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TIDAL ENERGY

TECHNOLOGY BRIEF

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Highlights

- **Process and Technology Status –** There are three categories of tidal energy technologies. The first category, *tidal range technologies* use a barrage – a dam or other barrier – to harvest power from the height difference between high and low tide. The power is generated through tidal turbines (most of them come from hydropower design, such as bulb turbines) located in the barrage, and their commercial feasibility has been well established through the operation of plants in France (240 Megawatts (MW)), Canada (20 MW), China (~5 MW) and Russia (0.4 MW) from the 1960s and 1970s. In 2011/2012, South Korea opened the largest and newest tidal barrage (254 MW). New technologies developed for tidal range power generation are tidal 'lagoons', tidal 'reefs', and tidal 'fences', and low-head tidal barrages.

  The second category, *tidal current or tidal stream technologies* have had more than 40 new devices introduced between the period 2006-2013. The major differences among the devices are the turbines, which can be based on a vertical or horizontal axis, and in some cases are enclosed (ducted). Full-scale deployment of single turbines have been achieved, and the next step is the demonstration of arrays of turbines (Energy Technologies Institute (ETI)/ UK Energy Research Centre (UKERC), 2014). Up to 2010, the industry was dominated by small entrepreneurial companies, but in the last three years large engineering firms and turbine manufacturers like ABB, Alstom, Andritz Hydro, DCNS, Hyundai Heavy Industries, Kawasaki Heavy Industries, Siemens, and Voith Hydro have entered the market. Furthermore, companies like General Electric (GE) have also shown an interest and are supplying the electrical power systems for some of the prototypes. Also, large utilities like Bord Gáis Energy, Électricité de France (EDF), GDF Suez, and Iberdrola are running demonstration projects.

  Some tidal current or tidal stream technologies are also used to harvest ocean currents. Compared to tidal currents, ocean currents are unidirectional and generally slower but more continuous. Ocean current technologies are in an early developmental stage, and no full-scale prototype has been tested or demonstrated yet.

  The final category, *hybrid applications* are forms of tidal range technologies that have great potential if their design and deployment can be combined with the planning and design of new infrastructure for coastal zones. Project proposals for hybrid applications exist in Canada (British Columbia), China, the Netherlands (Grevelingen), Norway (E39 road project) and the UK (Bristol Channel). Furthermore, there are plans for a hybrid form of tidal range and current power generation called 'dynamic tidal power'. Again, no full-scale prototype has been tested or demonstrated yet.

» **Potential –** Worldwide, the technically harvestable tidal energy resource from those areas close to the coast, is estimated by several sources at 1 terawatts (TW). The potential for tidal current technologies is larger than for tidal range. Total tidal range deployment in 2012 was around 514 MW, and around 6 MW for tidal current (of which 5 MW is deployed in the UK). Extensive plans exist for tidal barrage projects in India, Korea, the Philippines and Russia adding up to around 115 gigawatts (GW). Deployment projections for tidal current up to 2020 are in the range of 200 MW.

An advantage of both tidal range and tidal current energy is that they are relatively predictable with daily, bi-weekly, biannual and even annual cycles over a longer time span of a number of years. Energy can be generated both day and night. Furthermore, tidal range is hardly influenced by weather conditions.

» **Cost indications –** Tidal range power generation is dominated by two large plants in operation, the 'La Rance' barrage in France and the 'Sihwa dam' in South Korea. The construction costs for 'La Rance' were around USD 340 per kilowatt (/kW) (2012 value; commissioned in 1966), whilst the Sihwa barrage was constructed for USD 117/kW in 2011. The latter used an existing dam for the construction of the power generation technology. The construction cost estimates for proposed tidal barrages range between USD 150/kW in Asia to around USD 800/kW in the UK, but are very site specific. Electricity production costs for 'La Rance' and 'Sihwa Dam' are EUR 0.04 per kilowatt-hour (/kWh) and EUR 0.02/kWh, however these costs are very site specific. Tidal range technologies can be used for coastal projection or water management, which would reduce the upfront costs. On the other hand, additional operational costs may occur due to the control, monitoring and management of the ecological status within the impoundment.

Tidal current technologies are still in the demonstration stage, so cost estimates are projected to decrease with deployment. Estimates from across a number of European studies for 2020 for current tidal technologies are between EUR 0.17/kWh and EUR 0.23/kWh, although current demonstration projects suggest the levelised cost of energy (LCOE) to be in the range of EUR 0.25-0.47/kWh. It is important to note that costs should not be considered as a single performance indicator for tidal energy. For example, the costs for both tidal range and tidal stream technologies can fall by up to 40% in cases where they are combined and integrated in the design and construction of existing or new infrastructure.

» **Barriers and drivers –** The greatest barrier to tidal range technology advances are the relatively high upfront costs related to the developments of the dykes or embankments, and the ecological implications of enclosures or impoundments. Moreover due to tidal cycles and turbine efficiency, the load factor of a conventional tidal barrage is around 25%, which leads to high cost of energy. Improvement in turbine efficiency, in particular innovative reversible turbines for ebb and flood generation, should provide a significant increase in energy yield.

One important new avenue is the use of tidal range applications to promote ecological improvement. In all these solutions (*e.g.,* in the case of the Sihwa barrage or potentially in case of the Grevelingen lake in the Netherlands), the installation of tidal range technology leads to several important societal benefits besides renewable energy. These include flood defence, improved environmental and ecological water quality, and fisheries and tourism functions. An important new application for tidal range energy under development is one which is focused on harvesting energy from low head tidal differences of less than 2 metres (m).

For tidal stream technologies, continued support for demonstration and grid connection of larger scale arrays will be critical. With these experiences, the materials, operation and maintenance costs can be improved. Furthermore, high installation costs of both tidal range and tidal current solutions need to be overcome through capital investments, aiding commercialisation, feed-in tariffs or investment mechanisms in innovation. The simultaneous research and development of new infrastructure of flood defences, coastal restructuring, bridge and road construction, also offer opportunities to advance tidal energy technologies.

I. Process and Technology status

Tides are the result of the interaction of the gravity of the sun, earth, and moon. The rise and fall of the tides – in some cases more than 12 m – creates potential energy. The flows due to flood and ebb currents creates kinetic energy. Both forms of energy can be harvested by tidal energy technologies as renewable energy. Tidal energy technologies are not new: examples were already reported in Roman times and ruins of installations – tidal mills – are found in Europe from around the year 700. Since the 1960s, only five projects have been developed commercially in the period up to 2012. However, new technologies have advanced considerably over the past few years and there are a number of ongoing full-scale demonstration projects.

Tidal energy technologies can be subdivided into three categories.

A. Tidal Range technology

Tidal range technologies harvest the potential energy created by the difference in head between ebb tide and flood tide. Such resources exist in locations where due to geological and ecological conditions, large water masses flow into compounded areas or bays and estuaries. Furthermore, tidal range energy is predictable, as the energy production is not influenced by weather conditions, but rather by the cyclical constellations, the gravity of the moon, sun and earth, providing a predictable bi-week, biannual and annual cycle.

The first tidal barrage was completed in the Rance River in north-western France (Brittany) in 1966, but due to plans for greater use of nuclear energy, the further pursuit of tidal energy was abandoned. Between 1966 and 2011, a number of small tidal plants were built in countries such as Canada, China (Lu, *et al*. 2010), Iran (Gorji-Bandpy, Azimi and Jouya, 2013) and Russia, where tidal energy resource is abundant (International Energy Agency implementing agreement on Ocean Energy Systems (IEA-OES), 2014a).

The largest and newest tidal barrage in the world is the Sihwa dam in north-eastern South Korea, which was built in 2011 and became operational in 2012. The Sihwa dam, with a capacity of 254 MW, is an example of a multi-functional tidal barrage, which improves the ecology of a formerly closed sea-arm by creating openings in an existing sea defence and installing hydro-turbines. This project is a relevant example for a combined tidal range solution, where in the end the priority was placed on ecological water quality improvement.

Figure 1 - La Rance Tidal Barrage installation (top left-tl); Brouwersdam /Grevelingen Lake, where innovative turbines for low head are proposed to be installed for testing in 2014 (top right-tr); Bristol Channel, map of possible marine energy locations, (bottom left-bl); and the Sihwa Lake Power Station (bottom right-br).

Photo: EDF Médiathèque (tl); www.rcgroups.com/forums/showthread.php?t=1119713&page=2 (tr); Regen SW, 2012 (bl); ANDRITZ HYDRO GmbH, 2011 (br)

How does it work?

Most conventional tidal range schemes use bulb turbines, which are comparable to hydropower turbines that are installed in a dam (run of rivers hydro power plant).

Tidal range technology has a number of options for power generation:

I.) **One way power generation at ebb tide:** The reservoir is filled at flood tide through sluice gates or valves that are closed once the tide has reached its highest level. At the ebb tide, the water in the reservoir is released through the turbines and power is generated. With this single cycle, power is generated for only four hours per day. Annapolis in Canada is an ebb generation plant.

II.) **One way power generation at flood tide:** At flood tide the sluice gates are kept closed to isolate the reservoir while at its lowest level. When the tide is high, the water from the sea-side flows into the reservoir via the turbines, thus generating power. The disadvantage of this cycle is that it has less capacity and generates less electricity, and it may be ecologically disadvantageous as the water level in the impoundment is kept at a low level for a long time. Sihwa is a flood generation plant.

III.) **Two way power generation:** Both incoming and outgoing tides generate power through the turbines. This cycle generates power for four hours twice daily. However, reversible turbines are required. La Rance is an ebb and flood generation plant; bulb turbines can also pump water for optimisation.

Tidal range in the Severn Estuary, UK

In 2008 and 2009, a number of exploratory studies were undertaken regarding a tidal barrage in the Severn Estuary (schemes from 8 600 MW to 600 MW). In 2010, the UK government decided that the barrage would be too risky as costs were too high, including the environmental and ecological issues. Several other schemes for technology development for alternatives of so called 'embryonic technologies', had less of an ecological impact, and were thus continued. Alternatives to a barrage in the Severn included ideas for 'tidal reefs', tidal 'fences', tidal 'lagoons' (figure 2).

Corlon Hafran, a private corporate consortium, re-launched the idea for a tidal barrage in the Severn Estuary in 2010 and has since continued studies. In November 2012 another private consortium launched a discussion for a tidal scheme for the Bristol Channel that included a tidal impoundment but also offshore wind and tidal current devices in the Bristol Channel (Regen SW, 2012). Another consortium, Swansea Bay Tidal Lagoon, is currently developing a 240 MW lagoon. In January 2013, the UK Department of Energy and Climate Change (DECC), published a guidance noting that their "2-year cross-government Severn tidal power feasibility study could not see a strategic case for public investment in a Severn tidal scheme in the immediate term" (DECC, 2013).

Figure 2: Impression of a 'tidal lagoon'.

Source: www.aquaret.com

A number of new innovations are being considered. Tidal reefs would have a smaller head difference (2-3 m) than the conventional 5-10 m used for tidal barrage. The advantage of this smaller head difference is a reduced impact on the environment and easier construction due to the lower pressure exerted on the structure. On the downside, the lower head would slightly lower full flow efficiency of the turbines.

Tidal lagoons are similar to tidal barrage, except that they are not necessarily connected to the shore but could sit within the ocean. Environmental impact assessments of the proposed tidal lagoon in Swansea Bay suggest that lagoons would have lower environmental impacts than tidal barrages. Another development is the use of ultra-low-head tidal techniques.[1] For example, the tidal barrage project in the Grevelingen Lake in the Netherlands would be the first ultra-low-head barrage, as the tidal difference would be only between 50 centimetres (cm) and 1 m. Several low-head tidal techniques are currently being developed, notably by a number of UK universities and companies, and some smaller firms in Canada and France.

Finally, the use of tidal fences would consist of a number of individual vertical axis turbines that are connected to each other within a fence structure (Godfrey, 2012). The fence itself could be placed between the mainland and a nearby island, or between two islands (as proposed at the San Bernardino Straits in the Philippines). Thus far, these applications are in their early stages of development and there are no prototypes being tested in the water at present.

Who is developing projects?

There are many potential sites for tidal barrages worldwide, but the upfront construction costs of the tidal barrage and associated environmental impacts are a major obstacle to further development (O'Rourke, Boyle and Reynolds, 2010). In addition to focusing on power generation, a number of new initiatives therefore also focus on water management, flood defence, and the improvement of ecological water quality to enhance the economic and environmental functions around such basins (tourism, fisheries, better flood protection management of protected sites and reducing eutrophication). Leading countries are regions with good tidal resources, such as South Korea with tidal range differences of 9 m to 14 m, and Canada at various locations along the Lawrence River. Similarly, RusHydro is exploring tidal range projects in Western Australia together with Atlantis Resources. Most of these initiatives

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[1] In conventional hydro, "low" is generally considered to mean a head of less than 10 m.

are typically multi-stakeholder projects, seeking finance from the public as well as private partners.

Furthermore, current tidal range projects appear to have great benefits in cases where existing dams or compounds are used, and where the objective of energy production is combined with the objective to improve water quality. Besides the Sihwa barrage in South Korea, the Netherlands is developing a project in the Grevelingen Lake, and Canada is working on projects in British Columbia, where formerly closed impoundments are being transformed into energy producing impoundments.

B. Tidal Current Technologies

Tidal current or tidal stream technologies have made enormous strides in development towards commercialisation in the past five to seven years. Almost 40 new devices are currently being developed and few of them are tested – at full scale – in UK waters.

How do they work?

Tidal current or tidal stream technologies convert the kinetic energy into useable energy. Technology developments are comparable to the development of wind turbines. Although most larger-scale demonstration projects use horizontal axis turbines[2], three main categories can be distinguished:

A) Horizontal-axis axial and vertical-axis cross flow turbines

Horizontal and vertical axis tidal turbines currently use blades that are positioned either in parallel (horizontal) or perpendicular (vertical) to the direction of the flow of water (figure 3). The turbines are similar to designs used for wind turbines, but due to the higher density of water the blades are smaller and turn more slowly than wind turbines. Furthermore, they have to withstand greater forces and movements than wind turbines.

Most designs use blades that are connected to a central rotor shaft, which through a gearbox, is connected to a generator shaft. Open-centre turbines have a different design in that the blades are mounted on an inner, open-centred shaft housed in a static tube. As the water flows through the shaft,

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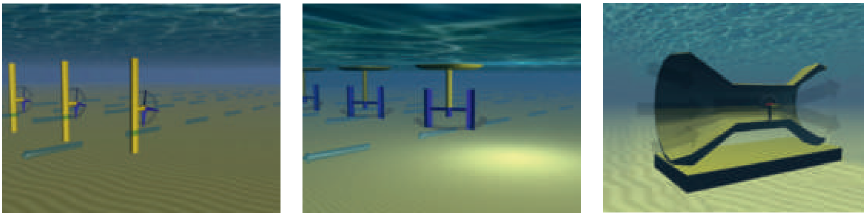
[2] A more detailed categorisation can be found on the website of the European Marine Energy Centre.

it rotates and electricity is generated. The advantage of this design is that it eliminates the need for a gearbox.[3]

The blades of horizontal or vertical turbines can also be enclosed within a duct. The latter turbines are referred to as Enclosed, Ducted or Shrouded turbines (figure 3). Due to the enclosure, the ocean current is concentrated and streamlined so that the flow and power output from the turbines increases.

Based on an overview of existing tidal current projects, 76% of all turbines are horizontal axis turbines and 12% are vertical axis turbines (International Renewable Energy Agency (IRENA), 2014). In 2011, 76% of all research and development (R&D) investments into tidal current technologies went into horizontal axis turbines, 4% into enclosed turbines, and 2% into vertical axis turbines (Joint Research Centre (JRC), 2013).

Figure 3: Horizontal Axis Turbines (left), Vertical Axis Turbines (middle), and Enclosed Turbines (right)



Source: www.aquaret.com

B) Reciprocating devices

Reciprocating devices have blades called hydrofoils – shaped like airplane wings – that move up and down as the tidal stream flows on either side of the blade.[4] The up and down movement of the hydrofoils is subsequently converted into rotation to drive a rotating shaft, or connected to pistons to support a hydraulic system for power generation (figure 4). The advantage of reciprocating devices is that the length of the blade is not constrained by water depth, however it also requires complex control systems to pitch

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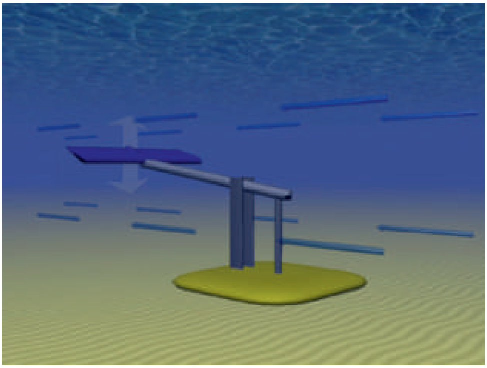
[3] Devices without a gearbox are called direct-drive generators.

[4] There are also proposals to use vortex induced cylinders to generate power in a similar way.

the blades correctly. Around 2% of all R&D investments in tidal current technologies went into reciprocating devices (JRC, 2013).

Figure 4: Hydrofoil shaped design concepts



Source: www.aquaret.com

C) Other designs

There are a number of other designs that are in the research and development stage. This category includes rotating screw-like devices and tidal kites that carry turbines below their wings.

Besides the conversion technology, there are a number of additional technological aspects that determine the performance and costs of tidal current technologies: 1) support structures, 2) array formation, and 3) electrical connections to shore.

All tidal current technologies require a support structure to keep the technology in place and withstand the harsh conditions at sea. The choice for the foundation depends – amongst others – on the position of the tidal current technology in the water, the depth of the water, the structure of the sea-bed, and the availability of vessels and offshore drilling devices to support the construction. There are three categories of support structures (O'Rourke, Boyle and Reynolds, 2010). The first category consists of *gravity structures* – often consisting of a large mass of concrete and steel – connecting the technologies to the seabed. The second category are *piled structures,* whereby one or more beams are drilled or pinned into the sea bed. Foundations with one single beam are called monopiles. The third category are so-called *floating foundations* which are connected to the sea bed through either rigid or flexible wires or chains. Although there seems to be a convergence in tidal current technologies towards horizontal axis designs, there is still quite a variety in mooring technologies used. Of the different tidal current concepts and projects developed so far, 56% uses rigid connection (mostly seabed), 36% uses mooring, and 4% monopiles (IRENA, 2014). For example, Marine Current Turbines (MCT)/Siemens' SeaGen changed from a monopile support structure to a new tripod design. Alstom, on the other hand, is working on turbines with individual components that can be mounted on different kinds of mooring structures.

Another technical aspect for tidal current technologies is their deployment in the form of farms or arrays. Individual generator units are limited in capacity, so multi-row arrays of tidal turbines need to be built to capture the full potential of tidal currents. However, turbines have an impact on the current flows, so the configuration in which they are placed is a critical factor to determine their potential yield and output (SI Ocean, 2012).

Additionally grid connection for tidal current technology deployment requires consideration. Turbines need to be connected to each other through array cables (typically 33 kilovolt (kV)). The array is then typically connected to an offshore substation, which is connected through an export cable (typically 150 kV) to an onshore substation and eventually to the grid (the International Energy Agency implementing agreement for Renewable Energy Technology Deployment (IEA-RETD), 2012). With the development of wind parks off shore, there is now considerable experience in developing both offshore alternating current (AC) and direct current (DC) grid infrastructures. Yet, grid connection remains one of the critical aspects for tidal energy deployment as delays and the costs for grid connection could put many projects at risk (RenewableUK, 2013).

Tidal current technologies can also be used to generate electricity from ocean currents. Ocean currents, although slow are a continuous flow driven by wind patterns and thermohaline circulation. Although there are currently no known applications, studies have been widely undertaken, for example in Florida (Yang, Haas and Fritz, 2012). Ocean currents are an interesting resource as they are very constant albeit with a slow speed. Studies of ideas for floating offshore platforms, are currently being undertaken and thus far, no near-future commercial applications have been reported.

Who is developing projects?

So far, most of the development of this technology is taking place in Canada, China, France, Ireland, Japan, South Korea, Spain, UK, and the USA (Carbon Trust, 2011). Most of these countries have at least one open sea test site. In particular, the European Marine Energy Centre (EMEC), based in Scotland, is one of the longest running sites where tidal current turbines have been tested since 2005. New test sites are planned in Chile, China, New Zealand, Portugal, Spain, and the USA.

In the last couple of years, five new industrial companies entered the market by supporting and taking over prototypes close to development: Andritz Hydro took over Hammerfest Strøm; MCT is now also part of Siemens; ABB invested in Scotrenewables Tidal Power; Alstom acquired Tidal Generation Ltd. (TGL); and DCNS took over Open Hydro with projects deployed in Canada, France, and the UK (Scotland). Hyundai Heavy Industries has finalised site trials with a 500 kW tidal, and Kawasaki Heavy Industries is testing full-scale technologies at European Marine Energy Centre (EMEC) and in Japan. Furthermore, GDF Suez is supporting the development of Sabella, an enclosed turbine, in France.

It difficult to determine which turbines are closest to commercialisation, although it seems that there is a convergence towards horizontal axis turbines (figure 6). Andritz Hydro Hammerfest, Alstom TGL, DCNS Open Hydro, Scotrenewables Tidal Power, MCT/Siemens, and Voith Hydro all deploy horizontal axis turbines of more than 1 MW demonstration units in the sea. Furthermore, Atlantis is working together with Lockheed Martin to optimise its new 1.5 MW tidal turbines. The turbine has also started being tested in China, where an increasing number of turbines are being developed. Of these technologies, the turbines from Andritz Hydro Hammerfest, MCT/Siemens and possibly Alstom TGL have been selected in three European funded demonstration projects for tidal arrays to be operational in the 2014 – 2016 time frame (Jeffrey, 2013). Furthermore, in April 2014 DCNS OpenHydro and Alderney Renewable announced plans for a 300 MW tidal array. However, most work on arrays still focuses on model development (Culley, Funke and Piggott, 2014; Thomson, Whelan and Gill, 2010).

Aside from advances in applications close to the coast, several smaller technologies are being developed. These technologies could also be used for inland applications or as river current generators. For example, Tocardo Turbines are in operation in The Netherlands in the North Afsluitdijk and soon also in the

Eastern Scheld barrage. In the USA, the Verdant turbine was tested in the East River of New York City and Ocean Renewable Power Company is demonstrating its vertical axis turbines near Eastport in Maine. Near Australia, HydroGen has been testing its turbines in the Torres Strait.

Figure 5 - Turbines of the Atlantis Resources Corporation (tl); Voith Hydro turbine (tr); Alstom TGL (bl); DCNS OpenHydro (br).

Photo: Atlantis Resources image library (tl), Voith Hydro (tr), Cyril Abad - Alstom (bl), DCNS (br).

Figure 6 - Tocardo T100 turbine for river tidal current (tl); Andritz Hydro Hammerfest HS1000 turbine (tr); Siemens SeaGen with crossarm fitted; Sabella deployed by GDF Suez.

Photo: Tocardo (tl), ANDRITZ HYDRO GmbH, Hammerfest (tr), Marine Current Turbines- a Siemens Business (bl), Sabella (br).

- **Hybrid Forms –** Hybrid forms of tidal energy can be found in the form of multi-purpose platforms where both tidal current and tidal range technologies are used for electricity generation. These platforms are in an early developmental and innovative stage.

  A recent development is called “dynamic tidal power” (DTP). It consists of a 30-60 kilometre (km) long dam that runs perpendicular to the coast line. At the end of the dam, there is a barrier forming a large “T” shape. The dam interferes with the oscillating tidal waves on either side of the dam, and creates a height difference between the water levels. This height difference creates potential energy, which can be converted into electricity using the low-head turbines that are being used in tidal ranges. A technical feasibility study – supported by the Dutch government – for a 8 GW DTP plant in China, is expected to be released in 2015.

Integration of tidal technology in new (and refitted) infrastructure

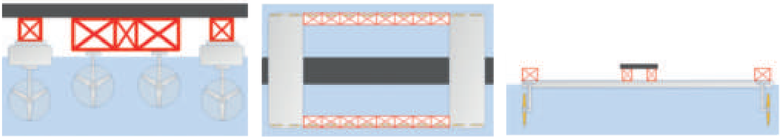
As previously mentioned, a new development in tidal energy is the move towards integration of renewable energy technologies, such as tidal energy, within coastal defence infrastructures, road connections, or other designated purposes. Although examples can be found in the Netherlands (Grevelingen/Brouwersdam) and South Korea (Sihwa), the most complete approach –integrated approach at a large scale (figure 7)- is probably the construction of the E39 in Norway.

Figure 7 - E-39 planned road trajectory from north to south coast. Technology survey for renewable energy integrated to bridge considering solar, wind, wave and tidal energy

Source: Norwegian Public Road Administration (NPRA), 2012a.

Most recently, Norway has sought to systematically apply this principle in the exploration and planning for the North South E39 road. Figure 8 further depicts certain possibilities for the integration of renewable energy into highway projects along the Norwegian coast. Through this approach, the installation costs of innovative renewables can be reduced, whilst at the same time, the new structure can be designed in such a way that it best fits tidal generators.

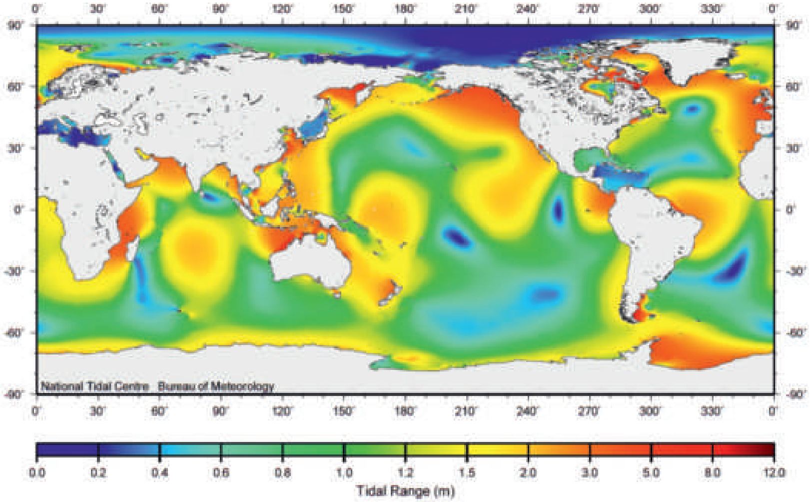
Figure 8. Coastal Highway Route: E39 Project Overview (NPRA, 2012b)



II. Potential and Future Prospects

Worldwide, the tidal resources are considerable and also largely unmapped. However, global resources are estimated at 3 TW (figure 9). The technically harvestable part of this resource, in areas close to the coast, is estimated by several sources at 1 TW (Carbon Trust 2011; Lewis, *et al.*, 2011). For an exact estimation of the actual resources, it is necessary to map the details per region or country. The shape of the coast also determines the tidal range with a fluctuating difference of up to 17 m between high and low tide (figure 10). Argentina, Australia, Canada, Chile, China, Colombia, France, Japan, Russia, South Korea, Spain, the UK, and the USA (Maine/Alaska) have very high tidal ranges. Furthermore, Eastern Africa has large resources for tidal range.

Figure 9. Tidal range resources worldwide



Source: Bureau of Meteorology, Australian Government

Figure 10: Tidal range potential in South Korea

Source: De Laleu, 2011, p. 237.

For tidal current technology, the stream speed needs to be at least 1.5-2 m per second (m/s). The resources for this technology are very large, depending on the form and shape of the coast. They have not been mapped systematically worldwide. For Europe, the resources that are harvestable are estimated at a minimum of 12 000 MW (European Ocean Energy Association[5] (EU-OEA), 2010). Only a small number of countries, *e.g.*, France, Ireland, Norway, the UK, USA, and some parts of the coast of China and Canada have been studied in detail. Other regions and countries with potential sources are Australia, Africa, India and Spain, but studies here are lacking (Lewis, *et al.*, 2011).

An advantage of both tidal range and current energy is that they are highly predictable with daily, bi-weekly, biannual and even annual cycles over a longer time span of a number of years. Energy can be furthermore generated both day and night. Furthermore, tidal range is hardly influenced by weather conditions. Tidal stream is slightly more affected by the weather, but the fluctuations in the long run are lower than, for example, wind and solar. Another advantage of tidal stream energy is that the impact upon the landscape in the coastal zones is relatively small. Most structures are underwater and the associated requirements on land infrastructure can be relatively low or in some cases may be integrated into existing buildings or structures.

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[5] The European Ocean Energy Association is also referred to as Ocean Energy Europe.

III. Costs and Performance

Tidal range energy has already been commercially applied since the late 1960s in Canada, China and France, and most recently in South Korea. With regard to the tidal range, the upfront costs associated with installation are high, however, they hold good pay-back properties over the longer term. Many of the installations from the 1960s and 1970s are still operational without many problems.

There is, however, little economic data available. This is partly due to the fact that the cost are very site specific. The two main cost factors are: the size of the barrage (length and height) determining the capital costs, and the difference in height between high and low tide determining the electricity production. Some estimates taken from web based sources, for the largest and oldest tidal range installation in La Rance, indicate that costs range from EUR 0.04 (Lena, 1998) to EUR 0.09-0.12/kWh (Wyre Energy Ltd., 2013), The Sihwa power plant in South Korea, is the largest tidal range installation in the world, is estimated to have cost around USD 300 million and produce electricity for USD 0.024/kWh (Wyre Energy Ltd., 2013).

A comparison of existing and proposed/planned tidal barrages is provided in Table 1.

Table 1 - Estimated construction costs for existing and proposed tidal barrages.

Barrage	Country	Capacity (MW)	Power generation (GWh)	Construction costs (million USD)	Construction costs per kW (USD/kW)
Operating					
La Rance	France	240	540	817[1]	340
Sihwa Lake	Korea	254	552	298	117
Proposed/planned					
Gulf of Kutch	India	50	100	162	324
Wyre barrage	UK	61.4	131	328	534
Garorim Bay	Korea	520	950	800	154
Mersey barrage	UK	700	1 340	5 741	820
Incheon	Korea	1 320	2 410	3 772	286
Dalupiri Blue	Philippines	2 200	4 000	3 034	138
Severn barrage	UK	8 640	15 600	36 085	418
Penzhina Bay	Russia	87 000	200 000	328 066	377

Note: [a] *Cost equivalent for 2012*

Based on Wyre Energy Ltd., 2013.

The construction costs, however, do not necessarily need to be assigned to power production. In the case of La Rance, the construction also functions as a highway, reducing travel distance by 30 km for up to 60 000 vehicles per day (De Laleu, 2009). Similarly, the Sihwa lake tidal barrage is constructed on top of an existing dam.

Besides the upfront costs, other considerable costs may be the control, monitoring and management of the ecological status within the impoundment. The costs for both tidal range and tidal stream technologies can fall up to 40% in the case where construction is combined and integrated in the design and realisation of new infrastructure (*e.g.*, sea defence, water quality measures or roads) as was noted from the study undertaken by the Norwegian Ministry of Road Administration (2012). Additionally, such an integrated approach that combines the planning and realisation of coastal defences and bridges with the realisation of tidal energy installations, can greatly reduce the maintenance and operation costs of devices.

The development of commercial arrays of tidal current technologies is still in the demonstration phase, so levelised costs of electricity (LCOE) are in the range of EUR 0.25-0.47/kWh with the lower range LCOE estimates based on high capacity factors and low capital cost estimates (SI Ocean, 2014). The Carbon Trust indicates that the highest current costs, are related to installation (35%), the structure (15%), and maintenance and operation (15%), with installation costs varying greatly according to the location (Carbon Trust, 2012).

Costs are projected to come down with deployment levels and resource quality as the important determinants. Furthermore, technology developers are working hard to increase the capacity factor of arrays from around 25% to 40% and availability factor from 70% to 90% by 2020 (ETI/UKERC, 2014). If deployment is in the order of 200 MW by 2020, SI Ocean estimates an LCOE with a central range of EUR 0.21-0.25/kWh (SI Ocean, 2013a). These estimates are similar to a study by the Carbon Trust, which estimated that the costs for tidal current devices will be around EUR 0.17-0.23/kWh in 2020 (Carbon Trust, 2012). Deployment in high or low quality resource area can increase this range to EUR 0.16-0.30/kWh (SI Ocean, 2013a). Scaling up to around 2-4 GW – assumed to be possible by 2030 – could bring LCOE below EUR 0.20/kWh (Carbon Trust, 2012; SI Ocean, 2013a).

IV. Drivers and Barriers

The potential of tidal energy is significant, particularly in certain locations, and the successful demonstrations of full-scale tidal current technologies in the last few years have mobilised the support of governments and private investment in the technology and project development in those regions. Table 2 provides an overview of a selected number of government support policies specific for tidal energy technologies in different countries.

Table 2. Tidal energy policies in selected countries

Country	Tidal energy targets	Ocean energy feed-in tariff (FiT)	Open sea testing centre	Research, Development & Demonstration support
Australia				Support for demonstration projects
Belgium		Eligible for green certificate scheme	1 operational	
Brazil				R&D programme for ocean energy
Canada	Marine Renewable Energy Technology Roadmap	Community FiT for tidal power	2 operational	CAD 4 million, Marine Renewable Energy Enabling Measures Programme
Chile		Special FiT being developed	1 planned	
China	National Ocean Technology Centre (NOTC) is developing 2030 strategic report	Specific FiT for ocean energy	1 under development	Special funding programme for ocean energy (SFPMRE); Establishment of Administrative Centre for Marine Renewable Energy (ACMRE)
Denmark		FiT of EUR 80/MWh (uniform across all renewables)	1 operational	EUR 3.4 million for wave projects 2014-2015
European Commission (EC)	Strategic Initiative for Ocean Energy			NRE300 programme;

Country	Tidal energy targets	Ocean energy feed-in tariff (FiT)	Open sea testing centre	Research, Development & Demonstration support
France	380 MW by 2020	FiT of EUR 150/MWh	2 test sites for tidal energy	Financial support for five demonstration projects
Germany		Tidal power covered under EEG[a]		Research programme for next generation maritime technologies
Ireland	Explicit target in NREAP[b]	Planned FiT of EUR 0.28/kWh	1 operational, 1 under development	R&D budget for tidal energy
Italy	Explicit target in NREAP			
Japan				Ocean energy technological research and development project
New Zealand			1 planned	Marine Energy Deployment Fund (2007-2011)
Portugal	Explicit target in NREAP	FiT halted	1 planned	
South Korea	Specific targets in renewable energy plan	Ocean under RPS[c]		Large and growing R&D fund for tidal power
Spain	Explicit target in NREAP	FiT suspended in 2012	1 operational 1 planned	National and state funding available
Sweden			3 operational	
UK	Explicit target in NREAP	Tidal projects covered under ROC[d] scheme	3 operational, 1 planned	Commercialisation and investment funds; Demonstration scheme;
USA		Eligible for Clean Renewable Energy Bonds and Renewable Electricity Production Tax Credits	2 operational, 1 planned	Grants available for companies

Notes: [a] The Renewable Energy Sources Act, or Erneuerbare-Energien-Gesetz (EEG) in German

[b] National Renewable Energy Action Plan

[c] Renewables Portfolio Standard

[d] Renewables Obligation Certificates

Based on: SI Ocean, 2013b; Asia-Pacific Economic Cooperation (APEC), 2013; IEA-OES, 2014b.

The most important driver for tidal range and tidal current energy is that both technologies can generate renewable electricity close to urban centres, without becoming a nuisance or having a negative environmental impact on the landscape. Positively, tidal range installation can, while also contributing to or being part of water defences or sluices, have a minimal effect on the landscape, with negligible emissions and noise. However, there are a number of barriers that need to be overcome (see *e.g.*, House of Commons (HoC), 2012; Karim, 2012; Tzimas, 2014).

Technology barriers

The technological challenge for tidal range is to increase the efficiency of the turbines. For tidal current technologies, the basic technologies exist but technical challenges continue to arise due to insufficient experience with materials, working and fixing structures in a harsh environment, demonstration, a lack of information and knowledge regarding performance, lifespan, operation and maintenance of technologies and power plants.

For tidal current technology to become a real alternative to conventional energy sources, increased attention needs to be paid to technical risks in design, construction, installation and operation. According to reports of the Crown Estate (2013) and the Carbon Trust (2012), costs need to be brought down to at least 50%, which is comparable to offshore-wind energy generation costs. Moreover, importing knowledge and experience from other industry sectors, such as offshore oil and gas installations and offshore wind farms, including risk assessments, environmental impact assessments and engineering standards, is of great importance. This is not an easy process as much of this information is proprietary and of competitive advantage to firms. Furthermore, oil and gas technologies are often not the same as technologies for renewable projects (*e.g.*, high spec, high cost, one-off uses vs. lower cost, mass produced)

More extensive research on new materials and methodologies, and rigorous testing on new sub-components and complete functional prototypes is still necessary to establish these new technologies. For tidal current technologies, costs of fixtures to the seabed, and maintenance and installation costs need to be brought down. Furthermore, more experience in deploying arrays is required.

Ecological

The potential for traditional tidal range technology, which closes streams or river arms with dams or in impoundments, is limited due to ecological constraints. Additionally, experiences with artificially closed compounds have demonstrated that the costs of managing an artificial tidal basin (*e.g.*, in the case of La Rance and Cardiff Bay) are high and need careful monitoring and planning. The Canadian plants are noteworthy; there was a well-documented discussion from the start of the operation in these plants about the effects on fish and marine life and how to mitigate them. This information is currently of high value as ecological issues set important requirements and conditions for the permitting of installations in protected water bodies.

On the other hand, the re-opening of dams and barriers, often built between the 1950s and 1970s can have great ecological benefits for the water bodies behind them due to a creation of a gradient that is beneficial to aquatic ecology (brackish water) and an increased oxygen content; in such instances, tidal technology can also be used as a tool for water quantity management, whilst generating power. A more innovative type of tidal range technology, which does not close impoundments completely, is currently in the developmental phase and will also be of interest.

The challenge for tidal stream technologies is different. The ecological impacts are deemed to be less than tidal range technologies, but environmental regulators lack the appropriate expertise or tools to assess the environmental risks (Copping, 2013). Furthermore, baseline data of biodiversity in sea waters is limited, resulting in increased costs for evidence gathering and post deployment monitoring (RenewablesUK, 2013).

Lack of industrial cohesion

The development of tidal stream technologies has been linked to small and micro enterprises, many of which have been spin-offs from university projects. Consequently, there is a lack of cohesion within the industry, with many different designs and a number of small-scale producers. However, large turbine manufacturers such as ABB, Alstom, Andritz, Siemens, and Voith Hydro have entered this emerging sector by becoming involved in the start-up phase. This new interest is creating the conditions necessary to scale up the existing full-scale demonstration turbines into arrays. Since the full-fledged development and operating costs are still not clear, but can be expected to be high, especially during the start-up phase, the projects can become unviable for small and medium enterprises.

Tidal energy still requires investment and R&D to develop and deploy viable and scalable commercial technology and infrastructure, better understand environmental impacts and benefits, and to achieve market entry. Most of the new projects are oriented towards helping bring technologies to a pre-commercial status, promoting easy access to research facilities or supporting the creation of new demonstration sites at sea. There remains a lack of knowledge of many different issues including those on various environmental impacts (*e.g.*, mammal interaction or the impacts on the coastline due to tidal dissipation).

Tidal energy technologies will require similar supply chains to offshore wind and oil and gas. The involvement of large and multi-disciplinary industries can be expected to promote synergies, which will generate economies of scale and reduce costs.

The need for new finance mechanisms

Most project costs for tidal stream technologies are provided through government funds, or by technology developers themselves. Australia, Canada, France, Ireland (SEAI, 2010), South Korea (Hong, Shin and Hong 2010), and the UK have had active policies to support research and demonstration of tidal current technologies (IEA-OES, 2014c). Some countries promote a number of selected projects (*e.g.*, in the Netherlands), while others have started a more active policy on marine energies (*e.g.,* feed in tariffs and requests for proposals in the Canada, France, and the UK). However, it is still difficult to provide the necessary financial framework conditions in the long term (beyond 2020).

The need for new finance mechanisms is particularly relevant for the tidal stream technologies that have been tested at full scale, but will require market pull mechanisms to deploy at scale (Bucher and Couch, 2013). Possible ways of attracting investments could be by offering tax rewards for investors, by attracting end-users, or by feed-in tariffs that would make high-cost, pre-commercial installations more attractive. Furthermore, suitable mechanisms for risk sharing or lowering insurance risks could reduce the overall project costs.

Insufficient grid infrastructure

For tidal stream technologies, grid connections to onshore grids can also be problematic. Some coastal countries, such as Portugal, the Netherlands, Norway, the South West of the UK and some regions of Spain, have high voltage transmission lines available close to shore, but many coastal regions, where the tidal energy resource is available, lack sufficient power transmission capacity to provide grid access for any significant amount of electricity. Equally, a number of open sea test centres have yet to establish grid connections.

Similar problems have been identified for offshore wind. In Europe, the European Commission together with industry and Member States is supporting the devleopment of an integrated offshore grid structure to deliver offshore wind to consumers, notably through the activities of the North Seas Countries Offshore Grid Initiative (NSCOGI). This takes into account the growth possibilities for offshore wind farms and defines options to build a European offshore grid.

However, as its name suggests, this initiative particularly covers the North Sea, which is surrounded by large conurbations and industries. It will be harder to make a case for the less-populated Atlantic coasts which have the greatest potential for tidal energy. Nevertheless, taking into account the needs of tidal energy, as well as wind energy, developing joint projects can be more efficient than retro-fitting. Costs can be shared and the developments of hybrid or multiplatform solutions are encouraged.[6]

Port facilities will also be important for further development. Installation, operation and maintenance (O&M) of marine systems is expensive and even more if this will be performed in highly turbulent and changeable waters. In order to reduce time and cost on O&M, the alternative of unplugging the tidal energy converters from their offshore emplacement and performing the maintenance at a safe and more accessible port facility, is being considered as a real option. This, together with other auxiliary services would need the appropriate space and port facilities, making it necessary to consider the correct planning and management of infrastructure for the coastal areas where tidal energy represents a real energy alternative. Furthermore, a number of open sea test centres have not established grid connections yet.

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[6] Multi-purpose platforms with both tidal stream and offshore wind are also being discussed, however it is should be noted that in most cases offshore wind parks avoid places with strong tides as they increase the cost for mooring the wind turbines.

Planning and licensing procedures

Coastal communities and those engaged in more traditional marine activities tend to be critical of the impact of new, innovative technology. Planning and licensing processes for ocean energy therefore need to be open and comprehensive enough to take these concerns into account. However, in contrast to spatial planning on land, countries generally have limited experience with, and sometimes inadequate governance and rules for, planning and licensing in the marine environment. This is particularly true for sensitive areas in relation to environmental protection and nature conservation. The lack of processes for guidance, planning and licensing marine activities in areas where many different interests (transport, energy, tourism, fisheries, etc.) coincide, tends to increase uncertainty and therefore a risk of delays or failure in marine projects. This can be a barrier to securing investments. Early and adequate involvement of stakeholders is also important under these circumstances. The challenge, for particularly innovative tidal energy projects, is to develop plans, which from the start significantly mitigate any negative environmental effects.

Integrating the technology with other economic and societal functions

Given that tidal range technology is relatively new, most of the projects and work are particularly focused on the technology of the device itself and its direct infrastructure. However, for larger schemes, a connection to other factors such as shipping, recreation, water defence and ecological impact could not only bring down installation costs (by better coordination of infrastructure), but also other types of costs and societal acceptance. This is in part demonstrated through the Norwegian Road Administration (2012).

For tidal stream technologies, there are a number of plans for hybrid systems combining floating offshore wind with tidal current technologies (*e.g.*, a 500 kW demonstration plant by MODEC in Japan). However, in most cases tidal current technologies do not match well with offshore wind parks as the required strong tides increase the installation costs of the offshore wind parks.

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