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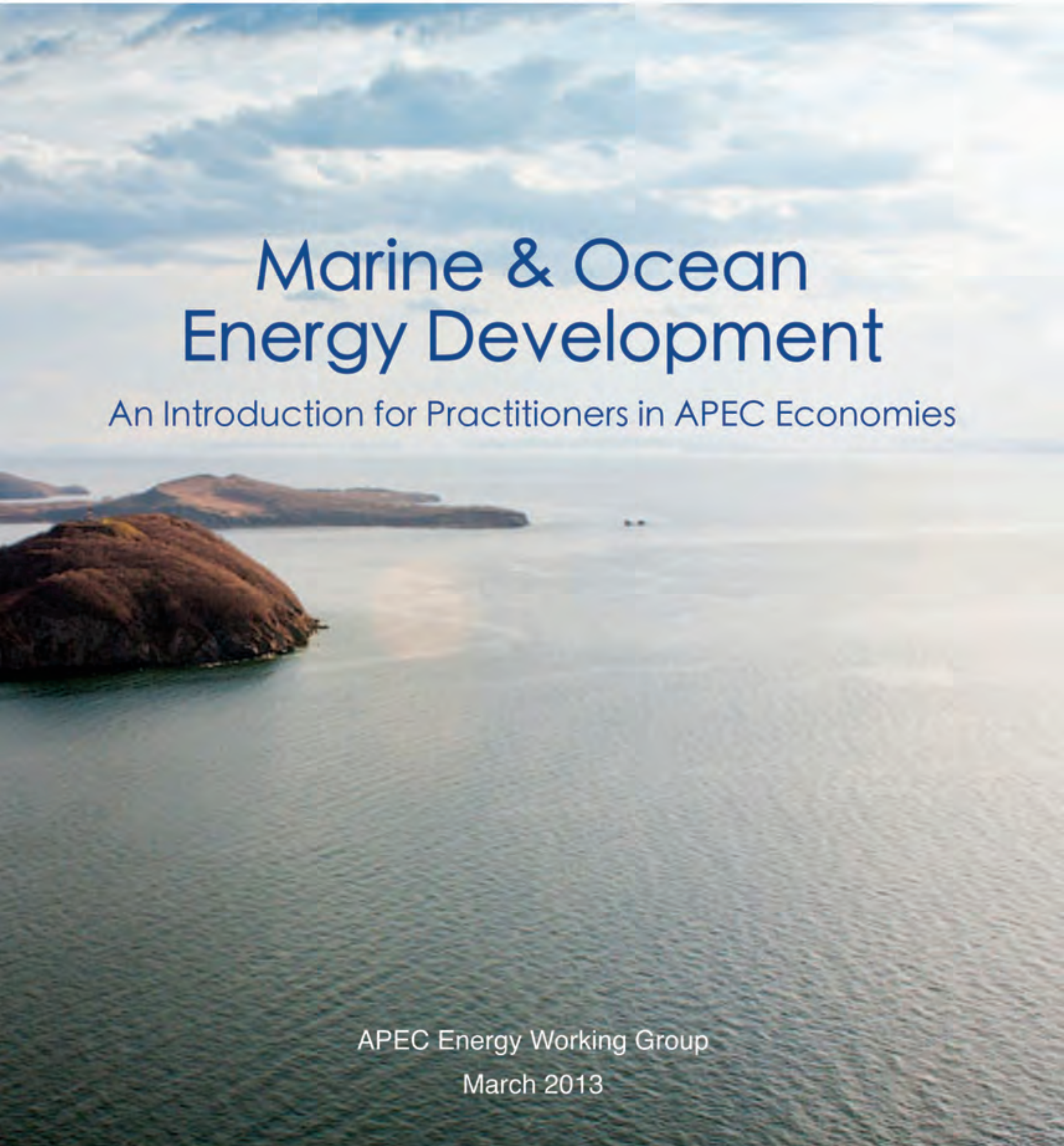

Marine & Ocean Energy Development

An Introduction for Practitioners in APEC Economies

APEC Energy Working Group

March 2013

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APEC Energy Working Group

Expert Group on New and Renewable Energy Technologies

Institute of Lifelong Education, Moscow

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APEC Project No. S EWG 23/2011A
Prospects for Marine Current Energy Generation in APEC Region

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Message from the Project Steering Committee

Tidal stream technology is one of the most recent forms of renewable energy to be developed. Energy originating in tidal and ocean currents appears to be more intense and predictable than other renewables. Large multi-national engineering companies and power equipment suppliers are now entering the emerging global market, seeking to capitalize on the latest technological advances and new funding opportunities to develop commercially viable ways to harness the bountiful supplies of sustainable, indigenous, predictable power present in world's oceans.

For Asia Pacific nations, the Pacific Ocean was historically a vital channel of communication, offering indispensable routes for economic and cultural interchanges, and also its rich biological resource. Nowadays, the ocean can also supply clean energy to most economies on both sides of the Pacific. Indeed, by definition of membership, all APEC member economies have access to this vast energy resource. The available estimates of exploitable tidal stream resource in the APEC region is 11GW of potential capacity or 330TW/h in terms of energy output which may make up ½ to ⅔ of the total world resource. Besides offering green renewable power the emerging tidal power industry will have a sizable spillover effect on job creation, carbon savings and income generation.

Yet many treat marine renewable power as an exotic renewable or are even not aware of the recent developments. To highlight that the interest and investment in the marine power sector has grown rapidly over the past five years with significant advances in the development of commercial scale marine power technologies and projects, we designed and implemented an APEC project "Prospects for Marine Current Energy Generation in APEC Region" (S EWG 23/2011A). We brought in leading developers and consultants to review the most essential topics in tidal stream energy development.

This publication is a summary of presentations made at the project final conference (October 16-17, 2012 – Vladivostok, Russia) and also draws on various most influential reports on marine power. We designed it to raise awareness among the policy makers and energy practitioners in APEC economies of the tidal power resource and opportunities. A wider audience of interested officials and businesses in APEC economies may also benefit from this concise non-technical reading.

We thank the APEC Energy Working Group (EWG), Expert Group on New and Renewable Energy Technologies (EGNRET) and APEC Secretariat for their strong support to this initiative.

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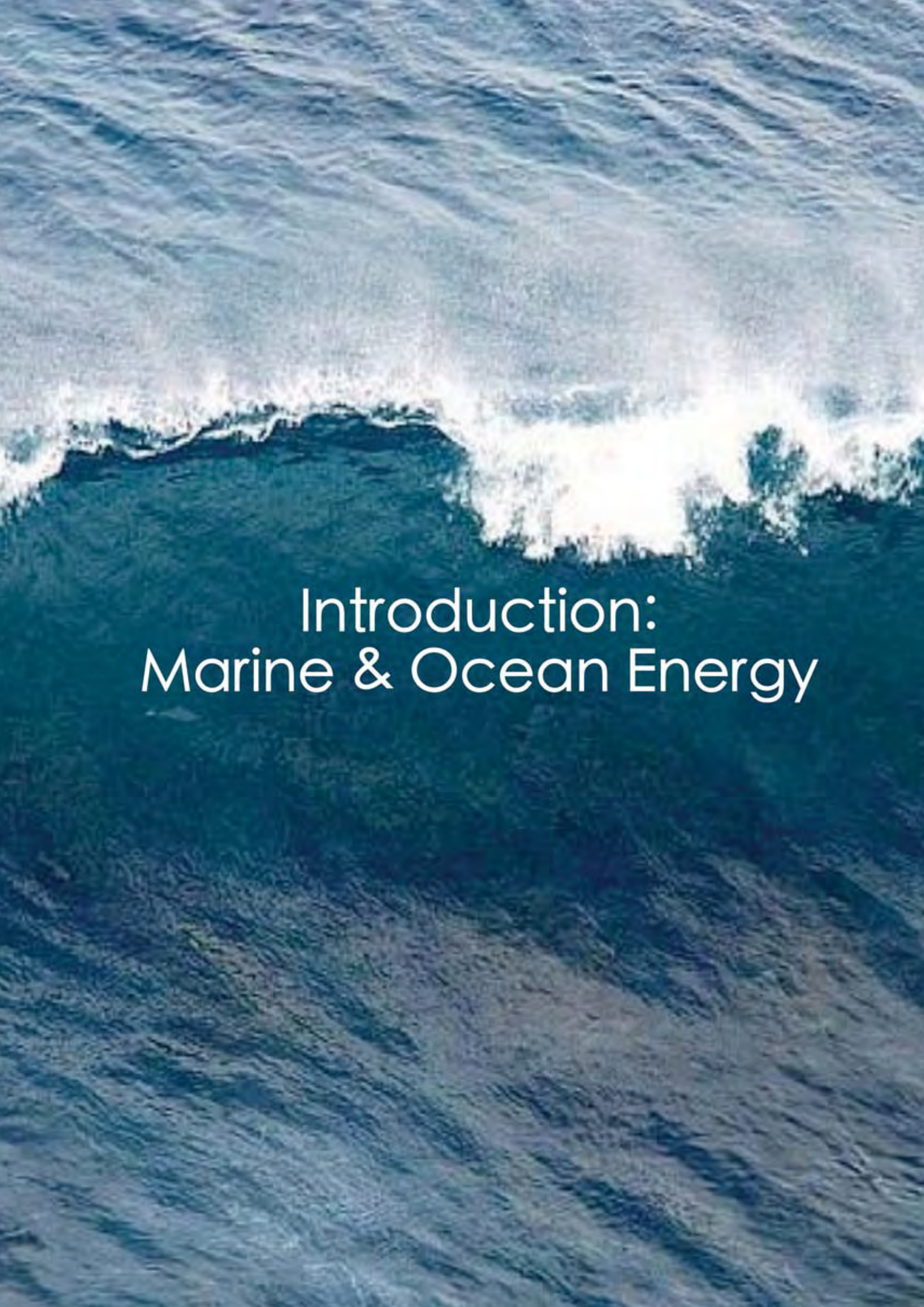


Introduction: Marine & Ocean Energy

Introduction:
Marine and Ocean Energy

This section reviews various types of marine or ocean energy, its benefits and current status of global developments in this sub-sector[1].

Why use marine renewable energy?

More that two thirds of the Earth's surface is covered by oceans which offer huge resource of power and various vital products to coastal markets. Approximately 3 billion people live within 200 km of the coast and migration is likely to cause this number to double by 2025.

As any other type of renewable energy, marine or ocean energy offers a rewarding way to address climate change and security of supply. Tangible benefits include reduced dependence on imported fuels, uninterrupted and affordable energy supply, long term price stability, decoupling from hydrocarbon risk and resource constraint, environmental safety. Some forms of ocean energy will yield alternative products or services: drinking water, heating, cooling and biofuels which may be especially relevant for off-grid remote communities in developing economies. This may lead to emergence of new industries, generation of new jobs and spillover effect throughout the entire regional or national economy.

The ocean resources are vast but not evenly distributed. Wave energy tends to be greatest at higher latitudes, whilst ocean thermal energy is distributed about the equator. Salinity gradients and tidal range are more patchily distributed. The key point is that some form of ocean energy is available at every coast and often more than one form could supply local power needs.

[1] This section draws on Wright (2012a), Legrand (2012a), Ocean Energy Systems (2012a, 2012b).

Vision

According to the Ocean Energy Systems Implementing Agreement, there is the potential to develop 337 GW of wave and tidal energy worldwide by 2050 and possibly as much again from ocean thermal energy conversion. Developments will be in locations with high resource availability. Under this scenario, the cumulative rate of growth to 337 GW of installed wave and tidal energy between 2030 and 2050 is comparable with the growth of offshore wind over the last 20 years.

Deployment of ocean energy can provide significant benefits in terms of jobs and investments. Available estimates reveal that 1.2 million direct jobs could be supported by the ocean energy sector by 2050.

The global carbon savings achieved through the deployment of ocean energy are also thought to be substantial: nearly 1 billion tonnes of CO_2 by 2050.[1]

Status

During 2011 the installed capacity of all types of ocean energy more than doubled due to the commissioning of the Sihwa Lake Tidal Power Plant, near Seoul, Korea, in August 2011 and totalled around 550 MW. While the ocean energy now is overwhelmingly represented by large-scale tidal barrages (some built in 1960s), the future capacities are expected to explore new types of ocean power generation, including tidal streams, ocean thermal energy conversion and salinity gradients.

Tidal range (barrage)

Tidal barrages are usually developed at estuary locations and use the change in tide levels to generate electricity from potential energy of falling water. This is the oldest and most commercially exploited type of marine energy. Two large scale barrages are

[1] Estimates from Ocean Energy Systems (2012b).

Table 1

Status of Global Ocean Energy Development

Type of technology	Stage of development	Installed or tested capacity, location	Theoretical potential, worldwide
Tidal range (barrage)	Large commercial scale development, but low future prospects due to adverse environmental impact	France (240MW), Korea (254MW), Canada (20MW), China (11MW)	1,200 TWh/ year
Tidal stream	Few pilot projects, full-scale demonstration, including one commercial prototype	Mostly UK (4.8MW)	470 TWh/ year
Wave power	Few pilot projects, full-scale demonstration	Mostly UK (2MW), but also smaller scale in Portugal, Spain, Denmark, Sweden, New Zealand	29,500 TWh/year
Ocean thermal energy	Experimental	US (Hawaii) and Reunion/France	44,000 TWh/year
Salinity gradient power	Laboratory scale	Norway (4kW)	1,650 TWh/ year

Source: Ocean Energy Systems (2012a), Wright (2012a), Legrand (2012a).

in operation in France (La Rance River Estuary, built in 1966, 240MW) and in the Republic of Korea (Sihwa Lake near Seoul, open in 2011, 254MW).

Barrages largely fell out of favour in 1980s due to perceived environmental impact (e.g. loss of mudflats) and high capital costs. The largest project of the Severn Barrage at Severn River estuary, UK of 7,500MW total capacity, 16 km total barrage length and US $30 billion estimated cost was rejected in 2010 as uneconomical.

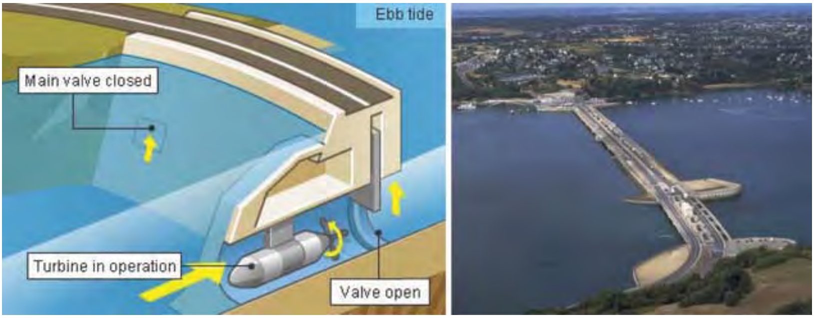


Figure 1. Tidal range: how it works (left) and La Rance tidal barrage (right)

Source: http://www.worldcolleges.info/Science-Tech/tidal-barrages.php; http://mhk.pnnl.gov/wiki/index.php/File:La_Rance.jpg

Some APEC members have built smaller scale tidal barrages: Canada (Annapolis Royal, 20MW), China (7 tidal plants with a total capacity of 11MW including Jiangxia of 3.9 MW), Korea (Uldolmok, 1MW) and Russia (pilot plant in Kislaya Bay, 0.4MW).

Tidal stream (tidal currents)

The movement of ocean water volumes, caused by the tidal cycle, creates kinetic movements. The resulting tidal current energy can be harnessed, usually nearshore and particularly where there is constraining topography, such as straits between islands.

Producing energy from tidal currents generally requires smaller, mostly sub-marine units which entail much lower environmental impact. There are various advantages over tidal barrages, but the tidal current devices are still in development. The 1.2 MW SeaGen, located in Northern Ireland's Strangford Lough, is the only tidal current turbine anywhere in the world to feed power regularly into a local electricity grid on a commercial basis. A number of full-scale prototypes were also installed at the European Marine Energy Centre (EMEC) in Orkney, UK, at Fundy Ocean Research Centre for Energy (FORCE) in Canada, Lofoten in Norway and Paimpol-Brèhat tidal farm in France.

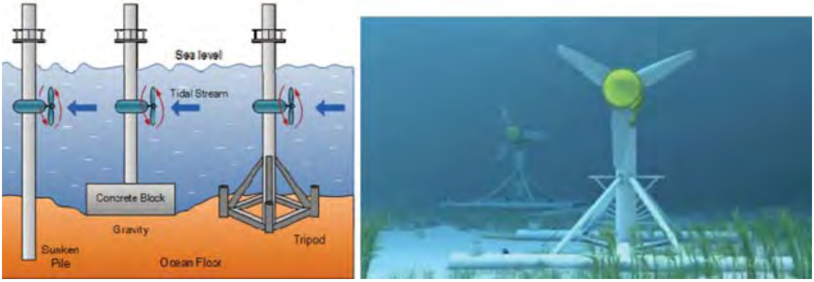


Figure 2. Tidal current devices

Source: http://www.alternative-energy-tutorials.com/tidal-energy/tidal-stream.html, http://voith.com/en/markets-industries/industries/hydro-power/ocean-energies-539.html

Tidal current energy as probably the most practical resource will be discussed in more detail in next sections.

Wave power

Waves can provide a completely sustainable source of energy. Wave power captures kinetic and potential energy from ocean waves to generate electricity. There are many methods to harness wave energy and even more wave energy devices that could be developed. But there is little consensus about the preferred design for wave energy converters. Familiar devices include: terminator, attenuator, point absorber, overtopping device, oscillating water column, oscillating wave surge. Due to the diverse nature of the wave resource it appears likely that there will be a small variety of device types to be exploited in different regions.

Two best known full-scale prototypes are P1 and P2 machines by Pelamis Wave Power (attenuator, uses hydraulic rams to drive generator) and the Oyster device by Aquamarine Power (point absorber, uses a pitch movement to extract energy from the surge motion of the waves and a high pressure hydraulic system linked to an onshore hydro power station), both deployed at the EMEC, UK.

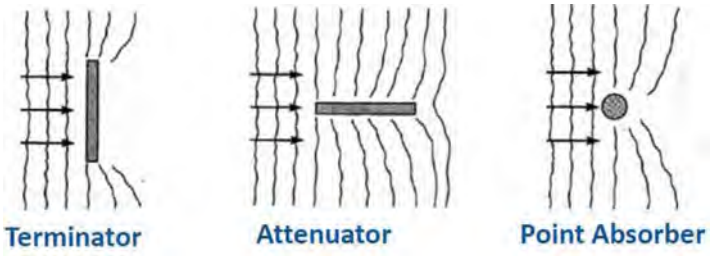


Figure 3. Several types of wave technology

Source: Legrand (2012a)

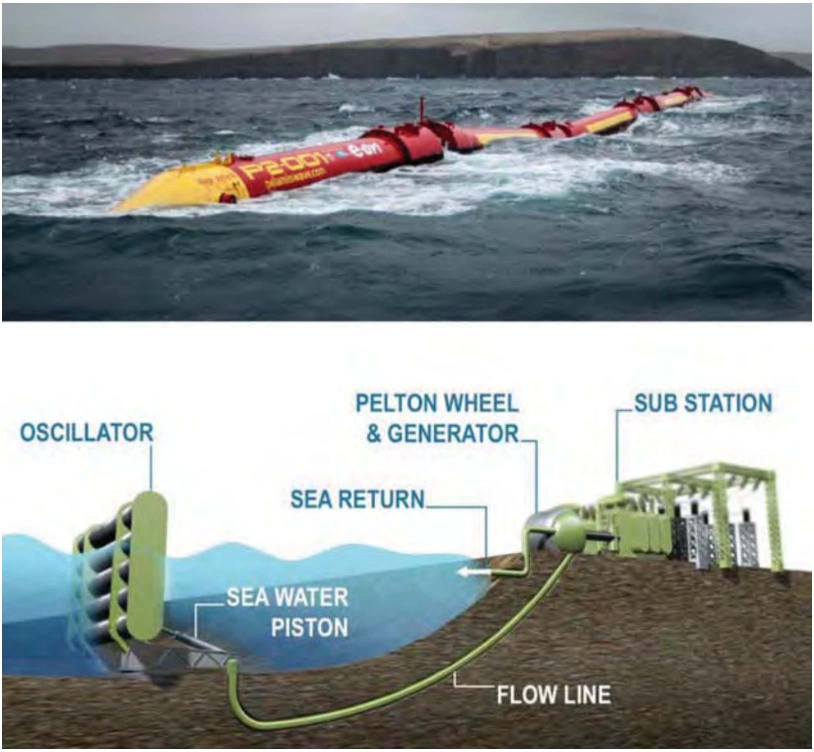


Figure 4. Pelamis Wave Power P2 Machine (top) and Oyster device by Aquamarine Power (bottom)

Source: EMEC Gallery, http://www.emec.org.uk/about-us/media-centre/gallery/, Legrand (2012a)/Aquamarine Power

Ocean thermal energy

Ocean thermal energy arises from the temperature difference between hot surface water and cold bottom water. The temperature of deep ocean water tends to be relatively constant at about 4° C while surface water may be more than 20° C hotter. Pumping

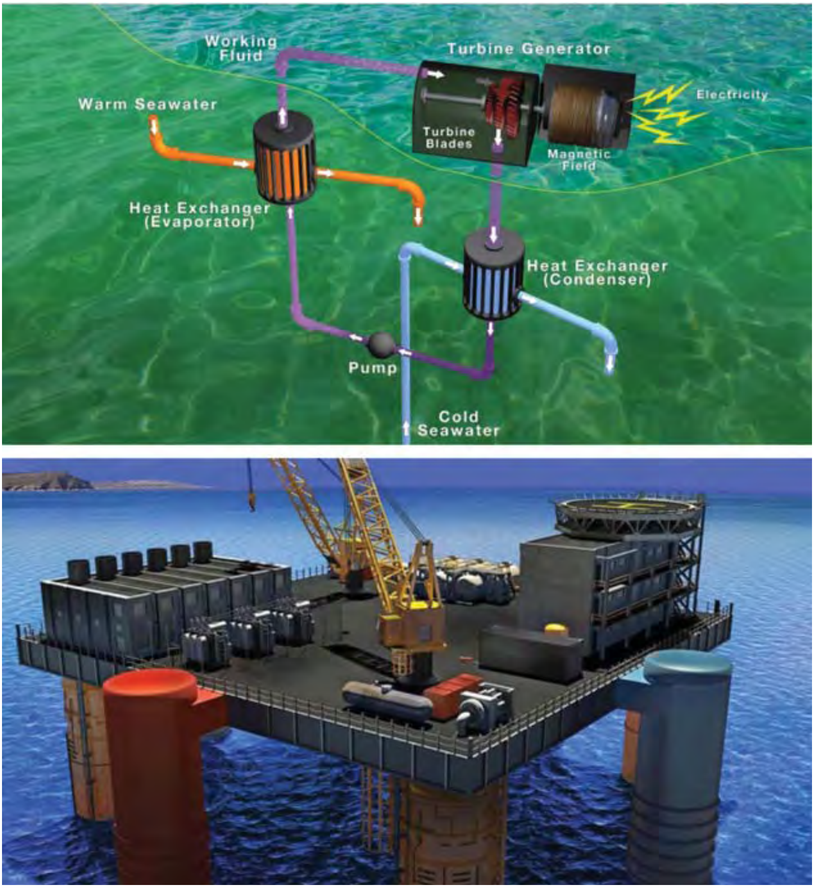


Figure 5. A diagram of an OTEC system (top) and an artist's impression of Lockheed Martin's Hawaii OTEC pilot plant (bottom)

Source: http://www.lockheedmartin.com/us/products/otec.html large quantities of this cold seawater to the surface enables a heat exchange process with the warmer surface waters, from which electricity can be generated.

High resource potential for ocean thermal energy conversion is in the Pacific area. This type of marine energy is technically feasible, but it's not yet understood whether it can be economically viable. Technology is currently under test in Hawaii (US) and Reunion (France) islands.

Salinity gradient (osmotic pressure) power

Seawater is approximately 200 times more saline than fresh river water. The relatively high salinity of seawater establishes a chemical pressure potential with fresh river water, which can be used to generate electricity. Salinity gradient power thus has its greatest potential at the mouths of major rivers, where large volumes of fresh water flow out to sea.

The world's first experimental osmotic power plant with capacity of 4 kW was opened by Statkraft in November 2009 in Tofte, Norway. The operation of the plant has proven that power from salinity gradients can supply a stable base load of renewable energy, with a minimal ecological footprint.

Countries involved in ocean energy and international initiatives

Since 1960s when first commercial tidal power plants were open, there have been significant advances in the development of commercial scale marine power technologies and projects. More countries built their competencies in marine power engineering and contributed to establishing a nascent market for this sector.

While the interest towards ocean or marine energy is growing internationally, it still remains an emerging technology area and will continue to benefit from international collaborations. One such authoritative mechanism is under the Ocean Energy Systems Implementing Agreement (OES).

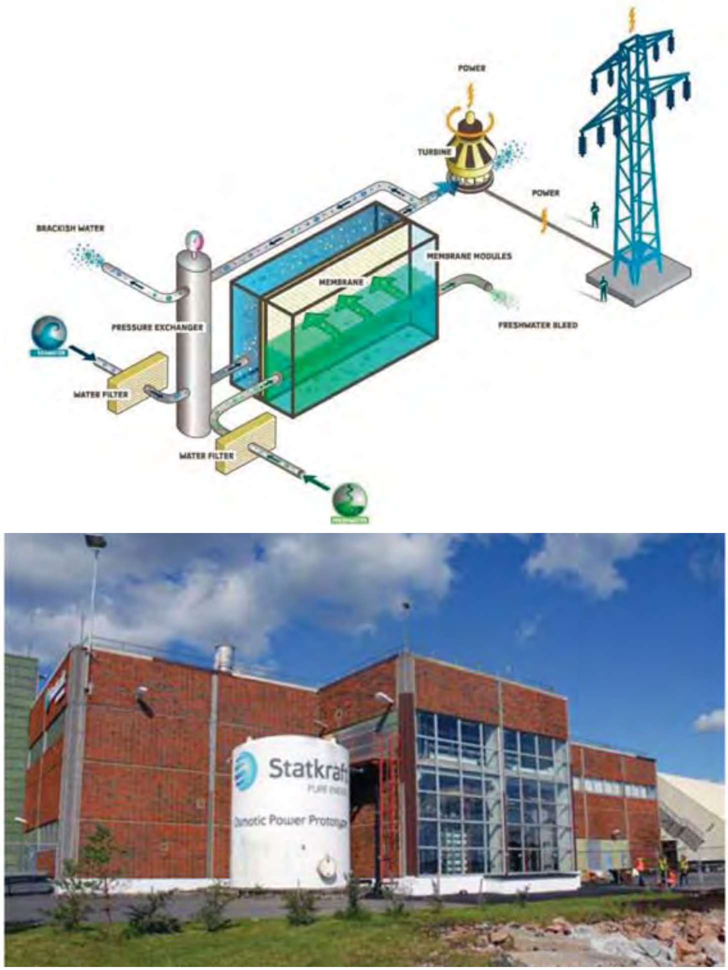


Figure 6. Osmotic pressure power system (top) and Statkraft's osmotic prototype at Tofte outside Oslo (bottom)

Source: Progress in the Development of Osmotic Power.
Presentation at the 2011 Quingdao International Conference on Desalination and Water Reuse by Werner Kofod Nielsen, Senior Advisor, Statkraft http://www.statkraft.com/Images/Osmotic%20Power%20Presentation%20Quingdao%20June%202011_tcm9-19287.pdf;
http://www.statkraft.com/energy%2Dsources/osmotic%2Dpower/prototype/

The OES is an intergovernmental collaboration between countries to advance research, development and demonstration of technologies to harness energy from all forms of ocean renewable resources where seawater forms the motive power, such as tides, waves, currents, temperature gradient and salinity gradient for electricity generation, as well as for other uses, such as desalination, through international co-operation and information exchange. OES operates under a framework established by the International Energy Agency in Paris as one of ten “Implementing Agreements” in Renewable Energies and Hydrogen.

The OES was initiated by three countries in 2001. As of March 2013, 20 countries are members of the OES: Portugal, Denmark, United Kingdom, Japan, Ireland, Canada, the United States of America, Belgium, Germany, Norway, Mexico, Spain, Italy, New Zealand, Sweden, Australia, Republic of Korea, South Africa, China and Nigeria ordered by sequence of joining the Agreement.

OES advocates an “International Vision for Ocean Energy”, which sets out the present status of the industry, benefits, cost trends, policies, markets, challenges and opportunities for ocean energy to 2050.

As the OES membership shows, APEC member economies play a visible role in exploring and promoting marine power. Given the huge resource available along the Pacific coasts of many APEC members, they are natural stakeholders. More APEC economies have been invited to join the OES: Chile, Indonesia and Russia.

Tidal Stream Energy: Overview of Global Resource & Technology Development

Tidal Stream Energy: Overview of Global Resource and Technology Development

This and the following sections focus on the tidal stream energy. We cite available estimates of tidal resource and review the technology development, including the first tidal turbines in commercial operation and some of the latest innovations[1].

The resource

The existing estimates of the global tidal stream potential should be treated with caution, especially in comparison to other types of marine energy, because theoretical and extractable resources do not equal. However, the available resource is now better understood, and is significant, at 470 TWh/year in terms of expected output (Wright 2012a, see Figure 7). Other estimates of the total capacity of potential extractable tidal stream resource range from 25GW (Cornelius 2012) to 120GW.

Specific challenges need to be considered to develop technology that harnesses energy from tidal stream and marine currents. The sea is a harsh and aggressive environment, marine renewable energy is diffuse and uneasy to collect, and finally, the energy needs to be brought ashore. All these impose special requirements on the equipment and raise costs of the generating devices. Demonstrable progress has therefore been limited to a handful of developers who were able to secure both private and public funding. However, tidal stream energy extraction technology is currently more mature than most other forms of ocean/marine

[1] This section draws on Cornelius (2012), Carbon Trust (2011), Blair (2011a), Wright (2012a, 2012b), information from EMEC website.

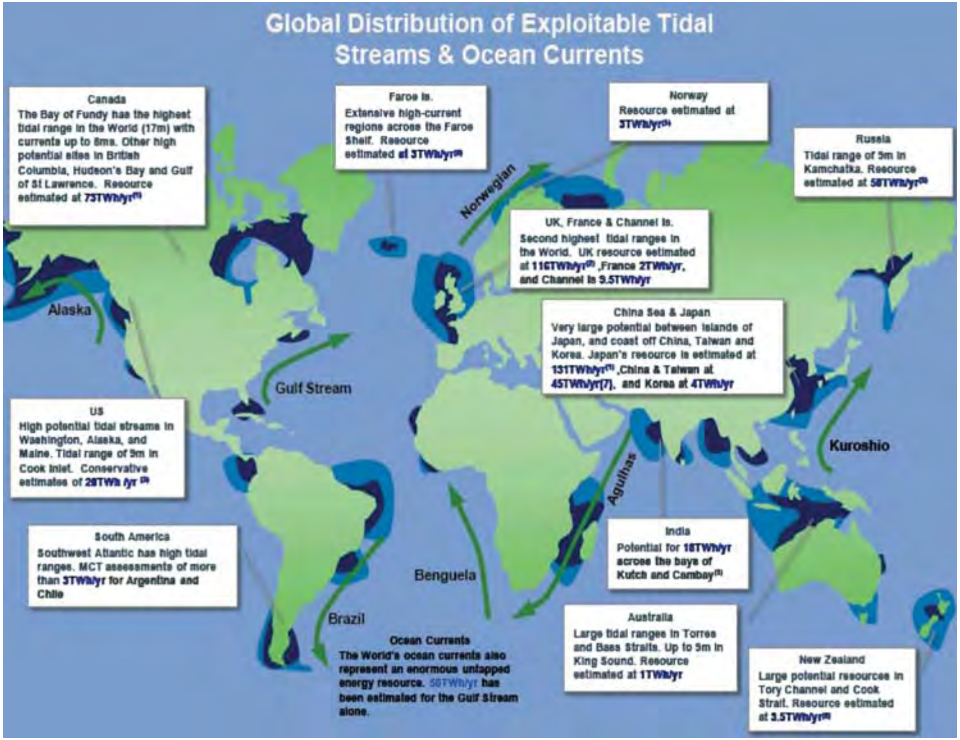


Figure 7. The Global Distribution of Exploitable Tidal Streams and Ocean Currents

Source: Wright (2012a).

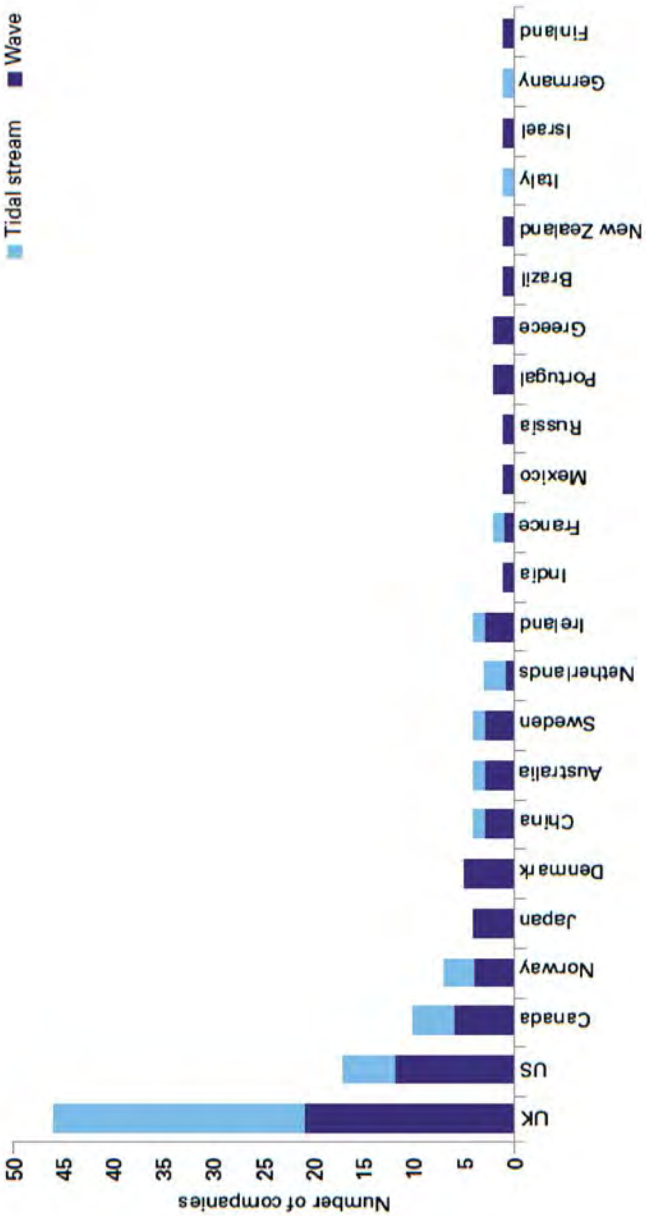


Figure 8. Indicative global wave and tidal activity

Source: Carbon Trust (2011), P. 5.

energy technologies, and there are more developers at full-scale demonstration stage. Figure 8 captures the global status of wave and tidal current energy technologies as at 2011.

According to Carbon Trust, there has been a shift away from reliance on venture capital money to fund the early stage of the industry, with major industrial companies and utilities taking equity stakes. Some key industrial players, including electricity utilities and equipment manufacturers, are developing in-house technologies, while others have bought into existing marine energy technology. The involvement of these key industry players, and the associated injection of significant funding, is an encouraging sign for the marine energy industry. Notable examples of direct investment by industrials in technology development companies include ABB and SSE's investments in Aquamarine Power, EDF Energy and Siemens' investment in Marine Current Turbines, Voith Hydro in-house development of hydro turbines, Rolls-Royce's purchase of Tidal Generation and Alstom acquiring stakes in AWS Ocean Energy and Clean Current power systems.

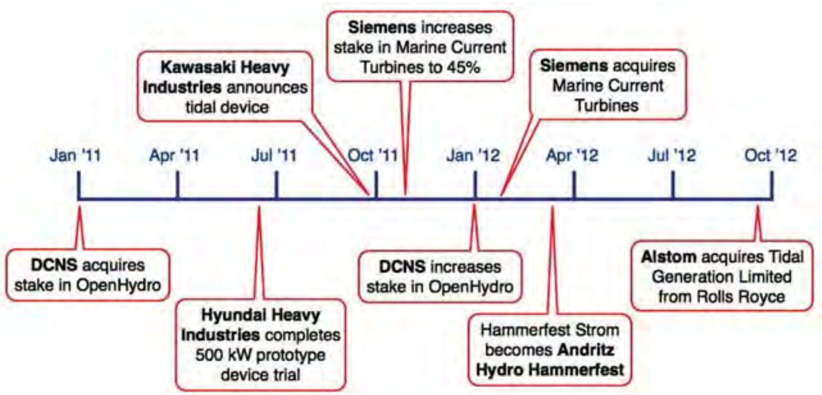


Figure 9. Recent activity of Original Equipment Manufacturers in Tidal Stream Energy

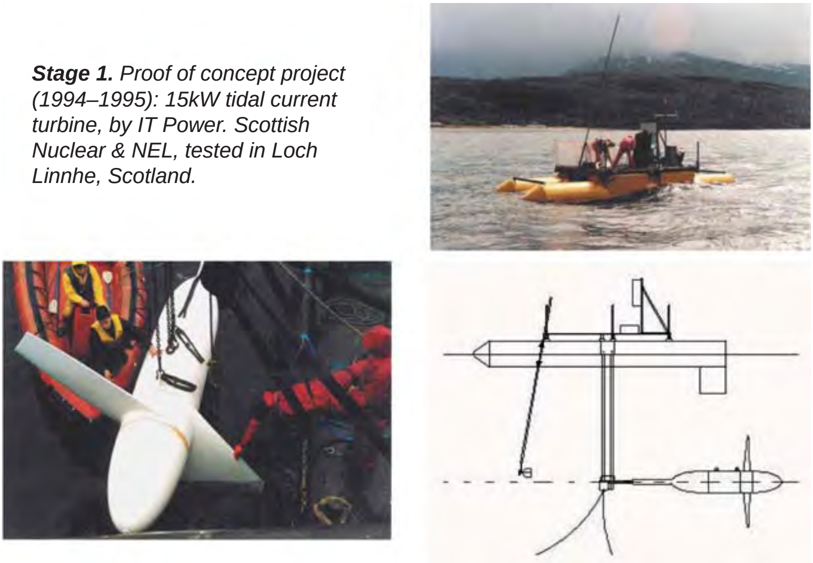
Source: Cornelius (2012).

Technology development path for tidal stream energy

Tidal turbines are very much like an underwater windmill where the blades are driven by consistent, fast-moving currents. Tidal turbines are installed on the seabed at locations with high tidal current velocities, or strong continuous ocean currents. Tidal streams, unlike many other forms of renewable energy, are a consistent and predictable source of kinetic energy caused by regular tidal cycles.

The submerged rotors harness the power of the tidal streams to drive generators, which in turn produce electricity. Water is 832 times denser than air, so consequently tidal turbine rotors can be much smaller than wind turbine rotors generating equivalent amounts of electricity, and they can be deployed much closer together.

The UK became the prime mover in the tidal energy sector and paved the way for the development and tests of world's first operational tidal turbines.



Stage 1. *Proof of concept project (1994–1995): 15kW tidal current turbine, by IT Power. Scottish Nuclear & NEL, tested in Loch Linnhe, Scotland.*

Figure 10. World's first tidal current turbine

Source: Wright (2012b).

Stage 2. *World's first full-size offshore tidal current turbine 2003: Seaflow, by Marine Current Turbines, 11m rotor diameter & 300kW, deployed in Lynmouth, UK.*

Figure 11. Seaflow, world's first full-size offshore tidal current turbine

Source: Wright (2012b).

SeaGen, installed in Strangford Lough, Northern Ireland in 2008, was the first marine renewable energy project to be accredited by OFGEM as a commercial power station and regularly runs at full rated power.

Stage 3. *First tidal turbine accredited by the UK Office of the Gas and Electricity Markets (OFGEM): SeaGen, by Marine Current Turbines, 1.2MW at 2.4m/s, operational since summer 2008*

Figure 12. SeaGen Tidal Turbine, test assembly, 2007

Source: Wright (2012b).

Figure 13. Crane Barge Rambiz arriving in Strangford Lough in late March 2008 to commence the installation of SeaGen (left). Drilling and grouting operations, carried out from temporary work platform (right)

Source: Wright (2012b).

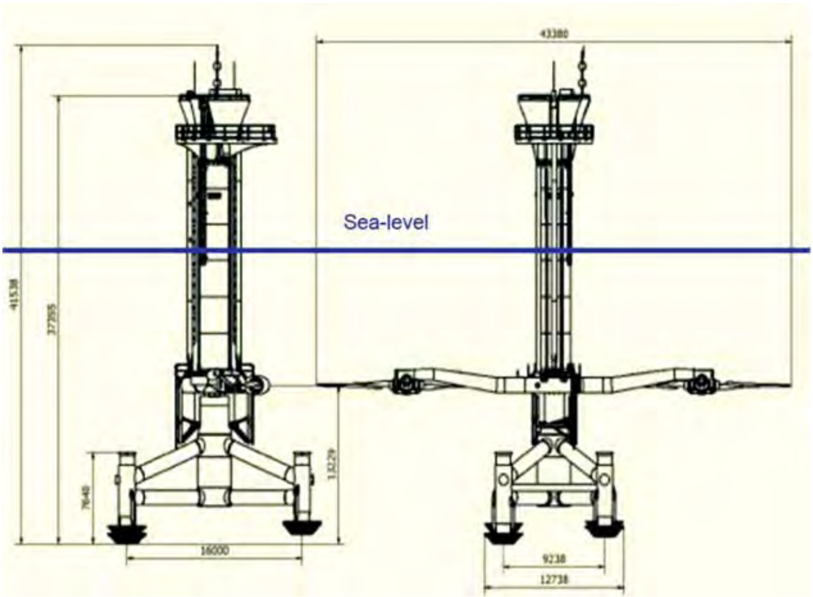


Figure 14. SeaGen layout

Source: Wright (2012b).

The SeaGen system consists of twin power trains mounted on a crossbeam. The cross beam can be raised above the water for routine maintenance by winching it up the monopole support structure. SeaGen is suitable for marine environments in water depths up to 38 m and achieves rated power in tidal currents of greater than 2.4 m/s.

Figure 15. Maintenance of SeaGen: Most maintenance and repair functions can be completed rapidly, using no more than small service vessels. Here: fitting a new rotor blade

Source: Wright (2012b).

The 1.2MW SeaGen is capable of delivering up to 10 MWh per tide in Strangford, which totals up to 6,000 MWh per year. This is approximately the rate of energy capture of a 2.4 MW wind turbine. Tidal energy is therefore more predictable than wind and potentially twice as productive.

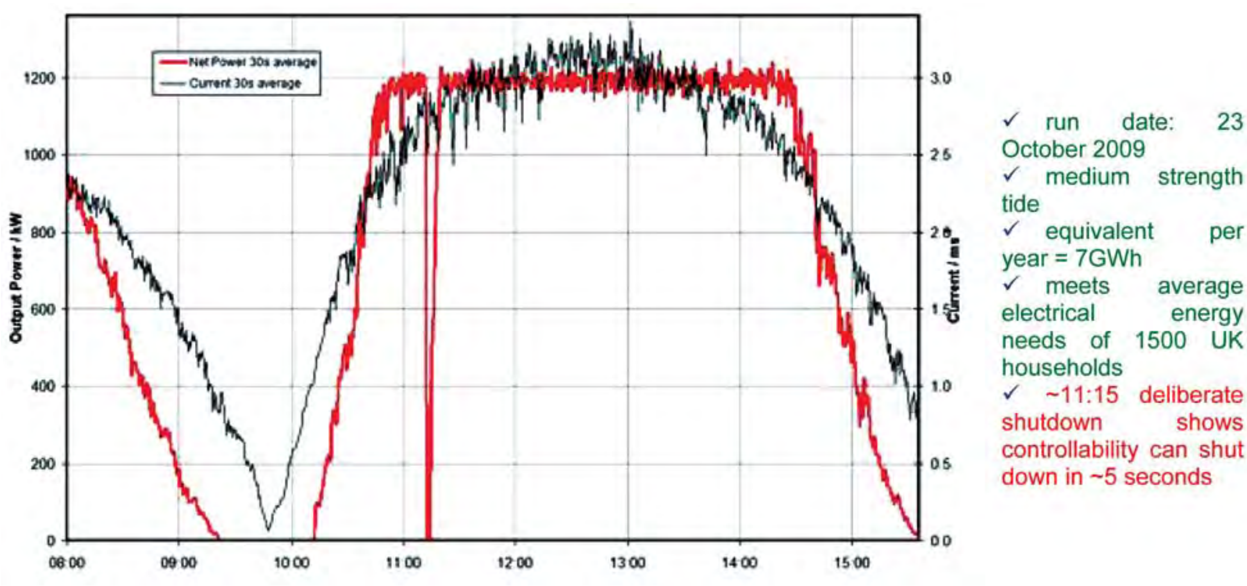


Figure 16. SeaGen delivers …. ~10 MWh per tide

Source: Wright (2012b).

Tidal devices are approaching a convergence of design, with most concepts based on a bottom-mounted horizontal axis turbine. A number of developers have recently deployed their full-scale grid-connected prototypes mostly at the EMEC, UK or FORCE Centre, Canada.

Hammerfest Strøm in Norway was one of the first developers of tidal turbines and is today part of the ANDRITZ HYDRO GmbH group, a global supplier of electro-mechanical equipment and services for the hydropower business. In December 2011, ANDRITZ HYDRO Hammerfest successfully deployed its 1 megawatt (MW) pre-commercial tidal turbine at EMEC's tidal test site, and has been testing it since then in order to validate the technology for future tidal power arrays. The device delivered its first energy to the grid in February 2012.

Based on the learning gained during its testing period at EMEC, ANDRITZ HYDRO Hammerfest will further develop the technology and plan to deploy a 10MW commercial array in the Sound of Islay, UK.

Rated capacity	*1.2MW (gross)*
Swept area	*300 – 500 m²*
Control	*Variable speed, variable pitch (280°)*
Weight (nacelle, substructure)	*130t, 150t*
Ballast (at EMEC)	*800t*
Foundation type	*Gravity or pinned*
Water depth	*45-100 m*
Installation	*Heavy Lift Vessel / barge*
Service life	*25 years*
Rated service interval	*5 years*

Figure 17. Andritz Hydro – Hammerfest (Germany – Norway) HS1000 tidal turbine 1MW at 2.7m/s, deployed at the EMEC

Source: http://www.mediatechnical.com/pressReleases.php?pr_id=205 (image), Wright 2012b (specifications)

Tidal Generation Ltd, a UK-based company, now a wholly owned subsidiary of Alstom, has developed a next generation 1 MW tidal stream turbine in a project partnership with the Energy Technologies Institute (ETI), known as Project ReDAPT (Reliable Data Acquisition Platform for Tidal). This project aims to collect and publish significant data in order to further the tidal energy industry as a whole.

The company then plans to install a 10 MW demonstration array in 2013-2014 in UK waters as a precursor to full commercial production, with the technology earmarked to be deployed in a commercial array in the Inner Sound of the Pentland Firth as part of the 400 MW MeyGen project.

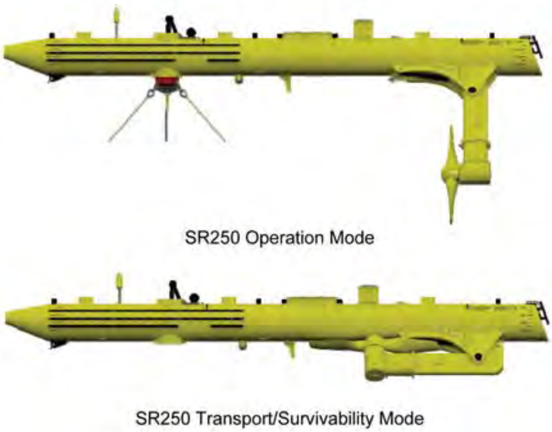
Rated capacity	*1MW*
Water speed, rated	*2.7 m/s*
Water speed, maximum	*3.4 m/s*
Rotational speed	*14rpm*
Rotor diameter	*18 m*
Turbine length	*21 m*
Service life	*30 years*
Rated service interval	*2 years*
Turbine weight, incl. seabed support	*135 t*
Water depth	*43-80 m*

Figure 18. Tidal Generation Ltd / Rolls Royce (UK) tidal turbine 1.0MW at 2.7m/s, deployed at the EMEC

Source: Wright (2012b).

Scotrenewables Tidal Power Ltd developed a tidal turbine which is a unique floating tidal technology designed to minimise installation and operational costs. The device hosts two propellers which fold up while being towed. The system has been extensively trialled through a 250kW prototype, the SR250, successfully connected to the UK national grid at the end of March 2011 and is currently in a two-year test programme.

Scotrenewables are in the process of developing a larger 2MW 'commercial scale' turbine more suited for tidal array deployment. This project will be developed in two phases with an initial 10MW array planned to be installed by 2017.



Design type	*Floating design, compliant mooring system*
Rated capacity	*250 kW*
Length	*33 m*
Tube (body) diameter	*2.3 m*
Rotor diameter	*8 m*
Control	*Variable speed, fixed pitch rotors*

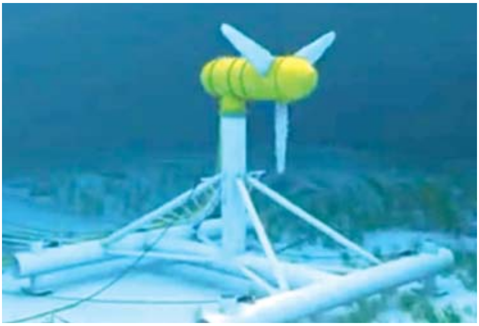
Figure 19. Scotrenewables SR250 (UK) floating tidal turbine 250 kW, deployed at the EMEC

Source: http://www.scotrenewables.com.

Voith Hydro is a subsidiary of the Voith Group, and is a leading supplier of hydropower equipment and services, having manufactured around a third of all hydroelectric turbines and generators.

The company is currently assembling a 1MW commercial size demonstrator. The 1MW horizontal axis turbine – HyTide – which is 13m in diameter and weighs 200 tonnes is due to be installed in 2013. The turbine is being designed to be simple, sturdy and low-maintenance, and a 1:3 scale prototype has been successfully tested in Jindo, Korea.

Atlantis Resources Corporation which is a vertically integrated marine renewable power company developing tidal power generation technology for commercial deployment globally



Rated power	*1MW (at grid connection)*
Diameter	*13 – 16 m*
Rated speed	*2.8 m/s*
Rotational speed	*0-55rpm*
Nacelle weight	*200t*
Water depth	*up to ~100 m, on drilled mono tower*

Figure 20. Voith Hydro (Germany) 1.0MW at 2.8m/s tidal turbine, deployed at the EMEC, 110kW scale model tested in Korea

Source: http://voith.com/en/markets-industries/industries/hydro-power/ocean-energies-539.html

deployed its AR1000 tidal turbine at EMEC in summer 2011. Following prototype testing, the company is planning large-scale commercial deployment in the Pentland Firth on the MeyGen project, as well as on several other commercial scale tidal project sites in Asia & North America.

Rated power	*1MW*
Diameter	*18 m*
Total height	*22.5 m*
Rated speed	*2.65 m/s*
Weight (nacelle, substructure)	*140 t*
Weight (gravity base)	*1,300 t*

Figure 21. Atlantis Resources Corporation (UK) AR1000 1.0MW at 2.65 m/s tidal turbine, deployed at the EMEC

Source: David Moir / Reuters (image), EMEC and Atlantis Resources Corporation websites (specifications)

Tokyo-based Kawasaki Heavy Industries has been developing a tidal stream energy converter in-house since 2010 and plans to begin testing their device at EMEC in 2013-2014. The device will be a sea-bed mounted horizontal axis 1MW machine.

Figure 22. Kawasaki Heavy Industries (Japan) 1.0MW

Source: http://www.hydro-international.com/news/id5183-MW_Prototype_for_Kawasaki_Tidal_Project.html (image)

Figure 23. Open Hydro / EDF project: a single 16m turbine rated at 2MW followed by an array of grid-connected units, deployed at Paimpol-Brèhat tidal fram in Brittany, France

Source: http://energie.edf.com/hydraulique/energies-marines/carte-des-implantations-marines/parc-hydrolien-de-paimpol-brehat/presentation-51512.html (image)

Dublin-based Open Hydro has been testing various open-centre turbines at EMEC and FORCE since 2006. It is currently progressing with a tidal array project in Brittany, France aiming to deploy four 16m tidal turbines, in partnership with Électricité de France (EDF), the largest French electric utility.

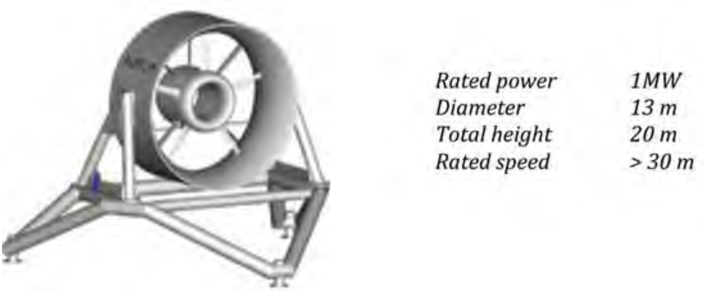


Figure 24. Alstom/Clean Current (France/Canada) BELUGA 9 machine, 1.0MW at 4.5 m/s

Source: Wright (2012b).

Figure 25. Tidal Stream 3MW "Triton" under development by TidalStream, backed by Schottel (Germany)

Source: http://www.tidalstream.co.uk/

To sum up, the industry moves from full-scale prototype stage to first arrays. The key challenge facing the marine energy industry is now lowering the cost of energy generation which will be briefly discussed in one of the next sections.

Project Development

Project Development

This section explains the basic principles of the marine tidal project development process, including due diligence. One feasibility study for the San Francisco Bay Area is briefly reviewd as a reference case[1].

Main issues in the project development process

Even if a mature technology is available, translating it into an economically sound extraction of marine energy requires a careful project development process. Given the complexity of the operation of marine power devices and the requirement for ad hoc technology solutions in many cases, there are perhaps even more challenges that need to be addressed.

Typical project development process can be classified into the following activities:

- Feasibility Study
- Consenting process
- Data Collection
- Technology assessment and choice
- Project engineering
- Grid design and connection

Feasibility studies are essential for due diligence and look at the costs, risks and benefits of a project through various dimensions: technical, economic, environmental, societal, legal. A core objective is to estimate the cost of energy using various assumptions, models and available data. The best practice is to obtain an independent estimate which may or may not be based on developer's method.

[1] This section draws on Wright (2012c) Legrand (2012b).

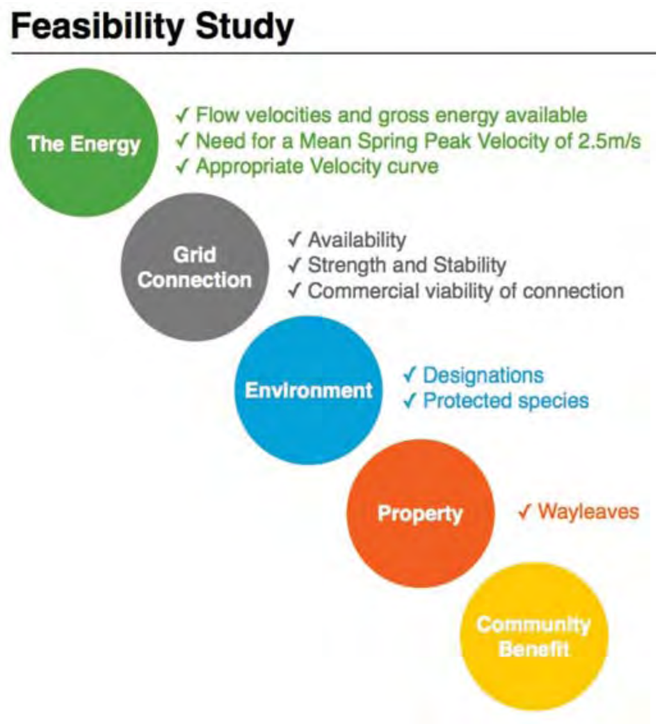


Figure 26. Main issues in a feasibility study of a marine energy project

Adapted from Wright (2012c).

Information collected on-site is required to validate the estimates and refine the design. This includes: bathymetry/topography data, geotechnical conditions (design parameters), water levels (tide levels/storm surge), current velocities (tidal stream/wind generated), wave data (recorded data/extreme waves) etc.

Marine energy converters are complex machines operating in an aggressive environment. In terms of selecting technology, it is essential to consider the following engineering disciplines: mechanical, electrical, structural, control systems and civil support (support structure/mooring system).

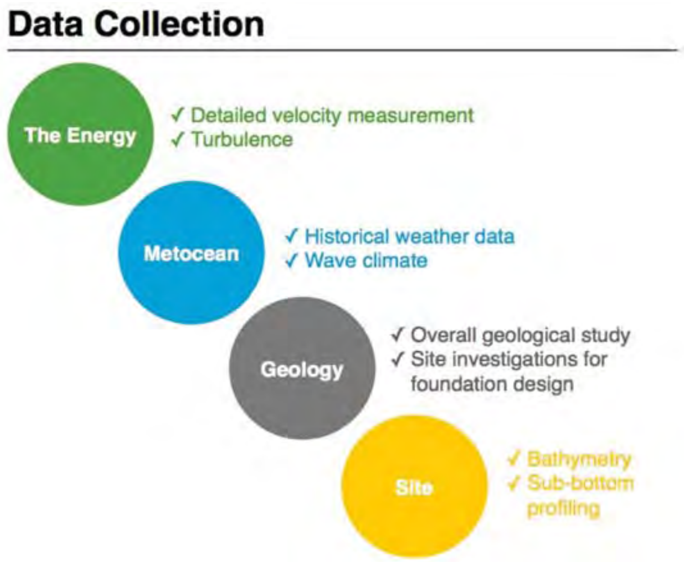


Figure 27. Data collection

Adapted from Wright (2012c).

Some technology shortcomings can be identified by deploying a full scale device which leads to more R&D, more delays and more expenditure. Critical parameters to be examined are therefore 'Survivability' & 'Availability' of the device: identifying all possible failure modes, considering short term extreme loads and long term cyclic loads (fatigue), enhancing the reliability of components (use proven 'off the shelf', innovation, testing) etc.

Funding is a challenge for developers of tidal current power, as the latter is less established than many other technologies. And there's only a limited amount of public funding for development and research for all marine energy technologies.

Ultimately, funding is a risk-reward balance which allows both investors and developers to understand their opportunities.

In sum, due diligence is important:

- for developers, because it helps to independently assess the feasibility of every task in technology & project development;

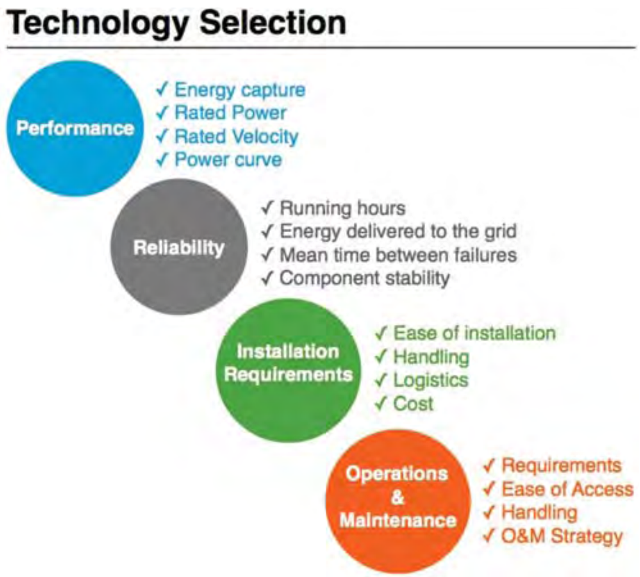


Figure 28. Technology selection

Adapted from Wright (2012c).

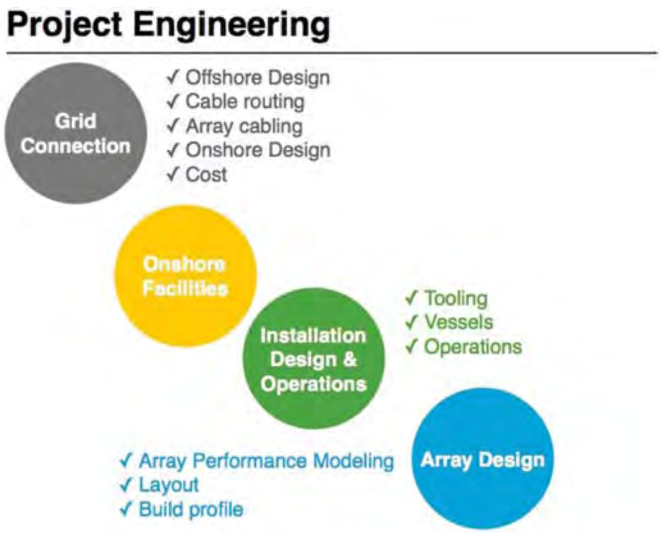


Figure 29. Marine Energy Project Engineering

Adapted from Wright (2012c).

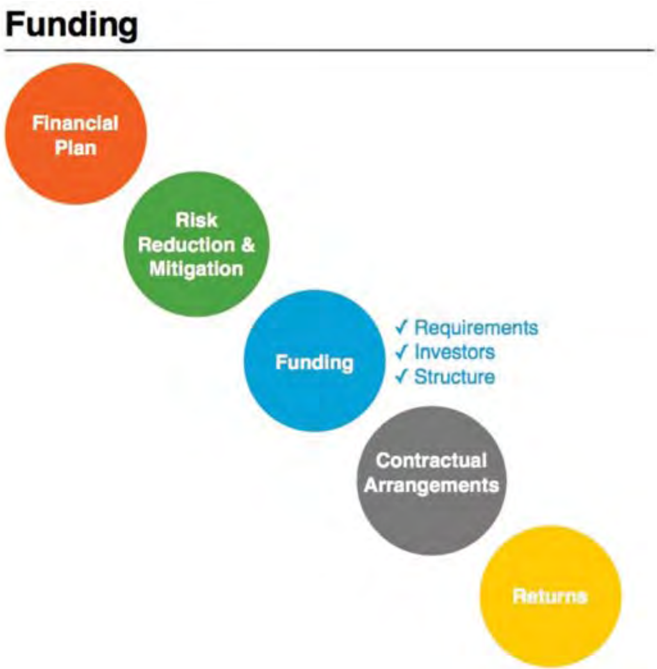


Figure 30. The Challenge of Funding

Adapted from Wright (2012c).

- for investors, because it helps weigh many inherent risks against many opportunities that characterise marine energy.

Feasibility study: San Francisco Bay Tidal Project

Below is a summary of a study to evaluate the technical and economic viability of tidal power generation in San Francisco Bay area, prepared by Black & Veatch in 2008.

Major steps of the study can be summarised as follows.

1. Identify Resource:
   - identify areas with highest generation potential;
   - estimate amount of power extractable in each area based on most developed technologies and the present knowledge of environmental and permitting constraints.

Figure 31. San Francisco Bay Area

Source: Legrand (2012b).

2. Develop Economic Analysis:
    - technology analysis;
    - energy yield analysis;
    - system costs.

Summary of the general approach:

- early findings on constraints and velocity data (initial data sources);
- modelling of currents (with e.g. 300m grid) to determine potential areas;
- resource calculation for potential tidal stream farms;
- identification of constraints and suitable technologies;
- initial Cost of Energy (CoE) estimates;
- refine modelling (with e.g. 100m grid);
- detailed cost model to determine CoE at high potential areas;
- data collection at/around the focus area to validate model (space/time);
- refinement of the model (to e.g. 20m grid) in the area of interest;
- calibration and validation of the model against the field data;
- finalised resource and cost assessment.

This general approach can be adapted for specific projects.

The framework built on basic assumptions and findings of earlier studies. Global experience in tidal stream to date shows:

- economic cut-off generally at peak velocity > 2-2.5m/s;

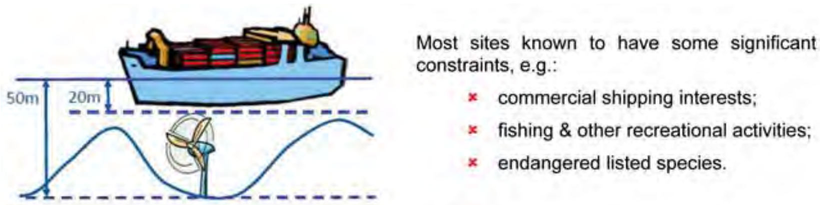


Figure 32. Site constraints

Source: Legrand (2012b)

- other factors move this criteria slightly – e.g. velocity in time and space, depth and seabed conditions, cable length, local issues.

State of the technology:

- many different technologies under development, all evolving rapidly;

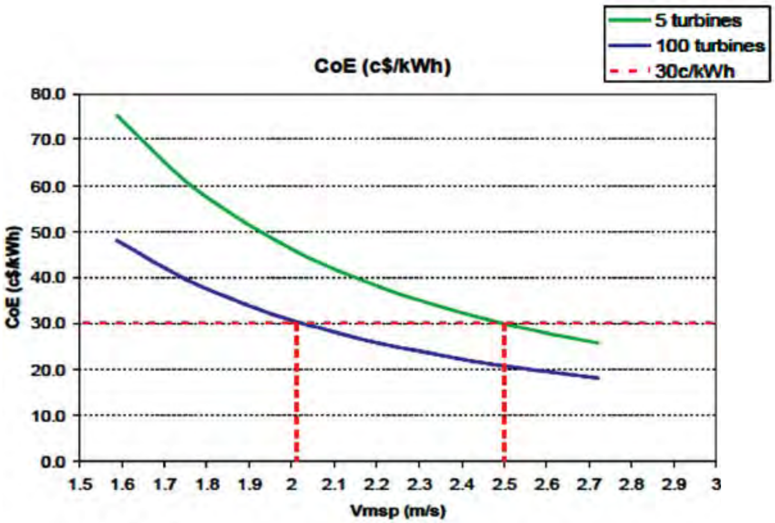


Figure 33. Expected Cost of Energy

Source: Legrand (2012b)

- limited deployment to date: ~5 technologies, none yet with proven operating experience although this should be resolved in next few years.

The study then focused on a potential farm size:

- Select potential areas that might be interesting;
- Chose a suitable technology;

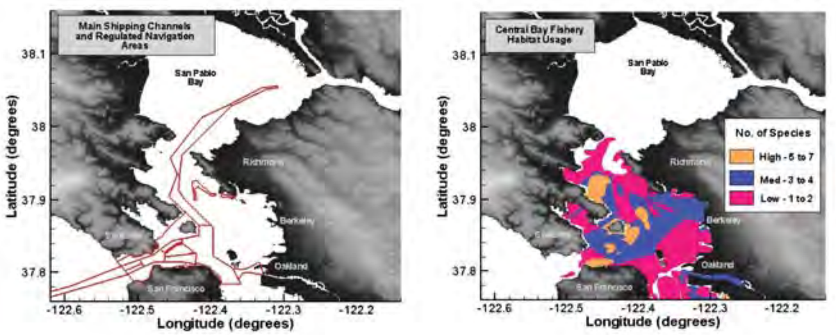


Figure 34. Identification of constraints used an initial analysis of basic hydrographical data, Environmental Impact Assessment and GIS mapping of constraints

Source: Legrand (2012b)

- Determinate the rotor diameter and number of rotors with depth limitation, clearance needed at top/bottom and size of areas / spacing needed between rotors.

Another issue is the Cost of Energy. Calculations showed that:

- at constant depth (55m) for 2 different farm sizes CoE decreases quickly with velocities;
- economic cut-off (here = 30c/kWh) at peak velocity > 2-2.5m/s;
- 5 turbines 30 c/kWh at peak velocities>2.5m/s;
- 100 turbines 30c/kWh at peak velocities >2m/s.

Some preliminary conclusions on the potential tidal farms for this area:

- Tidal Farm (> ~30MW) – economically, the most attractive type of development, but unlikely to prove technically feasible given current speeds and constraints;

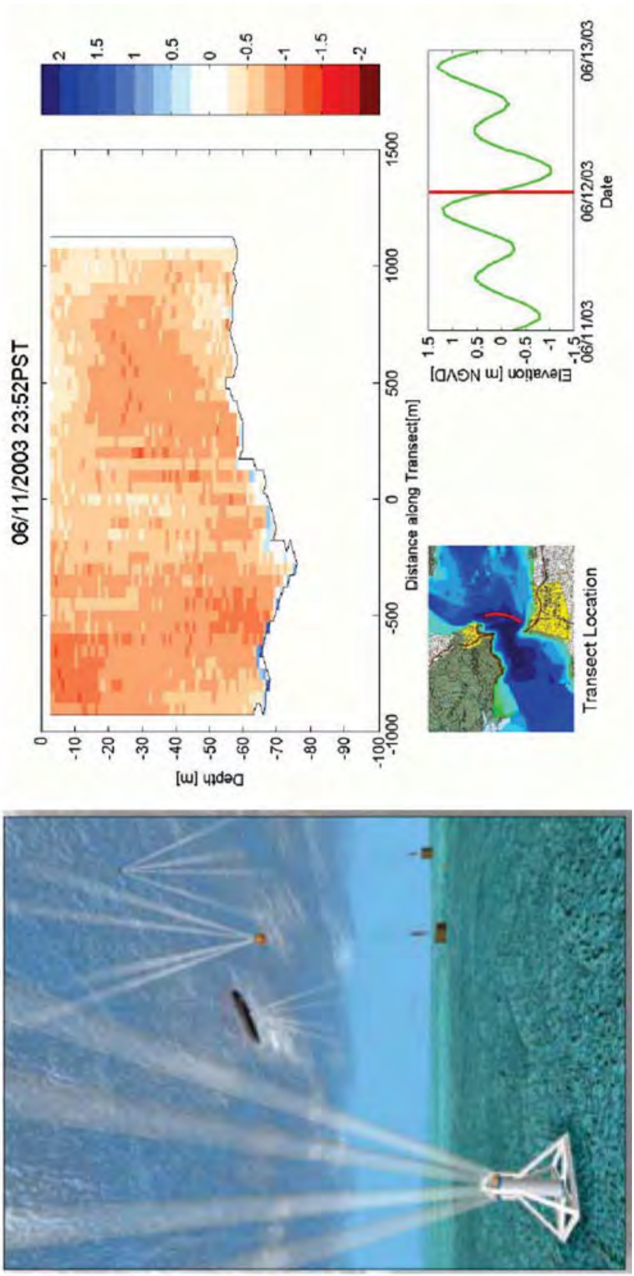


Figure 35. Survey data / Boat data

Source: Legrand (2012b)

- Distributed (10 - 20MW) – combining a number of small localized sites (probably outside shipping lanes) and connecting to the grid via a singe point of connection, possible but unlikely;
- Pilot (2 - 10MW) – small number of units deployed to demonstrate the viability (i.e. connected to the grid) or to demonstrate local effects (not grid-connected), likely to be possible, but not economic.

The purpose of the next step, field data collection is to correlate actual velocities with the results predicted from the model and find the exact place suitable for a demonstrator.

The methods for field data collection include:

- boat-mounted (survey to verify the spring velocities on crucial transects, ~2-4 days);
- bottom-mounted (2 surveys at specific places close to the proposed location, 1 month of continuous data recorded).

Economics of Tidal Energy & Government Interventions

Economics of Tidal Energy and Government Interventions

This section explores the various factors affecting the cost of energy which largely determines its economic viability. We also review the common incentive frameworks and direct government support to marine power development[1]*.*

Cost of tidal energy

The Carbon Trust – a not-for-profit company set up by the UK Government with the mission to accelerate the move to a low carbon economy – worked with the leading industry developers to undertake a new bottom-up analysis of the costs of wave and tidal energy. In 2007, the Carbon Trust developed and published a cost of energy methodology which is considered a standard framework for the assessment of wave and tidal energy costs.

The cost of energy calculation (usually in pence per kWh, p/kWh) includes all capital and operating costs associated directly with the array, including offshore electrical connections. It does not include contribution to any onshore grid upgrades that might be required. Levelised cost of energy (CoE) is calculated by adding together the discounted lifetime costs of a device or farm, then dividing the total by the expected lifetime output. Figure 36 shows the different costs involved in a marine energy generator, as appears in Carbon Trust 2011 Marine Energy Accelerator (MEA) report. A discount rate of 15% was used for the base case numbers, to take account of the risk involved in a marine energy project.

Estimates from the MEA put the baseline cost of energy for tidal at 29p–33p/kWh for the first farms. This reflects the modelled cost of energy from leading tidal device concepts at medium and high energy sites with depths of around 30m.

[1] This section draws on Carbon Trust (2011), Blair (2012a, 2012b), Ocean Energy Systems (2012a), IEA-RETD (2011).

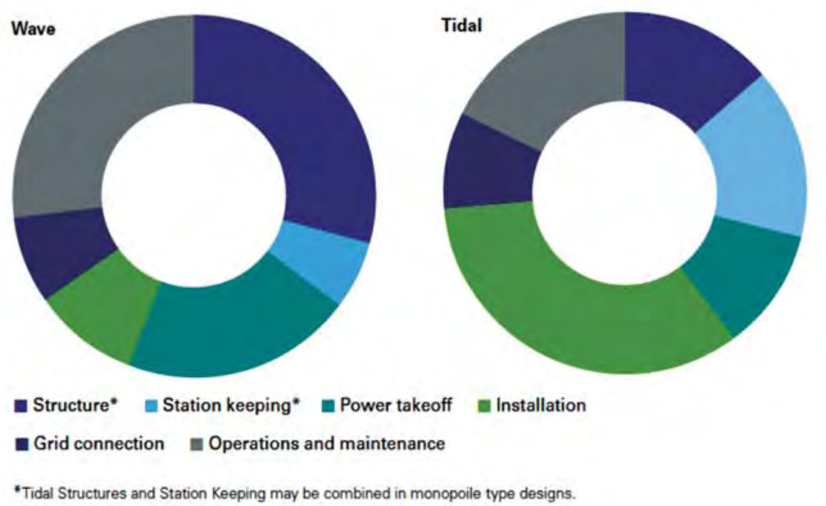


Figure 36. Indicative levelised cost of energy components for wave and tidal energy converters in an early commercial farm. The coloured segments are capital costs, while the grey segment represents O&M costs and includes all other spend including insurance and leases

Source: Carbon Trust (2011).

It should be noted, however, that these baseline costs are for the first farms of devices – small-scale arrays of around 10MW. The cost of energy from future farms is likely to drop significantly. Costs need to come down to below ~€25c/kWh in the long term to compete with other renewables and fossil generation.

In the Cost Report prepared by Black & Veatch for the National Renewable Energy Laboratory, US wave and tidal current resource assessment and technology costs were developed based on European demonstration and historical data obtained from studies. Tidal current technology is immature with many technical options. Capital cost in 2015 was estimated at 5,880 $/kW –10% and + 20%. A cost improvement of 45% was assumed as the resource estimated to be available is fully utilized by 2030. Estimated oper-

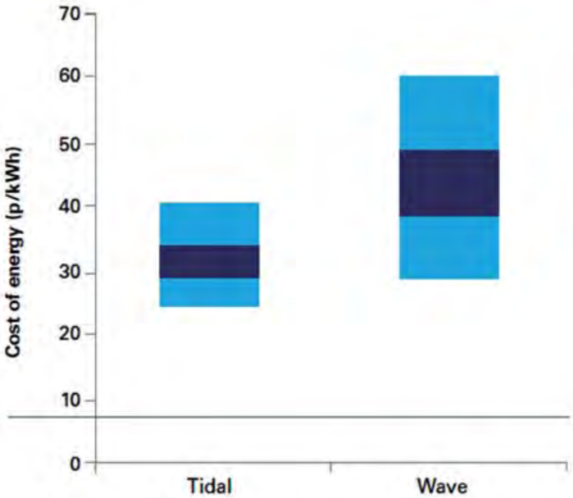


Figure 37. Baseline costs for benchmark first farm wave and tidal devices. These costs assume a discount rate of 15% and a lifetime of 20 years. The dark bars represent CoE at medium energy (upper bound) and high energy (lower bound) sites, using base case cost and performance assumptions; while the outer bars add optimistic and pessimistic cost and technical assumptions to these limits

Source: Carbon Trust (2011).

ation and maintenance costs include insurance, seabed rentals, and other recurring costs that were not included in the one-time capital cost estimate. The capital cost breakdown for current power plants are shown in Figure 38.

The current baseline costs of energy from marine devices are higher than conventional fossil fuel generation and more developed renewable energy technologies such as onshore and offshore wind. There is therefore a clear need to explore the potential for cost reduction, and to understand how this can be accelerated to make wave and tidal a cost-effective option for low carbon energy generation.

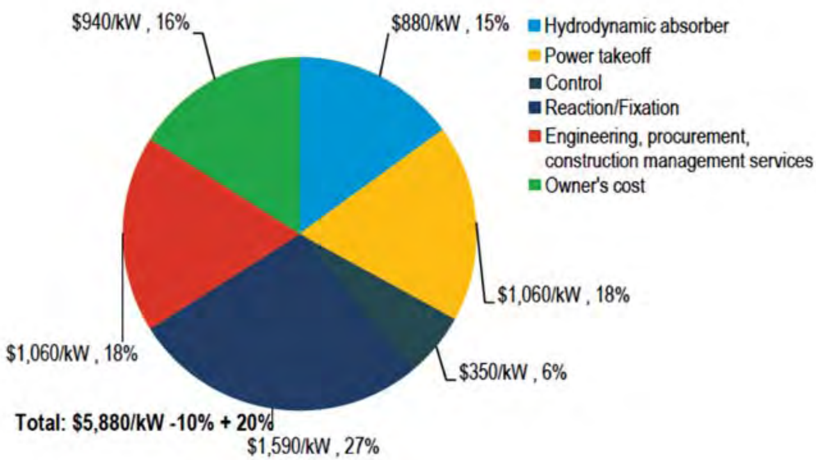


Figure 38. Capital cost breakdown for an ocean tidal power plant

Source: NREL (2012).

The cost of energy from marine devices is expected to fall, for a number of reasons that have been observed in other technologies. These include learning by doing as the cumulative installed capacity increases; scale effects as the size of arrays (and, probably, devices) increases enabling economies of scale; and innovation.

The effect of learning by doing and scale effects have been assessed by looking at comparable industries. Learning rates of 5%-6% can be realized in the early stages of a product's life simply through smarter manufacturing and procurement. If this is applied to marine devices with roughly 1MW of installed capacity per device the following cost reduction can be modelled.

As can be seen from Figure 39, adding innovation to the learning by doing curve significantly accelerates cost reduction relative to the baseline case. At 2020, costs have reached 16p/kWh for tidal energy. By 2025, the cost reduction has reached the level of today's offshore wind (~15p/kWh).

The Carbon Trust targets cost of energy reduction through innovation. Development of new generation devices and concepts is

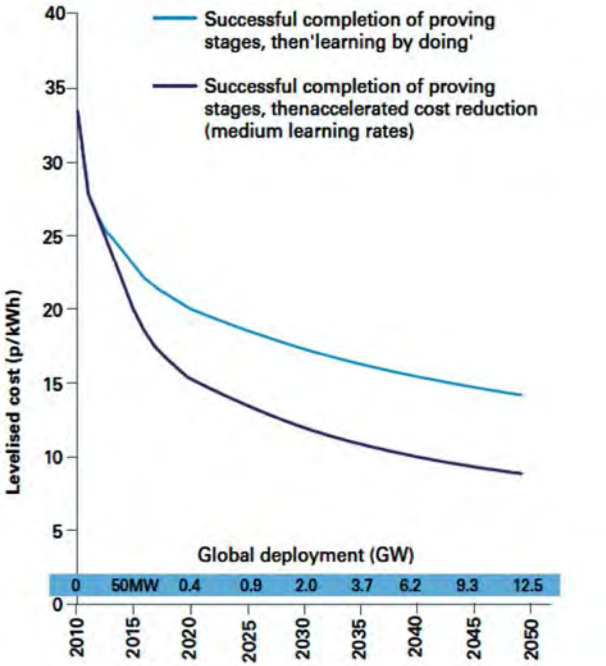


Figure 39. Possible cost reduction pathways for tidal stream energy under a 'business as usual' and innovation scenario

Source: Carbon Trust (2011).

expected to provide a step change reduction in the costs of energy. Meanwhile, working with existing device concepts may also lead to a set of cost reductions in two areas:

- component technology innovation in areas such as blades, structural materials, costs;
- reduction of installation, operation and maintenance costs.

It is clear that installation is a core focus area for tidal devices, since it accounts for ⅓ to ½ of the cost of energy and has a high potential for cost reductions. This potential arises because there has so far been limited experience of designing and installing tidal energy devices offshore.

What's next for marine energy?
Priorities for the first generation of tidal concepts

A number of tidal stream energy converters have now been built and installed, mostly in UK waters. These devices, which typically have one or two tidal turbines (or similar) per support structure, are described as first generation tidal technologies. Innovation for this first generation of devices will be driven by the need for lower cost of energy, but energy from these first generation devices will remain expensive when compared to most other renewable generating technologies. Cost of energy reductions for first generation technologies will come through improved reliability, lower installation costs and lower manufacturing costs.

Carbon Trust investigation into cost of marine energy showed that the cost of installing bottom mounted tidal stream devices makes up around one third of the levelised cost of energy. Developers report that installation accounts for 50% of the project costs and 75% of the risks. They also refer to the problems in relationship with the installation contractors. Throughout the MEA, ways of decreasing installation costs have been explored. Some of these developments are design-led and can be implemented now. Others, such as more capable vessels or subsea drilling, could yield cost improvements but only become economic at a certain scale: for a subsea drilling platform that is likely to be first farm stage, while for bespoke vessels several tens of MW are likely to be needed to justify the investment. One lesson from the MEA and other Carbon Trust projects is that jack up barges for installation can be problematic in tidal streams. Dynamic positioning vessels that have much better potential for manoeuvring within an array are likely to play a key role in future tidal deployments. Additionally, designs could be scaled up in such a way that there is more power produced for each difficult sea operation or foundation.

According to an existing estimate for the UK, to unlock marine energy, the overall installation costs must fall to £500k-£1.0m per 1MW and the total project costs to £2.0-£2.5m per 1MW (Wright 2012b). From the business perspective, vessel is the critical element in this expected dramatic cost reduction.

To achieve low cost of energy developers will need to go to high resource. Priorities for the second generation of tidal concepts – accessing the full resource

The Carbon Trust's resource work shows that the majority of the technical tidal resource is in waters over 30m deep. A second generation of tidal devices will be needed to effectively extract energy from the whole water column at deep sites, many of which have additional challenges such as more extreme met-ocean events and higher wave loading see Figure 40. There will be a need for continued cost reduction through more innovative structures and innovation to ensure that future costs of energy are no greater than those from the best first generation sites. A key conclusion is that second generation devices will be needed to enable tidal energy to become a full scale industry.

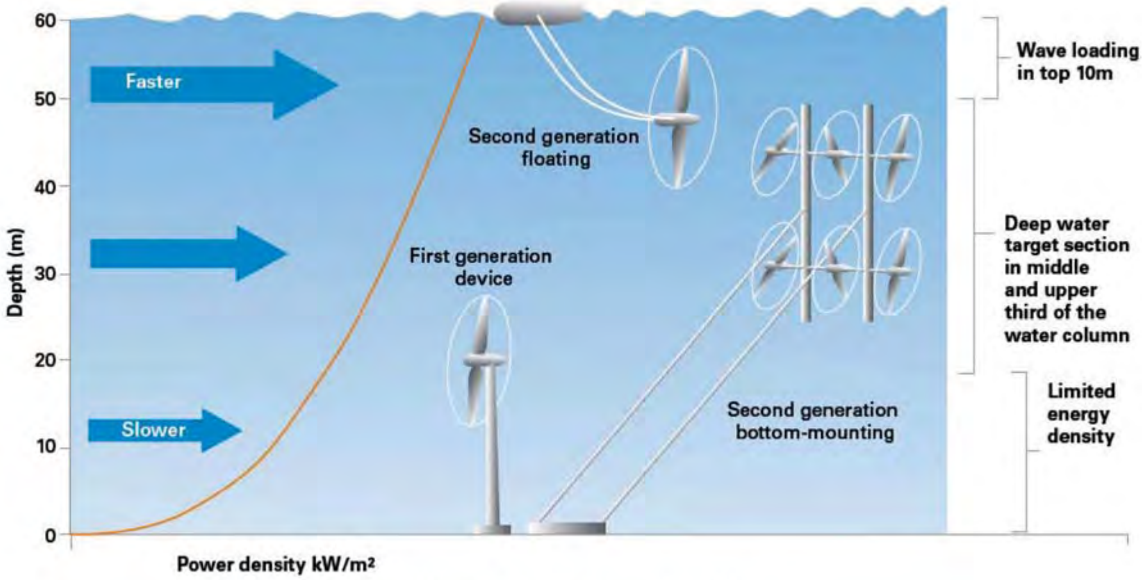
The Prognosis

Major OEMs are getting involved and help establishing viable supply chains and market for tidal energy devices. Project developers are growing in number and capacities to undertake complex projects. New innovation is also happening. These are the principal drivers behind the desirable manufacturing and installation cost reduction: £1.5m-£2.0m/MW per device and £500k-£1.0m/MW Installation cost. A target total cost of £2.5m per 1MW installed may therefore be within reach!

Funding and Government Interventions

The cost of the power generated through tidal technologies remains too high to be competitive with conventional generation. A commitment from governments for public assistance will be needed to ensure that marine energy solutions is viable going forward.

Currently, there are only a handful of tidal current developers who have enough funds to install their first commercial-scale prototype technologies. Many of these developers are supported by the UK's Marine Renewable Proving Fund. This greater focus of funding will inevitably move the industry forward more quickly.



Source: Carbon Trust (2011).

Figure 40. The high energy flows in a deep water column are nearer the surface, away from the bottom. A second generation of tidal turbines will be needed to access the optimum section of a deep water column – these might involve floating or neutrally buoyant devices

Source: Carbon Trust (2011).

An overview of the supporting programmes and mechanisms is given in Table 2 for those APEC economies which are most active in marine energy development. Information on UK is included for reference.

Government-backed fiscal mechanisms for overcoming barriers to finance in developing and deploying marine renewables can be categorised as:

- expenditure support measures (capital grants, soft loans, tax allowances, accelerated depreciation);
- income or revenue support measures (feed-in tariffs, renewable quotas, green premiums, tradable green certificates).

Typically, expenditure support measures (market "push") are more prevalent for technology development and early stage deployment, while income support measures become the main support mechanism as technologies move into larger scale "commercial" deployment (market "pull").

Unlike other renewables for which there are more or less established markets, marine power development relies mostly on expenditure support measures. Revenue support mechanisms like feed-in-tariffs for marine energy have only recently been introduced in countries which lead marine power innovation – UK and Canada.

IEA-RETD (2011) report compared the value of support with the levelised costs in different countries in order to assess the current effectiveness of the market pull that these measures are trying to create. Assuming that projects start today, the authors estimated the value of revenues including income support measures, over the life of the project versus the projected levelised cost to provide an indication of underlying economic attractiveness expressed as a net present value (NPV, in €/MWh over life of project).

The results of the net value of income less levelised costs are reported in NPVs, which therefore takes account of the changing support arrangement over time. Positive values indicate that the financial support framework provides a level of support that would allow recovery of the project's levelised costs. Negative values indicate a shortfall. These figures are on a pre-tax basis. Results are reported in Figure 41.

The results clearly indicate that in most national jurisdictions the level of support is inadequate to cover levelised costs, even in the low end

Table 2

Government funding schemes and incentives for marine power in selected APEC economies and UK (as reference)

Economy	Programmes	Market support mechanisms and incentives
Canada	Marine Renewable Energy Technology Roadmap to advance the commercialization of marine energy in Canada.	$4 million (CAD) Marine Renewable Energy Enabling Measures programme to work towards the development of a policy framework for administering renewable energy activity in the federal offshore. Financial support at the federal and provincial level to marine energy development projects ($75 million (CAD) over the last five years). Feed-in-tariffs at provincial level. Fundy Ocean Research Centre for Energy (FORCE), in Nova Scotia, a model for incubation of the industry, operational since 2011.
China	Special Plan of Twelfth Five-Year for Marine Renewable Energy in China (under development, for 2011-2015). The State Oceanic Administration (SOA) established the Administrative Centre for Marine Renewable Energy (ACMRE) to co-ordinate and manage the development and utilization of marine renewable energy in China.	In 2010, with the support of Ministry of Finance, the State Oceanic Administration (SOA) established a special funding program for marine renewable energy. The total amount of 3 rounds of the special fund is RMB 600 Millions.

China	"Strategic report for the development and utilization of marine renewable energy in China" is being developed by the National Ocean Technology Centre (NOTC) to outline overall goals and different stages of marine renewable energy till 2030.	
Japan		Ocean energy technological research and development project with a total budget of approximately 7.8 billion yen for the years 2011-2015.
Republic of Korea	The Strategic Plan for ocean energy development in Korea: Korea targets to supply 11% of the national energy demand from new and renewable energy by 2030, of which ocean energy will contribute 4.7% to total new and renewable energy supply.	The FIT for ocean energy promotion is currently applied only to tidal barrage power. Practical Ocean Energy Technology Development Programme by the Ministry of Land, Transport and Maritime Affairs.
New Zealand		Marine Energy Deployment Fund, enacted in 2007: NZ$ 4 million of grants allocated in 2007-2011.

US	Water Power Program: to research, test, evaluate, develop and demonstrate deployment of innovative technologies capable of generating renewable, environmentally responsible and cost-effective electricity from water resources	There are a number of federal Renewable Energy Financial Incentives that can be leveraged to further marine and hydrokinetics in the U.S.: Clean Renewable Energy Bonds (CREBs); Qualified Energy Conservation Bonds (QECBs); Renewable Electricity Production Tax Credit (PTC); Renewable Energy Production Incentive (REPI) etc.
UK	UK Marine Energy Programme, established in January 2011, focusing on enhancing the UK marine energy sector's ability to develop and deploy wave and tidal energy devices at a commercial scale. Key areas: Support needed for small scale arrays and early commercial deployment; Planning and consenting issues; Knowledge sharing though a Marine Intelligence Network.	For the period up to 2017 – Renewables Obligation Certificate (ROC) 5 ROCs for wave and tidal stream energy up to a 30MW project cap for deployment. Beyond 2017 – feed-in tariff (FIT) Marine Renewable Proving Fund £22 million 2009-2011. Marine Energy Array Demonstrator (MEAD) scheme up to £20 million, announced in 2011. Marine Renewables Commercialisation Fund 2013-2015, Carbon Trust and other organisations' initiatives. European Marine Energy Centre in Scotland, a leading test and incubation facility.

Source: Ocean Energy Systems (2012a)

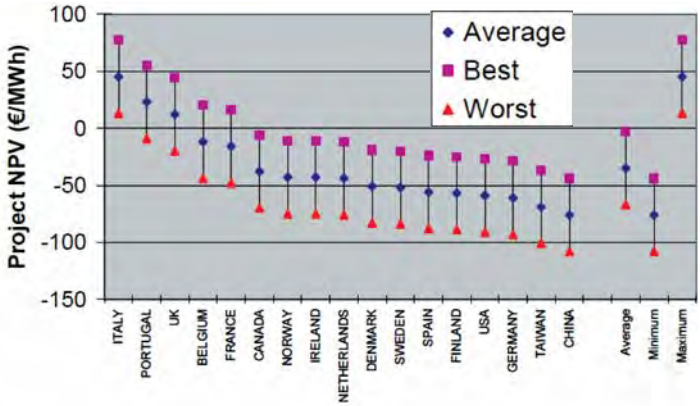


Figure 41. Tidal Energy Project Economic NPV in €/MWh based on existing income support schemes under a high and low levelised cost projection – differentiated wholesale prices

Source: Mott MacDonald, cited in IEA-RETD (2011), P.141.

of cost projections, assuming differentiated wholesale prices. Only in four countries (Italy, France, Belgium and the UK) are the support levels sufficient to cover the low end levelised cost projections across the three technologies. However, in no cases is national support sufficient to cover the higher end levelised cost cases.

Access to capital and financial barriers are therefore particularly important for tidal power technologies, which are typically at a pre-commercial/prototype stage, and consequently are seen by financiers and investors as containing large amounts of technology and performance risks.

The lack of long term or stable policy commitments from governments is another significant barrier as it affects developer and market confidence. In many countries, the level of financial support provided (feed-in-tariff or tradable certificates) often appears either insufficient or at best marginal in order to provide sufficiently attractive returns to investors compared to lower risk investment options in other sectors.

Environmental Impact

Environmental Impact

In this section, we look into some methods to quantify the environmental impact of marine energy devices. In particular, we refer to Life Cycle Assessment and the findings from a recent study[1].

Marine energy generating devices as any other renewable devices are known to produce clean, carbon-free energy. However, manufacturing, installation and the entire lifespan of marine energy devices require the use of materials and services which embody carbon emissions. Manufacturing of steel structures for tidal turbines and transportation to the installation sites are obvious examples of such carbon-intensive activities.

Given the recent interest in carbon trade and tax schemes to promote low-carbon economy, it is therefore important to estimate total emissions embodied in tidal turbines and other related devices against carbon savings and to compare with other renewable technologies and fossil fuels.

One widely used analytical framework for the above purpose is the Life Cycle Assessment (LCA), also known as a “cradle to grave” analysis. It captures all the environmental impacts of a product, process or service within its complete life cycle. LCA can identify energy and materials use and waste released to the environment, as well as evaluation and implementation of opportunities for improvements. LCA studies should comply with the international standard ISO 14040, which specifies the general framework, principles, and requirements for conducting and reporting such assessments. LCAs have been applied to a range of electricity generating technologies including nuclear, fossil fuelled plants, and renewables such as wind.

[1] This section draws on Douglas, Harrison and Chick (2008) and Moran (2012).

In principle, LCAs represent accounting framework that can be used to model the inputs of materials, energy, labour and even monetary costs throughout the production process of a given product. It is most commonly used to help designers and engineers to identify the environmental factors attributed to specific materials or life cycle stages, and ultimately allowing sound and informed decisions and improvements to be made. The LCA will also be of interest to potential investors, energy and government authorities who may consider the environmental implications of the product before investing or commissioning such a project.

The life cycle of the SeaGen marine current turbine can be modelled as a series of stages, as shown in a pioneering study (see Figure 42).

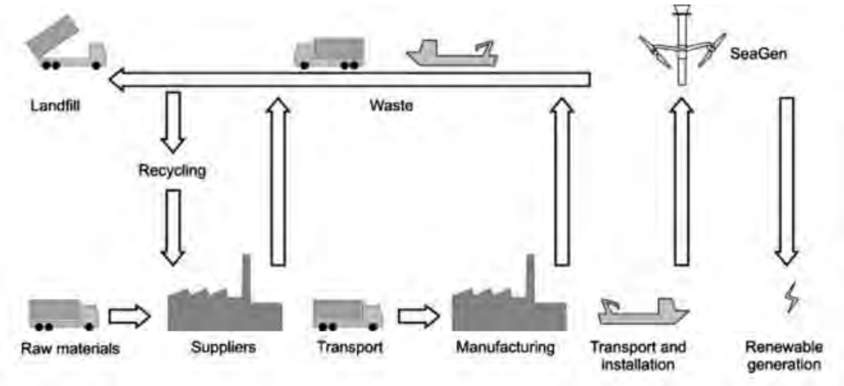


Figure 42. SeaGen life cycle stages

Source: Douglas, Harrison and Chick (2008).

The LCA results allow the calculation of the energy and CO_2 intensities, i.e. per unit of production (see Figure 43). The performance of the device can also be measured by payback periods which indicate how quickly embodied energy and CO_2 are ‘recovered’ by the carbon-free energy produced by SeaGen. The energy payback period is ascertained by dividing the lifetime energy input by the annual energy production:

$$\text{Energy payback} = \frac{\text{Life cycle embodied energy}}{\text{Annual energy production}}$$

The energy payback is therefore around 14 months. Similarly, the carbon payback can be ascertained by dividing the total embodied carbon by the annual carbon avoided by the use of the system as follows:

$$CO_2 \text{ payback} = \frac{\text{Life cycle embodied } CO_2}{\text{Annual } CO_2 \text{ avoided}}$$

SeaGen avoids 2036 t CO_2 per year indicating a carbon payback period of just over 8 months.

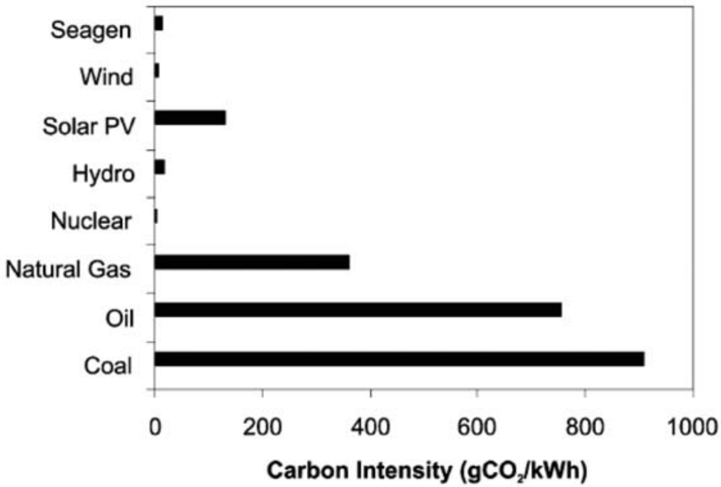


Figure 43. Life cycle carbon intensities of energy generating technologies

Source: Douglas, Harrison and Chick (2008).

From the LCA results, it is clear that the SeaGen marine current turbine is a significant improvement on fossil fuel electrical generation and compares well with established renewable technologies. However, it should be noted that conventional LCA analyses tend to always have errors due to undercounting and double-counting. The reason is that product or process based LCA frameworks cannot trace the whole supply chain (turbine requires steel, steel requires coal, coal requires mining, mining requires transportation and fuel, and so on). A solution is Hybrid Life Cycle Analysis which combines conventional LCA method with a national or international Input-Output table, but such assessments so far only exist for wind turbines.

Concluding Remark

APEC member economies have the privilege of facing the Pacific waters which offer vast quantities of predictable, reliable and consistent tidal stream energy. Given the recent technology development and various acceleration programmes, this form of electricity generation can play an important part in the future global energy mix.

The industry is in its demonstration phase and will need public support for some time to come. Governments across APEC region may offer mechanisms for overcoming barriers to finance in developing and deploying marine renewable technologies, such as R & D financing and incubation facilities, expenditure support measures (capital grants, soft loans, tax allowances, accelerated depreciation) and income support measures (feed-in tariffs, renewable quotas, green premiums, or tradable green certificates).

But government backing needs to sit alongside a new, focused industry. The most urgent challenge to unlock the potential of marine energy is reduce the costs of energy where the largest component appears to be installation costs.

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