursuing floating point absorbers for offshore (*i.e.*, deepwater) applications. Nevertheless, there also remains a strong contingent of developers pursing nearshore applications, many of which are bottom-standing. A small number of WEC developers are designing their systems to be fully-submerged. This could be largely due to the fact that wave energy is strongest at the surface and drops exponentially with depth, and many developers are seeking to capture energy from the energetic surface region. There is no clear majority in terms of PTO technique, with hydraulic, direct-drive, hydro and pneumatic methods all being pursued.

3.4 Other ocean energy technologies

The number of international PCT publications for other ocean energy technologies is much smaller than that for wave and tidal energy, with the sample size being too small to permit detailed technical analysis. Nonetheless, the number and location of publications can be observed.

Tidal Range

A small number of international PCT publications in 2013 were for tidal range technologies. There were 6 publications, coming from five different countries (USA, Germany, China, South Korea, and Japan), and all of these were submitted by individual inventors. This could imply that there is relatively little effort coming from industrial organisations to innovate and generate new Intellectual Property (IP) in tidal range energy, and indeed less international interest in pursuit of innovation in tidal range projects as whole.

Ocean Current Energy

Only three international PCT publications in 2013 were for deep ocean current energy technologies. Two of the three came from companies in the U.S., while the third came from an individual inventor in South Korea. The interest in the U.S. to develop deep ocean current technologies is likely related to the domestic ocean current resource that can be found in the Gulf Stream. This would likely be one of the world's primary ocean current resources targeted for development. This small number in comparison to tidal stream, also reflects the global focus on developing tidal stream hydrokinetic turbine technology – which, as a sector, is believed to be closer to commercialisation than deep ocean current hydrokinetic technology.

OTEC

There were just eight OTEC-related international PCT publications in 2013, coming from five different companies. These all came from companies in either the U.S or France. Two of these were the industry heavyweights described in Table 2 2 for OTEC, Lockheed Martin and DCNS.

Salinity Gradient

In the field of salinity gradient technology, there were no international PCT publications in 2013. Although a detailed study of national patents is not conducted as part of this work, it could be observed that there were a few Korean national patents related to salinity gradient technology. This perhaps can be attributed to some of the university research occurring in Asia within this field.

4 BARRIERS TO OCEAN ENERGY TECHNOLOGY DEVELOPMENT AND DEPLOYMENT

At a high-level, ocean energy technologies have four key hurdles to overcome in their journey to mass deployment: technical, economic, socio-environmental and infrastructural. In short, the challenge is to design devices/arrays which generate power reliably, cost-competitively, with acceptable socio-environmental impacts, with the enabling infrastructure in place to enable mass roll-out. This challenge is summarised in Figure 4-1 below.

Despite the linear presentation, the reality is that the four hurdles are interconnected and iterative; for instance, the need to deliver energy cost-competitively may lead developers to reconsider the fundamentals of device design. Most of these challenges require action and collaboration by a broad range of stakeholders, including industry and academia. Nonetheless significant power lies in policy makers' hands, and so this section presents recommendations which can be implemented by government to help promote the development of ocean energy technologies. These are broken down into four broad categories.

Figure 4-1: Key hurdles to be overcome by ocean energy technologies in the path to commercial roll-out

4.1 Technology

The challenge

The technical potential for ocean energy technologies is exciting: both in terms of the scale of resource, and the promise of decarbonised, indigenous power that balances the generation profile of other renewable energy technologies. Yet as illustrated in Section 2, ocean energy technologies are still mostly at pre-commercial status. This means that there are a number of technical areas where understanding needs to be improved, which can be categorised in terms of the resource, devices and array configurations:

- **Detailed resource mapping is typically lacking:** Although the ocean energy resource has been mapped at a national level in a number of countries – such as Canada, Chile, the UK, and the USA – often this is at a low resolution. For most countries, resource mapping at the national level has not yet taken place. This remains a significant barrier to development: industry needs to know the characteristics of the local resource. A distinct, yet related, point is the need for industry to improve its understanding of the resource's impact on power output and energy capture.
- **Improvements required in device design: T**he three key challenges of device design are reliability, survivability and installability. For WEC, the survivability threat is particularly critical, given the extreme loads of the marine environment; meanwhile for tidal stream, installability in tidal flows remains challenging, given the short windows for operations.
- **Limited experience in array deployment:** Even where individual devices are well understood, their configuration in array formation remains subject to uncertainty. One challenge for wave and tidal stream arrays is understanding the impact of wake effects on yield, as well as managing the practical complexities of inter-array

cabling. There are some promising examples of public-private research consortiums tackling this challenge. For instance, the UK Energy Technologies Institute's PerAWaT[18] program has sought to establish and validate a suite of engineering models, which analyse the performance of wave and tidal array systems. Funding programmes for array deployments such as the European Union's NER300 programme will also help to provide practical experience to increase understanding of this area. Yet despite these early efforts, array deployments are still currently subject to high technical risk.

Policy recommendations

Given the pre-commercial status of most ocean energy technologies, policy makers have a vital role to play in helping to reduce their technical risk profile.

Resource mapping (see Case Study A, p. 38)

- **Conduct a resource-mapping exercise.** First and foremost, policy makers need to map the nearby resource, taking into account any technical constraints (such as distances to grid, shipping access, etc.), to understand which technologies they are targeting, the proximity to demand centres and to enable basic cost of energy modelling. Understanding the resource enables effective siting of test areas/pilot locations, and longer-term infrastructural development such as transmission planning.
- **Make capital grant funding available for research and demonstration:** Given the substantial capital requirements of prototype deployment and the first small arrays, and the high technical risk, public funding is needed to support R&D activities, channelled through university research and the private sector. The markets that provide this support are the ones where ocean energy technology deployment has taken place; for instance, funding awarded by the Australian Renewable Energy Agency (ARENA) has proved instrumental in wave energy demonstration projects in Australia. It is also important that this funding for prototype deployment is matched by support for academic research to improve modelling and scientific understanding of the ocean energy resource. A successful example of this is the Supergen UK Centre for Marine Energy Research.

Linking stakeholders through ocean energy associations (see Case Study B, p. 38)

- **Promote sharing of best practice and lessons learnt:** Technology development can be accelerated by ensuring that best practice is shared on a global, regional and national level. Policy makers can facilitate this through seeking membership of the appropriate organisations, and considering the conditions of policy support:
    - ○ *At a global level*: Seek membership of International Energy Agency's (IEA) Ocean Energy Systems (OES) programme
    - ○ *At a regional level*: Seek membership of bodies such as the European Ocean Energy Association and the South East Asian collaboration for Ocean Renewable Energy
    - ○ *At a national level*: Consider making funding programmes contingent upon a degree of knowledge-sharing, albeit carefully framed to protect device developers' IP. An example is Denmark's ForskVE programme, which has stringent reporting requirements.

There are already numerous examples of international cooperation, with some ocean energy projects bringing together a truly global team. For instance, Singapore-based tidal developer Atlantis Resources Corporation has listed on the London Stock Exchange, and amongst other activities, is currently pursuing deployment of its 1.5 MW turbine in Canada, supported by Lockheed Martin, which is headquartered in the US. Policy makers are encouraged to be supportive of such global consortia, rather than imposing market entry barriers. Open markets are likely to lead to accelerated technology development and the best value for energy consumers in the long-term.

At the same time, policy makers should ensure that foreign IP rights are protected in local regions where projects or technology development occurs – for instance, ensuring that international patents are respected to encourage the spirit of collaboration, and assuage developer concerns.

- **Encourage spreading risk:** Sharing of best practice should be accompanied by sharing of risk. It is suggested that all who stand to benefit from a successful ocean energy industry – *i.e.*, utilities, rate payers, governments, developers, investors, and supply chain – should take on their appropriate share of the early risk for these technologies to develop. Particularly for a nascent sector where there are more uncertainties and the risks are greater, effective spreading of risk generates

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[18] *Performance Assessment of Wave and Tidal Array Systems (PerAWaT).*

a vested interest in successful projects from a variety of stakeholders, as well as helping to minimise the burden on any one group should a project not succeed.

- **Continue to support test centres:** There is significant test centre activity for ocean energy technologies in Europe, North America and Asia. This is already reaping dividends in terms of device development, especially in the case of Europe, where limited but important deployment is evident (*e.g.*, off the coasts of Scotland and Portugal). Even if a dedicated test centre is not developed, policies should be in place that facilitate, rather than limit, the first pilot deployments in an area. Demonstration at test centres can help to address many of the innovation needs of ocean energy technologies – see Box on innovative solutions.

Innovative solutions needed for commercialisation of ocean energy technologies

Technical challenge

While ocean energy technologies come in many forms, there are challenges that are common to all. The nature of ocean energy technologies means that the greatest challenge is operation in the marine environment itself. Siting technology offshore means that the cost and complexity of any operation increases dramatically. Fixing an object to the seafloor becomes increasingly difficult with water depth, while floating vessels and platforms result in dynamic working conditions.

The ocean environment can be very energetic (and is often specifically targeted as such due to the resource being sought, *e.g.*, fast tidal currents, large ocean wave climates) and frequently hostile. Water in constant motion subjects equipment to large forces from waves and currents. Marine growth and corrosion must be accounted for and prevented. Once the systems generate electricity, it must also be collected and transmitted. Electrical aggregation and transport to shore is a significant challenge at sea. Cabling and common substation and power electronics solutions used on land are much more difficult and costly to implement, and require special design considerations to protect them from the marine environment while also retaining the ability to access them for required maintenance.

Economic implications

Experience from the offshore oil and gas and marine industries has shown that while it is technically feasible to construct structures to operate in extreme marine environments, this has significant cost implications.

Innovation priorities

There are a number of areas common amongst most or all ocean energy technologies where innovative solutions and technology breakthroughs could address the technical challenges of operating in the marine environment, and help bring down costs in order for ocean energy technologies to achieve commercialisation. These include:

- Cost-effective electrical wet-mate connectors, at relevant voltages;
- Robust dynamic umbilical cables;
- Robust, affordable water tight seals and bearings ;
- Cost-effective, durable moorings/foundations;
- Improved biofouling and corrosion resistant materials and/or coatings; and
- Lower-cost, technology-specific installation and O&M methodologies.

Many of these are directly related to the key technical challenges facing marine and offshore renewables as identified by KARIM in their 2012 report on Marine and Offshore Energy: operation and maintenance, durability, and grid connection (KARIM, 2012).

Case Study A

Resource mapping

In 2009, the Inter-American Development Bank (IDB) commissioned a preliminary marine energy resource assessment study of the Chilean coast (Garrad Hassan, 2009). The work identified the most promising wave and tidal areas for further investigation and quantified the huge marine energy potential for Chile.

The approach comprised three stages:

- Direct engagement with the key Chilean entities and stakeholders.
- Review of marine energy resource and additional data. For instance, the study identified the Chacao channel as particularly promising for tidal energy, due to unique geographical features that result in the formation of a large tidal elevation (head) difference, generating substantial tidal current, with flows of 4 m/s.
- Publication of guidelines and project design recommendations.

This resource study has laid the foundations for subsequent ocean energy plans. In December 2013 the IDB announced that it would support Chile to develop two marine energy pilot programmes on the southern coast of the country, with the first one to focus on tidal energy, while the second targets wave energy.

Country: Chile

Technology: Wave energy and tidal stream

Barriers: Technology and resource

The lesson

Conducting a resource study is the first step to harnessing the ocean energy resource – and can act as a springboard to local ocean energy technology development.

Case Study B

Linking stakeholders through ocean energy associations

In South East Asia, two key ocean energy associations, both with strong university representation, have been formed in recent years:

The South East Asian collaboration for Ocean Renewable Energy (SEAcORE): an initiative under the Energy Research Institute at Nanyang Technological University (ERI@N).

- *Asosiasi Energi Laut Indonesia (INOCEAN – Indonesian Ocean Energy Association).*
- Whereas SEAcORE seeks to promote intra-regional collaboration, INOCEAN has a specific national focus and places greater emphasis on capacity-building. Through workshops and informal knowledge-sharing, these two organisations provide a vital forum for the discussion of ocean energy technologies amongst stakeholders – academia, industry and government. They provide a network to disseminate information on progress, and to coordinate the activity of academics in addressing technical challenges.

For instance, following its first workshop in February 2013, the founding members of SEAcORE signed an agreement expressing the commitment of Southeast Asian academic organisation to work towards advancing ocean renewable energy in the region through research collaboration, regular meetings and organising activities on ocean renewable energy.

In the longer-term, as the local ocean energy technology market emerges, there is potential for these associations to increasingly engage with commercialisation challenges such as supply chain development. Models for this are provided in more advanced markets by bodies such as the Scottish Renewables Marine Working Group and Marine Renewables Canada.

Country: South East Asian region

Technology: OTEC, salinity gradient, tidal stream, wave energy

Barrier: Technology

The lesson

Policy makers should be supportive of the efforts of Ocean Energy Associations, engaging with their activities and workshops. When the ocean energy technology market is nascent, associations provide a hub where technical developments and challenges can be discussed. In the longer-term, these associations can address practical deployment concerns such as infrastructure development, and even represent the industry in government processes.

With thanks to SEAcORE and ERI@N.

4.2 Economics

The challenge

Once technical concepts have been proven, a key question is how do the cost and risk profile of the technology square up against that of other technologies in the market? Since both governments and utilities face pressure to adopt the least-cost and least-risk options towards decarbonisation, the importance of these considerations of economic competitiveness should not be underestimated. Despite potential long-term benefits of energy portfolios, which incorporate ocean energy technologies to compliment other resources, when projects are selected, the immediate LCOE and impact on rate payers is often the primary driver.

The 'competitiveness' challenge is a function of both the cost and risk characteristics of ocean energy technologies.

- **Levelised costs of ocean energy technologies are currently substantially higher than those of competing technologies:** The current LCOE of ocean energy technologies is highly uncertain for a number of reasons [see following Box on Cost Estimations]. Empirical cost data is limited, there is a wide variability in project cost strategies (due to the diversity of device design), and key LCOE drivers such as capacity factor and design life are still often not fully understood.
  Where data is available, it points to relatively high current levelised costs. Estimates published as part of the European Strategic Initiative for Ocean Energy suggest a mid-level case range of EUR 0.320 to 0.371 per kWh for the first tidal stream demonstration arrays, compared with approximately EUR 0.407 to 0.52 per kWh for the first wave demonstration arrays. It should be stressed that this is a mid-level case range, with 'low' and 'high' estimates even wider than the fig-

Cost estimations: leaping into the unknown

The current LCOE of ocean energy technologies is highly uncertain for a number of reasons:

- *Limited empirical cost data*: Deployment to date has been limited, and many prototypes have only been in the water for a limited period of time (often 1-2 years or less), meaning that operational data is particularly scarce. Furthermore, there are no arrays yet commercially operating anywhere in the world and, therefore, real data on array effects, economies of scale, and park O&M strategies and costs is not available. Key LCOE drivers such as capacity factor and design life are still often not fully understood.
- *Wide variability in project cost strategies:* For some technologies – notably WEC's – there has not yet been convergence in device design. Some device developers adopt a strategy of high complexity (and thus cost) and high yield (and thus revenue), whereas others seek simpler, cheaper options and accept a lower yield.
- *Cost is very site-specific:* The resource varies substantially from site to site, with an impact on the overall LCOE. Installation and O&M costs will also be highly site-dependent, as will availability and cost of the supply chain. As large bespoke civil engineering projects, tidal range projects in particular, have highly site-specific LCOE.

Technology type	Driver of LCOE uncertainty		
	Limited empirical cost data	Wide variety in cost strategy	Important site-specific factors
Wave energy converters	■	■	■
Tidal stream converters	■	▨	■
Deep ocean currents devices	■	▨	▨
Tidal range technology	▨	□	■
OTEC devices	■	□	▨
Salinity gradient technology	■	▨	▨

Key

■ Major driver of cost uncertainty	▨ Medium driver of cost uncertainty	□ Minor driver of cost uncertainty

ures presented here, due to inherent differences and uncertainty in CAPEX (capital expenditure), OPEX (operational expenditure) and the underlying resource (SI Ocean, 2013b).

The current high LCOE means that ocean energy technologies are currently unable to compete in the market without public sector intervention – although significant cost reduction is expected in the longer term.

- **The long-term pathway to cost reduction is difficult to predict:** As has occurred in other industries in the past, from computing to conventional energy to more similar renewables sectors like onshore wind, levelised costs are expected to substantially reduce with scale, experience, learning and innovation. The wave and tidal stream industry informally targets being cost-competitive with offshore wind by the mid-late 2020s. It should be stressed that such cost reduction is largely dependent on *deployment* and *investment* rather than *time*. Since deployment rates are subject to a high degree of uncertainty, this can make cost reduction projections – and thus assessments of the path to cost competitiveness – difficult. Policy makers are often understandably hesitant to incentivise technologies that do not have a clear long-term pathway to grid parity.
- **Technology profile is considered higher risk than competitors:** The pre-commercial status of ocean energy technologies leads to technical uncertainties, which elevate both cost risk and revenue stream risk. For instance, there is a risk of installation delays, and generation may be lower than expected. Where the private sector – such as OEMs – does engage with the sector, the evidence is that players are typically reluctant to provide finance for the entire capital expenditure, due to a desire to minimise risk exposure.

Policy Recommendations

Both 'market-pull' and 'market-push' measures are needed to help ocean energy technologies win the economic competitiveness challenge:

- **Provide capital support:** For technologies at demonstration stage and the first small arrays. Developers of early stage technologies often do not have sufficient confidence in generation levels for per MWh incentives to be sufficient; in addition to the promise of revenue support, capital grants are typically required in the journey to commercialisation. For instance, grants of USD 10-20 million are typically required to support the first small (5-10 MW) arrays, in addition to private capital.

  In addition, governments may wish to consider additional innovative approaches to financially supporting early projects – such as underwriting guarantees for particular risks such as performance and weather.
- **Provide a premium price per MWh:** Given the early stage/nature of most ocean energy technologies relative to other power generation technologies, there is a need for a per MWh top-up payment to secure project viability. Even where technologies are not yet ready for commercial-scale deployment, the introduction of a premium price per MWh provides the signal of a long-term market, which is necessary to attract the attention of OEMs and catalyse activity. Visibility of this premium price should be as far ahead as possible – this long-term assurance of future revenue support will help to give industrials the confidence they need to invest in the first arrays.

Tailoring financial support to technology type (see Case Study C, p. 41)

As this review has indicated (Sections 2 and 3), different technologies are at different levels of technical maturity. As a result, it is recommended that policy makers consider differentiating Feed-in tariffs (FiT) by technology type. Scotland's redesign of the Marine Renewables Commercialisation Fund in May 2013 indicates the importance of distinguishing, for instance, between wave and tidal stream technologies. Another example of FiT differentiation is Nova Scotia's Community Feed-in Tariff COMFIT Programme (for community-owned projects connected at distribution level) and the Developmental Tidal Array FiT (for larger deployments).

A number of countries with ocean energy resources have introduced per MWh support to offshore wind – with Japan being a notable recent example. There is potential for these countries to learn from their recent experiences in setting offshore wind tariffs and to apply these lessons to the development of tariffs specific to ocean energy. It should be noted that for large bespoke projects such as tidal range technologies, FiTs will likely need to be set based on bilateral negotiations.

Targeting niche markets as a near-term route to market (see Case Study D, p. 42)

- **Promote niche markets:** A standard approach for the commercialisation of innovative technologies is to target 'early adopters' in specific market niches. If ocean energy technologies currently struggle to compete with other grid-connected renewables, one solution is to pursue markets where generation options are more limited. Options for ocean energy technologies include aquaculture, defence and sustainable tourism in remote islanded communities; these areas are often otherwise dependent on diesel generators.

From a policy maker's perspective, promotion of niche markets requires overcoming traditional departmental silos whereby ocean energy falls solely under the remit of the Department of Energy. Working groups could be established which engage a broader group of government departments – for instance, Departments of Defence and Industry.

- **Quantify additional benefits:** Although ocean energy is still not typically able to compete on a strict cost/MWh basis, other positive spin-offs may justify deployment. The benefits of potentially high local content and job creation have featured strongly in the political discourse of ocean energy in Scotland, France, the USA, and Canada in particular. If the premium price required to support ocean energy appears too high for consumers to bear, policy makers should consider studying whether ocean energy technologies might bring additional 'added value', which means that the support from the public purse is still justified. Studies which demonstrate potential long-term value for portfolios that include ocean energy technologies, as well as discussions of improved socio-environmental effects, may help justify the development of ocean energy when the 'bigger picture' is considered.
- **Accelerate cost and risk reduction through roadmapping:** Roadmapping exercises can be particularly helpful for stakeholders to understand – and implement – the steps required to achieve a reduction in the LCOE. However, cost reduction pathways that have been produced to date have typically presented deployment projections that look unduly optimistic – and when ocean energy technologies have failed to deliver, this has undermined confidence in the sector.

  Policy makers are advised to be realistic about commercialisation timescales when conducting roadmapping exercises. In the past, both industry and governments have displayed a natural enthusiasm for the rate at which ocean energy will take off, but technology development takes time. This is especially true for large industrial

Case Study C

Tailoring financial support to technology type – differentiating support

Broadly speaking, financial support mechanisms in the UK have historically tended to treat wave and tidal stream technologies the same, often requiring them to compete against each other for funding.[19] Examples are the UK's GBP 20 million Marine Energy Array Demonstrator (MEAD) programme and the Scottish GBP 18 million Marine Renewables Commercialisation Fund (MRCF). The same has been true of the European NER300 fund, for which UK projects are eligible. However, the current LCOE of leading tidal stream devices is around GBP 300/MWh, compared with roughly GBP 400/MWh for wave devices (RenewableUK, 2013).

This cost difference has given tidal energy an advantage in funding competitions – and the result has been that the majority of funding awards to UK projects in the last 12 months have favoured tidal energy. Wave energy has lost out, left 'swimming against the tide'. But in May 2013, the Scottish Minister for Energy, Enterprise and Tourism, Fergus Ewing made a major announcement. In an explicit recognition of the need for separate policy support for wave and tidal stream energy, he stated that the MRCF would be redesigned to specifically target the needs of wave energy.

The UK Energy Minister Greg Barker has similarly acknowledged that *'If and when it is sensible to do so, we will, of course, treat the wave and tidal stream sectors separately'.*

Country: UK

Technology:
Wave energy,
Tidal stream

Barrier:
Economics

The lesson

Different ocean energy technologies have different cost bases and different levels of maturity. Policy makers seeking to promote these technologies should *differentiate* policy support where required, tailoring both the level and type of financial support to the distinct needs of each set of technology. This does not preclude cooperation in other areas – such as consenting and grid issues.

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[19] *The exception to this is the historic differentiated support under the Renewables Obligation in Scotland, where wave energy was eligible for 5 ROCs/MWh, and tidal was eligible for 3 ROCS/MWh.*

Case Study D

Targeting niche markets as a near-term route to market

A number of wave developers are targeting niche markets both as a stepping stone to future utility-scale grid-connected installations, and as viable long-term markets in themselves. Niche applications being pursued by wave developers include:

- *Defense:* US-based Ocean Power Technologies (OPT) has deployed its autonomous APB 350 PowerBuoy® off New Jersey, supported by the US Navy's Littoral Expeditionary Autonomous PowerBuoy (LEAP) programme for coastal security and maritime surveillance.
- *Water desalinisation:* In November 2013, Australian wave energy developer Carnegie Wave Energy was awarded the manufacturing and construction contract for a Desalination Pilot Plant to Perth-based company, Mak Water Industrial.
- *Aquaculture:* Russian device developer Vert Labs and Scottish device developer AlbaTERN are pursuing fish farms as a market.
- *Powering offshore wind met masts:* Norwegian wave device developer Fred Olsen has indicated that it is considering this market.
- *Powering remote communities:* U.S. developer Resolute Marine Energy is pursuing a project to produce wave energy for a remote Alaskan community.

Wave energy is often more competitive in these niche markets since power generation options are often limited (typically diesel generators). In addition, the smaller project size required has a lower risk profile than immediately moving from prototypes to large utility-scale arrays. However, a challenge facing niche applications is that government FiTs tend to only be available for grid-connected projects.

Country: US, Australia, UK

Technology: Wave energy

Barrier: Economics

The lesson

It should not be assumed that large grid-connected projects are the only viable commercialisation trajectory for ocean energy technologies; to the contrary, the industry is already pursuing a number of niche markets where limited alternatives mean that ocean energy technologies are more likely to be competitive. Aquaculture, desalinisation, defence, and remote off-grid applications are already being explored; looking to the future, displacement of diesel generators being used by islanded communities may prove a particularly promising niche market.

This has significant institutional implications. Although renewable energy tends to fall under the remit of energy departments, the commercialisation of ocean energy technologies may in fact depend on the sustainability policies of a range of departments – such as those responsible for defence or fisheries. It should be remembered, the first widespread use for solar photovoltaic technology was not on rooftops or utility solar farms, but in space applications.

technology designed to operate in a challenging, highly-energetic environment. The experiences of offshore wind show that long-term success can still be achieved even if development initially takes longer than expected. It is recommended that roadmaps are backed up by clear actions and milestones to track progress and take corrective action where required; one good example of this are the brief annual progress reports drafted by the industry association Scottish Renewables for wave and tidal stream energy in Scotland.

4.3 Environmental and social issues

The challenge

Deployment of ocean energy technologies brings the significant environment benefit of displacing carbon-intensive forms of power generation. However, as with any energy production technology, they also bring environmental and social risks that need to be identified and mitigated. At the prototype stage, test centres tend to minimise the burden on device developers through conducting studies at a central level; for instance, the Atlantic Marine Energy Test Site (AMETS) in Ireland is pre-consented. However, once developers are ready to transition to commercial-scale deployment, the policy regime for mitigating these risks has the potential, if poorly designed, to significantly impede ocean energy development and stifle opportunities for innovation.

The risks are of both an environmental and social nature:

- **'Blue tape' can be complex and time-consuming to navigate:** An initial challenge facing developers can be establishing which legislation they need to comply with, especially since multiple consents are often required. As a new industry involving both marine use and energy production, there can even be duplicate requirements and confusion over which regulating bodies have jurisdiction. Even once the regulatory process has been established, it may be unclear how environmental criteria should be met, or confusion can be caused by conflicting legislation

- **Environmental monitoring requirements are disproportionately high:** A further challenge faced by ocean energy technologies is that, comparative to the typically small size of prototypes, the environmental monitoring requirements can be large (National Renewable Energy Laboratory (NREL), 2009). This has been cited as a problem in the USA and the European Union, in particular, where a precautionary approach leads to substantial data-gathering both pre- and post- deployment, with the burden of evidence lying with developers. This is challenging since the environmental impact of ocean energy technologies is often poorly understood without operational experience. In some cases, early prototype deployments seeking an opportunity to "learn by doing" as is common in many other sectors, are met with consenting requirements that are equivalent for large scale conventional hydro plants, or offshore oil and gas structures – mature technologies from industries with steady revenue streams and clearly more significant environmental risk. Ocean energy technologies have been associated with a number of environmental risks, such as habitat destruction, marine life interactions, and noise in the marine environment. Ocean energy technology developers must often demonstrate and prove risks have been mitigated in these areas, although other existing industries that may have a more significant effect (*e.g.*, oceangoing vessels and maritime traffic may be orders of magnitude louder than tidal turbines), do not. In any case, the significance of these effects is often subject to high uncertainty, and will remain so until projects go forward and can be monitored.
- **Ocean energy technologies compete with other users of sea:** There are a number of parties with interests in the ocean environment, with activities including fishing, shipping, defence, tourism, recreation, and environmental conservation.
- **Lack of capacity in consenting bodies:** Organisations with responsibility for consenting may lack the specialist marine/technology expertise and resource to fairly assess ocean energy projects. This may result in long lead times for application assessment, or decisions that are excessively risk-averse.
- **Risk of public backlash to ocean energy technologies:** In the UK at least – one of the early leading ocean energy markets – the public appears to be generally very supportive of ocean energy technologies at the present time. The UK's Department of Energy and Climate Change (DECC)'s Public Attitudes Tracker indicates that 77% of the UK population is supportive of wave and tidal energy (DECC, 2014).

  Yet as deployment ramps up there is potential for a public backlash to factors such as the cost or visual impact of certain ocean energy technologies. In recent years, perhaps in part due to the economic downturn, renewable energy technologies have been subject to increasing scrutiny in many of the mature economies where they have been pioneered, particularly due to public cost of providing them financial support. These debates take on extra social significance in developing countries where disposable incomes are lower. Financial support for renewables is typically funded via consumer bills rather than taxation in order to fairly reflect the cost of decarbonisation in the price per kWh and incentivise energy efficiency. However, if support for ocean energy technologies is financed off electricity bills, this can hit the poor disproportionately hard due to the regressive nature of bill-based rather than taxation-based revenue-raising measures.

  At current low rates of deployment, the cost burden of supporting ocean energy technologies is sufficiently small for the impact on bills to be almost negligible. Nonetheless, the potential political sensitivities should not be underestimated in the longer-term if and when deployment ramps up.

Policy recommendations

Above all, addressing environmental risks requires increased *clarity*: clarity on what the requirements are, whose remit they fall under, what data is already available, and the relative impacts and net benefit. Meanwhile, addressing social risks requires public concerns to be anticipated early-on.

One-stop-shop consenting for ocean energy deployment (see Case Study E, p. 44)

- **Remove bottlenecks** in the process of granting **consent** for ocean energy technology deployment applications.
- **Improve access to baseline data:** The provision of baseline data through centrally-funded studies brings significant efficiencies, avoiding the need for developers to duplicate activities. Where baseline data is unavailable, policy mak-

ers may deem that, given the comparatively small scale of prototypes, a 'survey, deploy and monitor' or 'adaptive management' approach is more appropriate, and proportional to the risk, than extensive pre-deployment monitoring campaigns. Relaxation of site-specific requirements, so that studies don't have to be repeated entirely at each potential location, may also help reduce regulatory burdens.

- **Adopt a 'one-stop-shop' approach to consenting:** The examples of one-stop-shops in Scotland and Denmark showed that streamlined consent in terms of institutional design and processes can significantly aid project development, thereby simplifying the process for developers.
- **Incorporate ocean energy deployment in national maritime spatial plans:** A number of countries have Marine Spatial Plans in place – such as Germany, Sweden and the Netherlands. This spatial planning process can be used to anticipate and address concerns regarding competing uses of the sea, providing transparency for all.
- **Consult and engage the public early on:** Stakeholder consultations and awareness campaigns can help device developers to anticipate and mitigate concerns of the public and other ocean users. Many initial concerns can often be assuaged through simple education, *e.g.*, on the nature of the technologies and how they work. In the longer-term, where policy makers target rapid roll-out of ocean energy technologies with significant cost implications for bill-payers, they may wish to consider deploying welfare schemes to transfer money to the poor to compensate for renewable energy subsidies. An example of such a scheme is found in Malaysia. When Malaysia's largest electricity utility, *Tenaga Nasional Berhad*, substantially increased its electricity tariffs on 1 January 2014 (for reasons unrelated to ocean energy technologies), it also implemented a cash-transfer scheme targeted at the poor.

  However, it should be stressed that this is only likely to be applicable where high levels (order of GWs) of ocean energy deployment are planned, and even then other cost drivers (such as rising fossil fuel prices) are likely to have an even larger effect on utility pricing. Welfare transfer payments to address the costs of ocean energy technologies are unlikely to be appropriate within a 10 year timeframe.

4.4 Infrastructure

The challenge

The development of infrastructure to support ocean energy technologies brings an economic opportunity – regenerating the economies of remote coastal communities, developing local supply chains and providing

Case Study E

One-stop-shop consenting for ocean energy deployment

Denmark has been a significant player internationally in offshore wind technology deployment and has also seen a degree of wave energy prototype activity. Denmark is often cited as the archetypal model for 'one-stop-shop' consenting in offshore wind.

The development and deployment of marine renewables in Denmark is overseen by the Danish Energy Agency (DEA), which acts as a single point of contact for nearly all consenting, permitting and licensing activity. The DEA is part of the Danish Ministry of Climate, Energy and Building. The Danish State has the rights to the seabed in both the territorial waters and the Exclusive Economic Zone.

Concessionary (land tenure) rights, required permits along with relevant electricity generation and export licenses are issued by the DEA, under a so-called 'one-stop-shop' approach. As part of the process of permitting a project, the DEA coordinates communication for necessary consultations between developers and the various private and stakeholders and governmental bodies. This streamlined 'one-stop-shop' approach has been praised by offshore wind developers for simplifying the consenting process.

Country:
Denmark

Technology:
Offshore wind

Barrier:
Environmental and social issues

The lesson

Policy makers can apply the lessons learnt from offshore wind to ocean energy. There is a strong argument to keep consenting procedures simple for developers – streamlining the process to avoid discriminating against first movers.

jobs. To date, these benefits have most notably been reaped at EMEC in Scotland.

At prototype stage, the infrastructural challenge for ocean energy conversion device developers is often manageable due to the role played by test centres in providing key infrastructure; for instance, providing 'a socket in the sea' and promoting the development of local supply chain clusters. However, once developers progress in the longer-term to projects outside test centres, infrastructure can become a significant constraint. These challenges are beginning to be experienced by the most advanced ocean energy markets – such as the UK and Canada – as the first small tidal stream arrays are developed.

At a high-level, the infrastructural challenge for ocean energy technologies is twofold, relating to grid issues and the supply chain.

- **Grid access difficulties and cost:** For some markets, the grid is viewed as a critical bottleneck to the commercialisation of ocean energy technologies. The grid challenge occurs when the marine energy resource is far from major load centres, and on the edge of the existing electricity system, with significant implications in terms of grid access *cost* and *delay*. This challenge is not unique to ocean energy technologies; numerous examples can be cited of delays in transmission network reinforcement causing knock-on impacts to renewables – such as onshore wind in China.
  The most widely publicised example to date of grid challenges to ocean energy technologies has been Scotland, due to the relatively remote sites (*e.g.*, Orkney, Shetland) for wave and tidal arrays (RenewableUK, 2013). Developers fear that insufficient grid capacity will create long delays in providing connections for future projects. In addition, the UK principle of locational charging is said to have 'discriminatory' cost implications for wave and tidal arrays on the periphery of the grid network. The UK Government briefly considered implementing an 'uplift' in per MWh payments (via the Contract for Difference) to wave and tidal projects on Scottish islands to compensate for these additional costs; however, these plans have been shelved due to the slower than expected commercial deployment of the marine energy sector.
  It should be noted, however, that grid access and charging challenges are not expected to be so pertinent in all markets. The practices of different countries vary widely on who bears the cost of connection. Moreover, in many countries – for instance Portugal and parts of Australia, the Netherlands, the USA and Norway – the ocean energy resource is closer to both load centres and transmission capacity. In such situations, grid availability is not a barrier, but rather an advantage and a supporting reason for deployment of ocean energy technologies. The USA is an example of this, where other renewable resources like onshore wind are heavily located in limited population areas in the centre of the country. It has been pointed out that various coastal power plants built to use seawater for cooling, but that are now undergoing decommissioning, may provide grid-ready access points for ocean energy projects in several well-populated coastal areas.
- **The supply chain for ocean energy technologies is under-developed:** Given the pre-commercial status of most ocean energy technologies, the supply chain is relatively under-developed. Suitable port facilities and vessels are often lacking, or at least lack proximity to where projects are being developed.
  There are exceptions to this, notably the industry cluster, which has emerged to support EMEC in Orkney. However, the suppliers who have been engaged in the fabrication, assembly and installation of prototypes will not always have the capabilities or resource to scale-up production and deliver the value engineering required for mass deployment. New players will need to be attracted to the sector in the commercialisation process, and the entry of OEMs into the tidal stream sector is particularly welcome in this context – *e.g.* Siemens' investment in a dedicated tidal testing and assembly facility in Bristol. There is also potential to 'piggy-back' the supply chain being developed to support offshore wind.
  Developing a supply chain is particularly difficult given the diversity of ocean energy technology concepts being developed; spanning tidal range, tidal stream, wave energy, OTEC and salinity gradient. There will be technology-specific supply chain needs for each of the ocean energy technologies. There are also significant subdivisions even within these categories; for instance WEC subcategories include both floating offshore systems and nearshore seabed-mounted devices.

Policy recommendations

Addressing grid and supply chain challenges early will help accelerate the development of the ocean energy sector by giving investors the confidence that the infrastructure is in place for ocean energy technologies to be scaled up and rapidly deployed in the longer term. The recommendations to address infrastructural barriers are wide-ranging:

- **Ensure that Network Operators have transparent plans for accommodation of ocean energy technologies:** Even where locational charging is a strong principle that cannot be changed, policy makers may wish to consider financial compensation for high grid costs to enable this nascent sector to develop. In addition, providing *transparency* on whether/when transmission reinforcement can be expected will also significantly aid developers. Where possible, solutions to accommodate ocean energy technologies can be sought as part of wider discussions about grid access and charging for renewables, since many of the grid challenges faced by ocean energy technologies also apply, for instance, to other technologies such as onshore and offshore wind development.

- **Provide a premium price per MWh.** A clear premium price per MWh, signalled years in advance, will give potential suppliers confidence that this is a long-term market that merits their investment.

Promoting supply chain development (see Case Study F, p. 46)

- **Engage and inform the emerging supply chain:** Use national/regional economic development agencies to ensure that the supply chain is aware of the opportunity presented by serving the growing ocean energy sector, and build capacity amongst local companies.

  The flavour of supply chain engagement will need to be tailored to each country's existing industries and renewables activity. For instance, engagement of OEMs may be more straightforward in markets with major domestic industries (such as France, Japan, China and South Korea) than in those with fewer players fulfilling this role

Case Study F

Promoting supply chain development

Canada is one of the leading tidal stream markets globally. Both government and industry have been working to grow the supply chain needed to service the emerging tidal stream sector. Indeed, supply chain development has been viewed as a strategic economic opportunity, with Canada seeking to become an early adopter to seize the first mover advantage and position itself for future exports in the longer-term (Marine Renewables Canada, 2013)**.**

Canada, and particularly Nova Scotia, have adopted a number of best practice procedures to promote supply chain development:

- ***Articulate the vision:*** The report *Charting the Course: Canada's Marine Renewable Energy Technology Roadmap* (2011) clearly presents the tidal stream vision to the emerging supply chain. Clear deployment targets have been set to help the supply chain to understand the projected scale and growth rate of the market: 75 MW by 2016, 250 MW by 2020 and 2 000 MW by 2030. This has been matched by an estimation of what this deployment means in terms of annual economic value (CAD 2 billion)
- ***Provide economic signals for a long-term market:*** The tidal stream vision has been backed up by financial support to give credibility to the targets and confidence in the long-term market. FiTs have been announced for both community-scale and array-scale projects.
- ***Engage stakeholders:*** In early 2013, the Nova Scotia Department of Energy commissioned an extensive stakeholder engagement exercise to identify challenges facing the development of commercially-viable tidal energy, while highlighting the associated opportunities for industry and the public sector to remove barriers and develop a competitive local tidal stream supply chain.
- Meanwhile, to take a different international example, the UK's *GROW:OffshoreWind* programme provides another example of how to engage the supply chain for marine renewables. GROW:OffshoreWind offers businesses direct access to market experts and funding support to help facilitate market entry.

Country: Canada (particularly Nova Scotia)

Technology: Tidal stream

Barrier: Infrastructure (supply chain)

The lesson

Successful supply chain development requires a clear vision, backed up by economic incentives, and stakeholder dialogue to identify and address barriers. Supply chain development should be interpreted as a significant economic opportunity rather than just an infrastructural barrier to deployment.

(such as in South East Asia). In addition, given the potential transferability of skills and facilities from offshore wind, markets currently lacking offshore wind deployment (such as Canada, the USA, and Australia) may also need to take greater efforts to develop a supply chain than those with an emerging offshore wind track record (such as China, Chinese Taipei, the UK, Belgium, Denmark, Germany, Sweden and the Netherlands).

4.5 Differentiated approaches

As the technology review in Section 2 illustrated, ocean energy technologies are diverse in both technical characteristics and commercial maturity. Policy makers need to be sensitive to technology differences. Informed policy makers will examine their local resource, understand their targeted technologies, and then tailor their ocean energy strategy accordingly. While general recommendations can be made, a 'one size fits all' approach is unlikely to be optimal (Jones and Rawlinson-Smith, 2013). This section considers how the approach might be differentiated by country and technology.

Country-specific approaches

There are many relevant criteria determining country-specific approaches. Two key criteria include:

- **Economic development:** Country categorisation according to economic development is relevant to ocean energy promotion since it indicates rates of overall power demand growth, existence of grid infrastructure, and likely availability of resources to invest in ocean energy technologies.
- **Previous offshore wind experience:** Countries with experience in offshore wind will already have permitting regimes, financial support mechanisms and supply chains, which can be tailored to ocean energy technologies. This means that their starting point for ocean energy promotion is different from that of countries without such offshore wind experience[20].

Sample countries and tailored recommendations are provided in Table 4-1 and Table 4-2 below.

Technology-specific approaches

It is recommended that policy makers develop policies that are sensitive to the needs of different ocean energy technologies. Technology-specific recommendations are provided below.

- **For wave energy – address technology, infrastructure and economic barriers:** Since players exiting the industry in 2013 have largely cited delays in technology development, policy makers should prioritise investment on technology R&D and the required infrastructure, with subsidiary emphasis on economic barriers, including exploration of niche markets. For instance, there is a strong need for further research on load assessment, including validation of load data.
- **For tidal stream – address technology and economic barriers:** Build on the OEM momentum by addressing economic barriers through a clear premium price per MWh. In parallel, continue R&D on next generation technologies to accelerate cost reduction. As the technology commercialises, environmental, social and infrastructural issues will increasingly require attention too; offshore wind will provide useful experience in this respect.
- **For ocean current energy, salinity gradient and OTEC – address technology barriers.** As early stage technologies, R&D should be prioritised above all else. Collaborative research projects between industry and academia should be en-

Table 4-1: Examples of country offshore wind experience

		Previous offshore wind experience	
		None/very early stage	**Significant experience**
Economic development	**Frontier economy**	*Philippines, Pacific islands*	*No known 'pure' examples, though Vietnam has some intertidal offshore wind experience.*
	Emerging market	*South Africa, India, Chile*	*China, Chinese Taipei*
	Advanced economy	*Spain, Italy, Canada*	*UK, Germany, France, Denmark* *[and increasingly: Japan, U.S.].*

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[20] Another significant criterion shaping a country's approach to ocean energy technology development and deployment could be its tendency to export. If industrial players of a country decide to focus on external markets, the previous offshore wind experience of that country becomes less significant.

Table 4-2: Policy recommendations for countries at different stages of economic development

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="4">Previous offshore wind experience</th></tr>
<tr><th colspan="2">None/very early stage</th><th colspan="2">Significant experience</th></tr>
<tr><th rowspan="4">Economic development</th><th>Frontier economy</th><td rowspan="2">Work with development banks: There could be scope for development bank support, following the model of the Inter-American Development Bank in Chile (see Case Study A).</td><td>Research geography-specific considerations: For example, OTEC could be an area of particular relevance to many frontier economies, due to the location of many frontier economies in the tropics, where the resource is attractive. In addition, the potential to support or electrify remote islanded communities may be another research theme of relevance.</td><td colspan="2"><i>Examples: No known 'pure' examples, though Vietnam has some intertidal offshore wind experience.</i></td></tr>
<tr><th rowspan="2">Emerging market</th><td colspan="2">Consider tidal range for scale contribution: For the very limited number of countries which have suitable sites available, tidal range projects may provide substantial MW contribution for power-hungry economies, if environmental impacts can be mitigated.</td><td rowspan="3">Adapt/leverage infrastructure and supply chain from offshore wind: Many of the technical, consenting and infrastructural challenges associated with ocean energy technologies are similar to those experienced by offshore wind.</td></tr>
<tr><td colspan="2" rowspan="2">Build on existing synergistic industries: Consider how the resources and skillsets of other synergistic industries might be used to promote ocean energy technologies or provide niche markets (<i>e.g.</i>, offshore oil and gas, and maritime industries, aquaculture, defence).</td><td rowspan="2">Build an industry: Many of these countries have strong domestic OEMs with expertise in offshore renewables – meaning that ocean energy policy can be considered alongside industrial policy, with the potential for reaping long-term job creation and export benefits.</td></tr>
<tr><th>Advanced economy</th></tr>
</table>

couraged, since this model has worked well in Europe in several instances for wave and tidal stream energy, and directly involving industry partners in research, operations and experience can help facilitate knowledge transfer. Industrial involvement also helps encourage adoption of research findings by industry.

- **For tidal range technology – prioritise environmental and economic challenges:** Tidal range technology is structurally different to the other ocean energy technologies considered in this report, both in terms of project scale and maturity. Environmental impacts are often a showstopper, so policy makers should ensure that the risks are understood and mitigated before proceeding. The large project size brings economic risks, which will need to be addressed through bilateral negotiation on power prices. In recent years, the UK has undertaken a number of studies assessing the potential for a 'Severn Barrage'. Findings of a

Committee inquiry into a proposal from Hafren Power Ltd for an 18 km fixed tidal barrage uncovered the following challenges:

- Extensive research, data and modelling required to understand environmental issues;
- Lack of clarity on LCOE; and
- Need for transparent info to be provided to stakeholders (House of Commons Energy & Climate Change Committee, 2014).

It is recommended that policy makers contemplating promoting tidal range projects review this and accompanying reports on the Severn Barrage to gain a detailed and up-to-date understanding of key risks and mitigation options (DECC, South West RDA and Welsh Assembly Government, 2010).

Policy maker priorities for each technology are summarised in Table 4-3 below.

Table 4-3: High level summary of priority barriers to ocean energy technologies

Technology type	Barriers which policy makers should prioritise addressing			
	Technical	Economic	Environmental & social	Infrastructural
Wave energy converters	■	▨	□	▨
Tidal stream converters	■	■	▨	▨
Deep ocean currents devices	■	▨	□	□
Tidal range technology	□	▨	■	□
OTEC devices	■	▨	□	□
Salinity gradient technology	■	▨	□	□

Key

■	▨	□
High priority	**Moderate priority**	**Low priority**

5 CONCLUSIONS AND SUMMARY OF RECOMMENDATIONS

Vast potential

The ocean energy resource is vast – with an estimated theoretical potential that can more than meet current and projected global demand for electricity. The range of technologies to develop ocean energy is equally wide-ranging, spanning WECs, tidal stream converters, deep ocean currents devices, tidal range technologies, OTEC devices and salinity gradient technologies.

Ocean energy technologies offer CO_2 emission-free power and enable energy independence. They contribute to a diversified energy portfolio, with generation profiles that may complement those of other renewables – such as solar and wind – thus helping to balance the variable generation of different renewable energy sources. Proponents also point to the promise of the creation of 'green jobs' through building a new industry. Moreover, ocean energy technologies extend the range of options to densely populated coastal nations, as they gradually use up scarce sites for onshore renewables development.

Current technological status

There is already OEM involvement in selected ocean energy technologies, which is indicative of growing commercial readiness. Nonetheless, the rate of technology development has been slower than hoped. This is mostly due to challenges in technology development, and early over-optimism by device developers. However, subsidiary factors are the financial crisis that started in 2008, which has reduced the risk appetite of investors, as well as shaking policy makers' commitment to renewables in some markets.

When the leading pre-commercial ocean energy technologies (wave and tidal stream) are examined, patent activity (Appendix 1) clearly demonstrates an interest in developing them from countries across the globe. When active commercial ocean energy technology developers – who have met significant milestones in the pathway to commercialisation of their systems – are analysed it is observed that there are clear front-runner countries for each technology. Notably, the UK remains the leading market for both wave and tidal stream energy. The projects database reviewed in this report has also shown that the majority of shortlisted tidal stream developers are currently pursuing seabed-mounted, horizontal-axis, axial flow turbines, while the majority of shortlisted developers of wave energy converter devices are designing floating point absorber systems for offshore applications. Although, these are observed trends amongst the technology developers, there still is not a design for either wave or tidal energy that has yet proven itself capable of operating commercially. Those technology developers pursuing a 'less popular' concept may still ultimately prove to be capable of reducing LCOE to a competitive level. Much learning, innovation, and technology evolution remains for the fledgling ocean energy industry.

Policy maker recommendations

A number of barriers need to be overcome to unlock the potential of ocean energy relating to technology development, economic competitiveness, socio-environmental issues and infrastructure availability. It is recommended that policy initiatives are targeted to the maturity of each technology, rather than treating ocean energy converters as a homogenous group of technologies. For technologies that still face major reliability, survivability or installability challenges, policy makers should focus measures on accelerating technical development – for instance through capital grant schemes to support deployment and improved modelling techniques. These should be the focus for wave energy converters, deep ocean current devices, OTEC and salinity gradient technologies.

As technologies mature and move from prototypes to array-scale or larger commercial deployment, other barriers become increasingly significant. For instance, as tidal stream technologies move to the first small arrays, the primary barrier will change from technology to economics – with per MWh financial support becoming particularly important to create a market. Commercial-scale deployment will also bring increased socio-environmental, grid and supply chain challenges, which will need public sector cooperation to be overcome. Finally, for tidal range technology, which is largely mature, the primary challenge is managing the local ecological impact of such a large installation.

Table 5-1 summarises high-level policy priorities for each technology type, based on current industry status, patent analysis and assessment of barriers.

Table 5-1: High level summary of policy priorities for ocean energy technologies

Technology type	Barriers to address				Comments
	Technical	Economic	Environ-mental & social	Infra-structural	
Wave energy converters	■	▨	□	▨	Since players exiting the industry in 2013 have largely cited delays in technology development, prioritise investment on **technology R&D and infrastructure**, with subsidiary emphasis on **economic** barriers – including exploration of niche markets.
Tidal stream converters	■	■	▨	▨	Build on the OEM momentum by addressing **economic** barriers through a clear premium price per MWh. In parallel, continue **technology** R&D on next generation technologies to accelerate cost reduction. As the technology commercialises, **environmental, social and infrastructural** issues will increasingly require attention too.
Deep ocean currents devices	■	▨	□	□	Address **technology** barriers through R&D investments.
Tidal range technology	□	▨	■	□	**Environmental** impacts are often a showstopper – ensure that the risks are understood and mitigated before proceeding. The large project size brings **economic** risks, which will need to be addressed through bilateral negotiation on power prices.
OTEC devices	■	▨	□	□	Address **technology** barriers through R&D investments.
Salinity gradient technology	■	▨	□	□	Address **technology** barriers through R&D investments.

Key

■ **High priority** ▨ **Moderate priority** □ **Low priority**

Opportunities for ocean energy support in IRENA's work programme

There are six thematic areas in the agency's work programme, namely: planning for the global energy transition; gateway to knowledge on renewable energy; enabling renewable energy investment and growth; renewable energy access for sustainable livelihoods; islands: lighthouses for renewable energy deployment; and regional action agenda. In most of these areas of the agency's work there are avenues for support to ocean energy deployment.

Islands – lighthouses for renewable energy deployment: Ministers and other participants from 48 countries, gathered in St. Julian's, Malta on 6-7 September 2012, and issued the Malta Communique on Accelerating Renewable Energy Uptake for Islands. They called on IRENA to establish a Global Renewable Energy Islands Network (GREIN) as a platform for pooling knowledge, sharing best practices, and seeking innovative solutions for accelerated uptake of clean and cost-effective renewable energy technologies on islands. Ocean energy technologies provide an opportunity for niche applications to support the various GREIN clusters, including water desalination and tourism.

Planning for the global energy transition: At the Sustainable Energy for All (SE4ALL) Forum on 4-6 June 2014 at UN Headquarters in New York, IRENA, as the hub for the renewable energy objective of SE4ALL and Co-Chair of the Renewable Energy Committee of the SE4ALL initiative, launched its REmap 2030 (www.irena.org/remap). This global roadmap shows that it is possible and very affordable to more than double the share of renewables in the global energy mix by 2030. Ocean energy so far plays a very small role in this roadmap. IRENA can also work with various stakeholders and organisations (such as the IEA Ocean Energy Systems Implementing Agreement) to increase the role of ocean energy in REmap 2030 and contribute to the acceleration of cost and risk reduction through roadmapping of ocean energy technology deployment with realistic timescales at national, regional and global levels. IRENA's country-led renewable readiness assessments (RRA) provide an opportunity for countries with ocean energy resources to consider supply chain and job creation opportunities and benefits of ocean energy technology investment when considering their renewable energy options.

Gateway to knowledge on renewable energy: IRENA – through its costing, global atlas resource assessment and mapping, policy and best practice repository, and investment dynamics programmes – can cooperate with other organisations to continually improve knowledge on ocean energy technology deployment costs, best policy practices, and global resource potentials and distribution, as a way of assisting countries in their energy resource planning. In particular, OEMs and other stakeholders are invited to join the IRENA Renewable Energy Costing Alliance to share anonymously cost information of ocean energy technology deployment (www.irena.org/costs).

Enabling renewable energy investment and growth: The renewable energy policy assessment, energy pricing analysis, quality assurance and standardisation, and innovation and collaborative research, development and demonstration aspects of this thematic area of IRENA's work programme could contribute to increasing understanding of enablers for commercialisation of ocean energy technologies. Mobilising finance for scaling up renewable energy in developing countries is challenging. In support of the mission of IRENA, the United Arab Emirates (UAE) in 2009, through the Abu Dhabi Fund for Development (ADFD), committed concessional financing of up to USD 350 million for seven cycles for renewable energy projects in developing countries recommended or endorsed by IRENA. The IRENA/ADFD Project Facility (www.irena.org/adfd), born out of this commitment, helps to meet the challenge of financing renewable energy projects, including niche applications of ocean energy technologies such as water desalination and energy services for remote island areas.

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APPENDIX: LIST OF RECENT PATENTS

These patent listings are based on data compiled from the 2013 technology watch bulletins of the INPI and OEPM18, and the European Patent Office's Espacenet patent search portal.

Tidal Stream Patents

The following summarises international PCT (Patent Cooperation Treaty) publications in 2013 in the tidal stream sector.

Summary of international tidal stream PCT applications published in 2013

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/005707 A1	Albatross Technology LLC	10 Jan 2013	Japan
WO 2013/004369 A2	Voith Patent Gmbh	10 Jan 2013	Germany
WO 2013/017213 A1	Seyfarth, G.	07 Feb 2013	Germany
WO 2013/017214 A1	Seyfarth, G.	07 Feb 2013	Germany
WO 2013/017215 A1	Seyfarth, G.	07 Feb 2013	Germany
WO 2013/030582 A2	Mitchell, J.S.	07 Mar 2013	UK
WO 2013/021006 A1	OpenHydro IP Ltd.	14 Feb 2013	Ireland
WO 2013/025837 A1	Hydrovolts Inc.	21 Feb 2013	USA
WO 2013/038721 A1	Kamiya, M.	21 Mar 2013	Japan
WO 2013/041965 A2	Ferguson, F.D.	28 Mar 2013	USA
WO 2013/043057 A1	Tidal Sails AS	28 Mar 2013	Norway
WO 2013/048007 A2	Hyundai Construction Co. Ltd.	04 Apr 2013	Korea
WO 2013/052011 A1	Nanyang Technological University	11 Apr 2013	Singapore
WO 2013/054085 A1	Moorfield Tidal Power Ltd.	18 Apr 2013	UK
WO 2013/057512 A2	Coxon, C.	25 Apr 2013	UK
WO 2013/057521 A1	Angus Jamieson Consulting Ltd.	25 Apr 2013	UK
WO 2013/062160 A1	Jang, H.J.	02 May 2013	Korea
WO 2013/069854 A1	Kim, H.E.	16 May 2013	Korea
WO 2013/072274 A1	Schepers, J.L.M.	23 May 2013	UK
WO 2013/075192 A1	Monteiro de Barros, M.	30 May 2013	Brazil
WO 2013/079829 A1	Sabella;	06 Jun 2013	France
WO 2013/079830 A1	Sabella;	06 Jun 2013	France
WO 2013/079831 A1	Sabella;	06 Jun 2013	France
WO 2013/079638 A1	Alstom Hydro France	06 Jun 2013	France
WO 2013/083863 A1	Lorenzo Perez, A.	13 Jun 2013	Spain
WO 2013/083976 A1	TidalStream Ltd.	13 Jun 2013	UK
WO 2013/089398 A1	Park, J.W.	20 Jun 2013	Korea
WO 2013/092664 A1	OpenHydro IP Ltd.	27 Jun 2013	Ireland
WO 2013/092676 A1	OpenHydro IP Ltd.	27 Jun 2013	Ireland
WO 2013/092686 A1	Tidal Generation Ltd.	27 Jun 2013	UK
WO 2013/092687 A1	Tidal Generation Ltd.	27 Jun 2013	UK
WO 2013/093452 A1	Ocean Flow Energy Ltd.	27 Jun 2013	UK
WO 2013/100849 A1	Minesto AB	04 Jul 2013	Sweden
WO 2013/104847 A1	Sabella	18 Jul 2013	France

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/108412 A1	Nishioka, T.	25 Jul 2013	Japan
WO 2013/107724 A2	E&H Building Contractors Ltd.	25 July 2013	UK
WO 2013/107639 A1	Andritz Hydro Gmbh	25 Jul 2013	Austria
WO 2013/110715 A1	GE Energy Power Conversion Technology Ltd.	01 Aug 2013	UK
WO 2013/110721 A1	GE Energy Power Conversion Technology Ltd.	01 Aug 2013	UK
WO 2013/110928 A2	Nova Innovation Ltd.	01 Aug 2013	UK
WO 2013/113108 A1	Incurrent Turbines Ltd.	08 Aug 2013	Canada
WO 2013/113109 A1	Bateham, L.	08 Aug 2013	Canada
WO 2013/116899 A1	Hermatika Pty. Ltd.	15 Aug 2013	Australia
WO 2013/117502 A1	GE Energy Power Conversion Technology Ltd.	15 Aug 2013	UK
WO 2013/120203 A1	Sieber, J.	22 Aug 2013	Canada
WO 2013/124968 A1	Ogawa, H.; Toyooka, M.	29 Aug 2013	Japan
WO 2013/123923 A1	Lorenz, H.H.; Schiel, H.J.	29 Aug 2013	Germany
WO 2013/131404 A1	Dalian University of Technology	12 Sep 2013	China
WO 2013/131196 A1	Genesis Group Inc.	12 Sep 2013	Canada
WO 2013/131137 A1	Axis Energy Group Pty. Ltd.	12 Sep 2013	Australia
WO 2013/148243 A1	Swamidass, P.	3 Oct 2013	USA
WO 2013/144792 A2	Dufeu Lopez, J.	3 Oct 2013	Chile
WO 2013/154421 A2	Oryon Consultancy & Development	17 Oct 2013	Netherlands
WO 2013/157759 A1	Tidal Generation Ltd.	24 Oct 2013	UK
WO 2013/169341 A2	The Boeing Company	14 Nov 2013	USA
WO 2013/178996 A1	Tidal Generation Ltd.	5 Dec 2013	UK

Wave Patents

The following table summarises international PCT publications related to wave energy in 2013.

Summary of international wave energy PCT applications published in 2013

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/003184 A2	Atmocean Inc.	03 Jan 2013	USA
WO 2013/003640 A1	Liquid Robotics Inc.	03 Jan 2013	USA
WO 2013/005668 A1	Nishimura, I.	10 Jan 2013	Japan
WO 2013/006136 A1	Lam, T.C.	10 Jan 2013	Singapore
WO 2013/006088 A1	Kolevatov, M.N.	10 Jan 2013	Russia
WO 2013/008108 A1	Biteryakov, A.	17 Jan 2013	Russia
WO 2013/007520 A1	Crolet, F.	17 Jan 2013	France
WO 2013/007265 A1	Floating Power Plant A/S	17 Jan 2013	Denmark
WO 2013/009198 A1	Peterson, P.	17 Jan 2013	Portugal
WO 2013/012137 A1	Mun, N.H.	24 Jan 2013	Korea
WO 2013/011251 A1	Mace Wave Ltd.	24 Jan 2013	UK
WO 2013/014682 A2	Ghouse, S.M.	31 Jan 2013	India
WO 2013/013534 A1	Dong, W.; Wang, G.	31 Jan 2013	China
WO 2013/013266 A1	Drake, J.L.	31 Jan 2013	Australia
WO 2013/017400 A2	Robert Bosch Gmbh	07 Feb 2013	Germany
WO 2013/019214 A1	Oregon Energy Innovations, LLC	07 Feb 2013	USA
WO 2013/021089 A3	Sendekia Arquitectura e Ingenieria Sostenible SL	14 Feb 2013	Spain
WO 2013/024268 A1	Browne, G.	21 Feb 2013	UK

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/029012 A1	Resolute Marine Energy Inc.; Duke University	28 Feb 2013	USA
WO 2013/029195 A1	Egana Castillo, E.J.	07 Mar 2013	Chile
WO 2013/033667 A1	Rohrer, J.W.	07 Mar 2013	USA
WO 2013/033685 A1	Rohrer, J.W.	07 Mar 2013	USA
WO 2013/030359 A2	Wavebob Ltd.	07 Mar 2013	Ireland
WO 2013/036276 A1	Grossi, T.R.	14 Mar 2013	USA
WO 2013/034636 A1	Electric Waves SL	14 Mar 2013	Spain
WO 2013/038721 A1	Kamiya, M.	21 Mar 2013	Japan
WO 2013/037508 A1	Bayer MaterialScience AG	21 Mar 2013	Germany
WO 2013/041756 A1	AW-Energy Oy	28 Mar 2013	Finland
WO 2013/049590 A1	Resolute Marine Energy, Inc	04 Apr 2013	USA
WO 2013/048915 A1	Ocean Power Technologies Inc.	04 Apr 2013	USA
WO 2013/052447 A1	Wave Electric International LLC	11 Apr 2013	USA
WO 2013/050924 A1	Wave For Energy SRL	11 Apr 2013	Italy
WO 2013/053321 A1	Qu, Y.	18 Apr 2013	China
WO 2013/054326 A1	Eck Wave Power Ltd.	18 Apr 2013	Israel
WO 2013/053575 A2	Robert Bosch Gmbh	18 Apr 2013	Germany
WO 2013/056587 A1	Tal, K.W.	25 Apr 2013	China
WO 2013/056711 A1	Absalonsen, A.	25 Apr 2013	Denmark
WO 2013/057343 A1	Universidad del Pais Vasco	25 Apr 2013	Spain
WO 2013/062160 A1	Jang, H.J.	02 May 2013	Korea
WO 2013/060204 A1	Zouh, J. & Zouh, D.	02 May 2013	China
WO 2013/062300 A1	Park, S.P.	02 May 2013	Korea
WO 2013/064607 A1	Greco, P.	10 May 2013	Italy
WO 2013/068742 A2	Steel Eel Ltd.	16 May 2013	UK
WO 2013/068748 A2	Marine Power Systems Ltd.	16 May 2013	UK
WO 2013/074018 A1	Vigor Wave Energy AB	23 May 2013	Sweden
WO 2013/072123 A1	Robert Bosch Gmbh	23 May 2013	Germany
WO 2013/072551 A1	Wello Oy	23 May 2013	Finland
WO 2013/072633 A1	Claude, W.	23 May 2013	France
WO 2013/073954 A1	Oeigarden, H.	23 May 2013	Norway
WO 2013/079582 A1	Jospa Ltd.	06 Jun 2013	Ireland
WO 2013/079585 A1	Jospa Ltd.	06 Jun 2013	Ireland
WO 2013/083663 A1	Blue Wave Co S.A.	13 Jun 2013	Luxembourg
WO 2013/093149 A2	Peraza Cano, J.L.; Cano, J.F.	27 June 2013	Spain
WO 2013/107934 A1	Subsea Energy OY	25 July 2013	Finland
WO 2013/115581 A1	Han, Y.H.; Han, H.D.; Han, H.U.	08 Aug 2013	Korea
WO 2013/137744 A1	NTNU Technology Transfer AS	19 Sep 2013	Norway
WO 2013/137568 A1	Chang, H-S.	19 Sep 2013	Korea
WO 2013/143482 A1	Waves New Energy Ltd.	03 Oct 2013	China
WO 2013/150320 A2	Chorianopoulos, D.	10 Oct 2013	Greece
WO 2013/156584 A2	Weiss, O.	24 Oct 2013	Spain
WO 2013/156637 A1	Martinez Lopez, S.	24 Oct 2013	Spain
WO 2013/156674 A2	Wello Oy	24 Oct 2013	Finland
WO 2013/157016 A1	Devanand Totaram Ingle	24 Oct 2013	India
WO 2013/159056 A1	Chevron USA Inc.	24 Oct 2013	USA
WO 2013/160617 A2	GEPS Innov	31 Oct 2013	France
WO 2013/164555 A2	Edwards, D.	07 Nov 2013	UK

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/166529 A1	Freidenthal, R.	07 Nov 2013	South Africa
WO 2013/167667 A2	Single Buoy Moorings Inc.	14 Nov 2013	Switzerland
WO 2013/170496 A1	Guangzhou Institute of Energy Conversion	21 Nov 2013	China
WO 2013/170450 A1	Wang, W.	21 Nov 2013	China
WO 2013/174220 A1	Qu, Y.	28 Nov 2013	China
WO 2013/174221 A1	Qu Y.	28 Nov 2013	China
WO 2013/176535 A1	Ortega Garcia, M.J.	28 Nov 2013	Mexico
WO 2013/177491 A1	University of Massachusetts	28 Nov 2013	USA
WO 2013/180645 A1	Sun, Y-L.	05 Dec 2013	Singapore
WO 2013/182837 A1	Mace Wave Ltd.	12 Dec 2013	UK
WO 2013/181701 A1	DDNT Consultants Australia Pty. Ltd.	12 Dec 2013	Australia
WO 2013/181702 A1	DDNT Consultants Australia Pty. Ltd.	12 Dec 2013	Australia
WO 2013/185466 A1	Wang, M.	19 Dec 2013	China
WO 2013/188397 A1	Resolute Marine Energy Inc.	19 Dec 2013	USA
WO 2013/189500 A1	Subcpartner Holding Aps	27 Dec 2013	Denmark

Tidal Range Patents

The following table summarises international PCT publications related to tidal range energy in 2013.

Summary of international tidal range PCT applications published in 2013

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/025240 A1	Atiya, R.	21 Feb 2013	USA
WO 2013/053356 A2	Sebald, O.	18 Apr 2013	Germany
WO 2013/123923 A1	Lorenz, H.H.; Schiel, H.J.	29 Aug 2013	Germany
WO 2013/137594 A1	Kim, D.	19 Sep 2013	South Korea
WO 2013/143086 A1	Zhang, C.	03 Oct 2013	China
WO 2013/157760 A1	Santasmarinas Raposo, E.	14 Nov 2013	Spain

Ocean Current Patents

The following table summarises international PCT publications related to ocean current energy in 2013.

Summary of international ocean current PCT applications published in 2013

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/066897 A2	Aquantis, Inc.	10 May 2013	USA
WO 2013/089398 A1	Park, J.W.	20 Jun 2013	South Korea
WO 2013/162520 A2	Anadarko Petroleum Corporation	31 Oct 2013	USA

OTEC Patents

The following table summarises international PCT applications related to OTEC in 2013.

Summary of international OTEC PCT applications published in 2013

International Publication Number	Applicant	Date	Country of Applicant
WO 2013/000948 A2	DCNS	03 Jan 2013	France
WO 2013/013231 A2	Kalex LLC	24 Jan 2013	USA
WO 2013/025797 A2	The Abell Foundation, Inc.	21 Feb 2013	USA
WO 2013/025802 A2	The Abell Foundation, Inc.	21 Feb 2013	USA
WO 2013/025807 A2	The Abell Foundation, Inc.	21 Feb 2013	USA
WO 2013/050666 A1	IFP Energies Nouvelles	11 Apr 2013	France
WO 2013/078339 A2	Lockheed Martin Corporation	30 May 2013	USA
WO 2013/090796 A1	Lockheed Martin Corporation	20 Jun 2013	USA

Salinity Gradient Patents

There were no international PCT (Patent Cooperation Treaty) publications observed related to salinity gradient energy in 2013.

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