6

Ocean Energy

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This chapter should be cited as:

Lewis, A., S. Estefen, J. Huckerby, W. Musial, T. Pontes, J. Torres-Martinez, 2011: Ocean Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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Executive Summary

Ocean energy offers the potential for long-term carbon emissions reduction but is unlikely to make a significant short-term contribution before 2020 due to its nascent stage of development. In 2009, additionally installed ocean capacity was less than 10 MW worldwide, yielding a cumulative installed capacity of approximately 300 MW by the end of 2009. All ocean energy technologies, except tidal barrages, are conceptual, undergoing research and development (R&D), or are in the pre-commercial prototype and demonstration stage. The performance of ocean energy technologies is anticipated to improve steadily over time as experience is gained and new technologies are able to access poorer quality resources. Whether these technical advances lead to sufficient associated cost reductions to enable broad-scale deployment of ocean energy is the most critical uncertainty in assessing the future role of ocean energy in mitigating climate change. Though technical potential is not anticipated to be a primary global barrier to ocean energy deployment, resource characteristics will require that local communities in the future select among multiple available ocean technologies to suit local resource conditions.

Though ocean energy resource assessments are at a preliminary phase, the theoretical potential for ocean energy easily exceeds present human energy requirements. Ocean energy is derived from technologies that utilize seawater as their motive power or harness its chemical or heat potential. The renewable energy (RE) resource in the ocean comes from six distinct sources, each with different origins and requiring different technologies for conversion: waves; tidal range; tidal currents; ocean currents; ocean thermal energy conversion (OTEC); and salinity gradients. Ocean energy could be used not only to supply electricity but also for direct potable water production or to meet thermal energy service needs. The theoretical potential for ocean energy technologies has been estimated at 7,400 EJ/yr, well exceeding current and future human energy needs. Relatively few assessments have been conducted on the technical potential of the various ocean energy technologies and such potentials will vary based on future technology developments. One assessment places the global technical potential for 2050 at 331 EJ/yr, dominated by OTEC (300 EJ/yr) and wave energy (20 EJ/yr), whereas on the other end of the spectrum, another assessment lists the 'exploitable estimated available energy resource' at just 7 EJ/yr. Whilst some potential ocean energy resources, such as ocean currents and osmotic power from salinity gradients, are globally distributed, other forms of ocean energy have complementing distributions. Ocean thermal energy is principally distributed in the tropics around the Equator (latitudes 0° to 35°), whilst wave energy principally occurs between latitudes of 30° to 60°. Some ocean energy resources, such as ocean thermal, ocean currents and salinity gradients may be used to generate base-load electricity, whereas others have variable generation profiles that differ in their predictability. Though the available literature is limited, the impact of climate change on the technical potential for ocean energy is anticipated to be modest.

Ocean energy systems are at an early stage of development, but technical advances may progress rapidly given the number of technology demonstrations. With the exception of tidal range energy, which can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, most ocean energy technologies have not yet been developed beyond the prototype stage. Although basic concepts have been known for decades, if not centuries, ocean energy technology development really began in the 1970s, only to languish in the post-oil-price crisis period of the 1980s. Research and development on a wide range of ocean energy technologies was rejuvenated at the start of the 2000s and some technologies, specifically wave and tidal current energy, have reached full-scale prototype deployments. Unlike wind turbine generators, there is presently no convergence on a single design configuration for ocean energy converters and, given the range of options for energy extraction, a single device design is unlikely. Worldwide developments of devices are accelerating with a large number of prototype wave and tidal current devices under development.

Government policies are contributing to accelerate the implementation of ocean energy technologies. Some national and regional governments are supporting ocean energy development through a range of initiatives, including R&D and capital grants to device developers; performance incentives for produced electricity; marine infrastructure development; standards, protocols and regulatory interventions for permitting; and space and resource allocation.

Ocean energy has the potential to deliver long-term carbon emissions reductions and appears to have low environmental impacts. Ocean energy technologies do not generate GHGs in operation and have low lifecycle GHG emissions, providing the potential to significantly contribute to emissions reductions. Utility-scale deployments with transmission grid connections can be used to displace carbon-emitting energy supplies, while smaller-scale developments may supply electricity and/or drinking water to remote communities. As shown by a review of a limited number of existing global energy scenarios, ocean energy has the potential to help mitigate long-term climate change by offsetting GHG emissions with projected deployments resulting in energy delivery of up to 1,943 TWh/yr (~7 EJ/yr) by 2050. The local social and environmental impacts of ocean energy projects are being evaluated as actual deployments multiply, but can be estimated based on the experience of other maritime and offshore industries. Environmental risks from ocean energy technologies appear to be relatively low, but the early stage of ocean energy deployment creates uncertainty on the degree to which social and environmental concerns might eventually constrain development.

Successful deployment will lead to cost reductions. Although ocean energy technologies are at an early stage of development, there are encouraging signs that the investment cost of technologies and the levelized cost of electricity generated will decline from their present non-competitive levels as R&D and demonstrations proceed, and as deployment occurs. Whether these cost reductions are sufficient to enable broad-scale deployment of ocean energy is the most critical uncertainty in assessing the future role of ocean energy in mitigating climate change.

6.1 Introduction

This chapter discusses the potential contribution that energy derived from the ocean can make to overall energy supply and hence its potential contribution to climate mitigation. The RE resource in the ocean comes from six distinct sources, each with different origins and requiring different technologies for conversion. These sources are:

- **Waves**, derived from the transfer of the kinetic energy of the wind to the upper surface of the ocean;
- **Tidal Range (tidal rise and fall)**, derived from the gravitational forces of the Earth-Moon-Sun system;
- **Tidal Currents**, water flow resulting from the filling and emptying of coastal regions as a result of the tidal rise and fall;
- **Ocean Currents**, derived from wind-driven and thermohaline ocean circulation;
- **Ocean Thermal Energy Conversion (OTEC)**, derived from temperature differences between solar energy stored as heat in upper ocean layers and colder seawater, generally below 1,000 m; and
- **Salinity Gradients (osmotic power)**, derived from salinity differences between fresh and ocean water at river mouths.

Marine biomass farming—production of biofuels from seaweed and/or algae—is covered in Chapter 2, whereas submarine geothermal energy—high-temperature water issuing from submarine vents at seabed ocean ridges—is covered in Chapter 4.

All ocean energy technologies, except tidal barrages, are conceptual, undergoing R&D, or are in the pre-commercial prototype and demonstration stage. The globally distributed resources and relatively high energy density associated with most ocean energy sources provide ocean energy with the potential to make an important contribution to energy supply and to the mitigation of climate change in the coming decades, if technical challenges can be overcome and costs thereby reduced. Accordingly, a range of initiatives are being employed by some governments to promote and accelerate the development and deployment of ocean energy technologies.

Information on the environmental and social impacts is limited mainly due to the lack of experience in deploying and operating ocean technologies, although adverse environment effects are foreseen to be relatively low. The current and future costs of most ocean energy technologies are also difficult to assess as little fabrication and deployment experience is available for validation of cost assumptions.

This chapter is presented in eight sections covering different aspects of ocean energy. Resource potential from different ocean sources is treated in Section 6.2, with a focus on both theoretical and technical potentials. The present state of development of ocean technologies and applications is considered in Section 6.3. Discussion about markets and industry developments, including government policies, is presented in Section 6.4. Environmental and social impacts are covered in Section 6.5. Finally, prospects for technology improvement, cost trends and potential deployment are considered in Sections 6.6, 6.7 and 6.8, respectively.

6.2 Resource potential

Relatively few assessments have been conducted on the technical potential of the various ocean energy technologies, and such potentials will vary based on future technology developments. As presented in Chapter 1, the theoretical potential for ocean energy technologies has been estimated to be 7,400 EJ/yr (Rogner et al., 2000), whereas Krewitt et al. (2009) report a global technical potential for 2050 of 331 EJ/yr, dominated by OTEC (300 EJ/yr) and wave energy (20 EJ/yr). On the other end of the spectrum, the IPCC Fourth Assessment Report reports what it lists as an 'exploitable estimated available energy resource' of just 7 EJ/yr (Sims et al., 2007). Given the early state of the available literature and the substantial uncertainty in ocean energy's technical potential, this section covers selected estimates of both theoretical and technical potential. Moreover, because of the inherent differences among the various ocean energy sources, resource potential assessments are discussed for each ocean energy source in turn.

Also discussed in this section is the potential impact of climate change on the technical potential for ocean energy. In summary, though the available literature is limited, the impact of climate change is anticipated to be modest. In a number of instances, climate variables simply have little to no influence on the underlying energy sources (e.g., tidal range, tidal current), whereas in other cases the impacts do not seem likely to greatly influence global technical potential estimates (e.g., OTEC, wave, salinity gradient, ocean current).

6.2.1 Wave energy

Ocean wave energy (as distinct from internal waves or tsunamis) is energy that has been transferred from the wind to the ocean. As the wind blows over the ocean, air-sea interaction transfers some of the wind energy to the water, forming waves, which store this energy as potential energy (in the mass of water displaced from the mean sea level) and kinetic energy (in the motion of water particles). The size and period of the resulting waves depend on the amount of transferred energy, which is a function of the wind speed, the length of time the wind blows (order of days) and the length of ocean over which the wind blows (fetch). Waves are very efficient at transferring energy, and can travel long distances over the ocean surface beyond the storm area and are then classed as swells (Barber and Ursell, 1948; Lighthill, 1978). The most energetic waves on earth are generated between 30° and 60° latitudes by extra-tropical storms. Wave energy availability typically varies seasonally and over shorter time periods, with seasonal variation typically being greater in the northern hemisphere. Annual variations in the wave climate are usually estimated by the use of long-term averages in modelling, using global databases with reasonably long histories.

A map of the global offshore average annual wave power distribution (Figure 6.1) shows that the largest power levels occur off the west coasts of the continents in temperate latitudes, where the most energetic winds and greatest fetch areas occur.

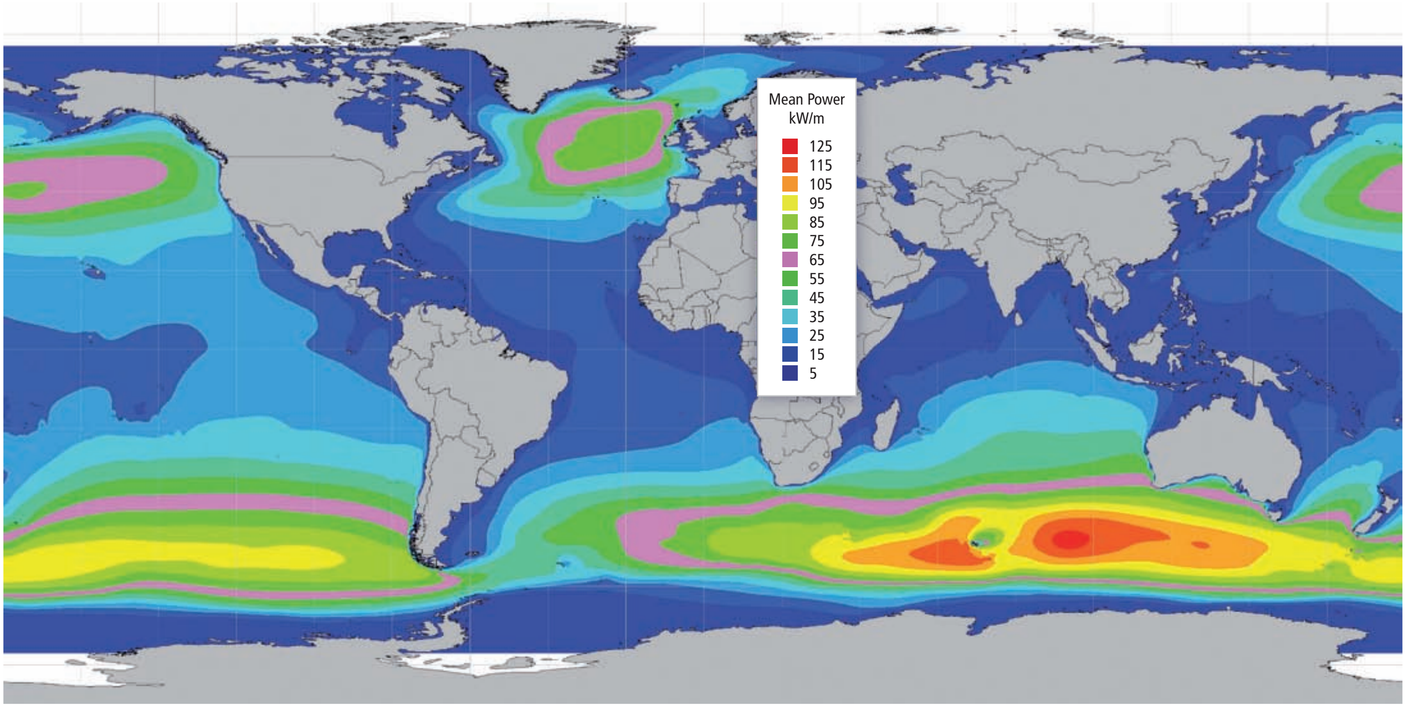


Figure 6.1 | Global offshore annual wave power level distribution (Cornett, 2008).

The total theoretical wave energy potential is estimated to be 32,000 TWh/yr (115 EJ/yr) (Mørk et al., 2010), roughly twice the global electricity supply in 2008 (16,800 TWh/yr or 54 EJ/yr). This figure is unconstrained by geography, technical or economic considerations. The regional distribution of the annual wave energy incident on the coasts of countries or regions has been obtained for areas where theoretical wave power P ≥ 5 kW/m and latitude ≤66.5° (Table 6.1). The theoretical wave energy potential listed in Table 6.1 (29,500 TWh/yr or 10^6 EJ/yr) represents a decrease of 8% from the total theoretical wave energy potential above (it excludes areas with less than 5 kW/m), but should still be considered an estimate of theoretical potential. The technical potential of wave energy will be substantially below this figure and will depend upon technical developments in wave energy devices. Sims et al. (2007) estimate a global technical potential of 500 GW for wave energy, assuming that offshore wave energy devices have an efficiency of 40% and are only installed near coastlines with wave climates of >30 kW/m, whereas Krewitt et al. (2009) report a wave energy potential of 20 EJ/yr.

Potential changes in wind patterns, caused by climate change, are likely to affect the long-term wave climate distribution (Harrison and Wallace,

Table 6.1 | Regional theoretical potential of wave energy (Mørk et al., 2010).

REGION	Wave Energy TWh/yr (EJ/yr)
Western and Northern Europe	2,800 (10.1)
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300 (4.7)
North America and Greenland	4,000 (14.4)
Central America	1,500 (5.4)
South America	4,600 (16.6)
Africa	3,500 (12.6)
Asia	6,200 (22.3)
Australia, New Zealand and Pacific Islands	5,600 (20.2)
TOTAL	**29,500 (106.2)**

Note: The results presented in Mørk et al. (2010) regarding the overall theoretical global potential for wave energy are consistent with other studies (Cornett, 2008). No further studies of regional theoretical potential of wave energy are available to validate the data provided in Table 6.1.

2005; MCCIP, 2008), though the impact of those changes is likely to have only a modest impact on the global technical potential for wave energy given the ability to relocate wave energy devices as needed over the course of decades.

A range of devices are used to measure waves:

- Wave-measuring buoys are used in water depths greater than 20 m (see Allender et al., 1989). Seabed-mounted (pressure and acoustic) probes are used in shallower waters. Capacity/resistive probes or down-looking infrared and laser devices can be used when offshore structures are available (e.g., oil or gas platforms).

- Satellite-based measurements have been made regularly since 1991 by altimeters that provide measurements of significant wave height and wave period with accuracies similar to wave buoys (Pontes and Bruck, 2008). The main drawback of satellite data is the long interval between measurements (several days) and the corresponding large distance between adjacent tracks (0.8º to 2.8º along the Equator).

- The results of numerical wind-wave models are now quite accurate, especially for average wave conditions. Such models compute directional spectra over the oceans, taking as input wind fields provided by atmospheric models; they are by far the largest source of wave information.

The different types of wave information are complementary and should be used together for best results. For a review of wave data sources, atlases and databases, see Pontes and Candelária (2009).

6.2.2 Tidal range

Tides are the regular and predictable change in the height of the ocean, driven by gravitational and rotational forces between the Earth, Moon and Sun, combined with centrifugal and inertial forces. Many coastal areas experience roughly two high tides and two low tides per day (called 'semi-diurnal'); in some locations there is only one tide per day (called diurnal). The lunar day of 24 hrs and 50 min means that the timing of subsequent high and low tides advances each day as this constituent is the predominant one. Diurnal and semi-diurnal tides also occur at different times in different locations around the Earth.

During the year, the amplitude of the tides varies depending on the respective positions of the Earth, the Moon and the Sun. Spring tides (maximum tidal range) occur when the Sun, Moon and Earth are aligned (at full moon and at new moon). Neap tides (minimum tidal range) occur when the gravitational forces of the Earth-Moon axis are at 90 degrees to the Earth-Sun axis. The spring-neap tide cycle is driven by the 29.5 day orbit of the Moon around the Earth and is experienced throughout the world at the same time. Longer-period fluctuations in tide height also occur, but are of very low magnitude compared to diurnal, semi-diurnal and spring-neap cycles (Sinden, 2007).

The timing and magnitude of the tide varies depending on global position and also on the shape of the ocean bed, the shoreline geometry and Coriolis acceleration. Within a tidal system there are points where the tidal range is nearly zero, called amphidromic points (Figure 6.2). However, even at these points tidal currents will generally flow with high velocity as the water surface on either side of the amphidromic point is at different levels. This is a result of the Coriolis effect and interference within oceanic basins, seas and bays, creating a tidal wave pattern (called an amphidromic system), which rotates around the amphidromic point. See Pugh (1987) for full details of tidal behaviour.

Tidal periodicities can resonate with the natural oscillatory frequencies of estuaries and bays, resulting in greatly increased tidal range. Consequently, the locations with the largest tidal ranges are at resonant estuaries, such as the Bay of Fundy in Canada (17 m tidal range), the Severn Estuary in the UK (15 m) and Baie du Mont Saint Michel in France (13.5 m) (Kerr, 2007). In other places (e.g., the Mediterranean Sea), the tidal range is less than 1 m (Shaw, 1997; Usachev, 2008).

Tidal range can be forecast with a high level of accuracy, even centuries in advance: while the resultant power is variable, there is no resource risk due to climate change. The world's theoretical tidal power potential (tidal range plus tidal currents) is in the range of 3 TW, with 1 TW located in relatively shallow waters (Charlier and Justus, 1993), though Sims et al. (2007) and Krewitt et al. (2009) note that only a fraction of the theoretical potential is likely to be exploited.

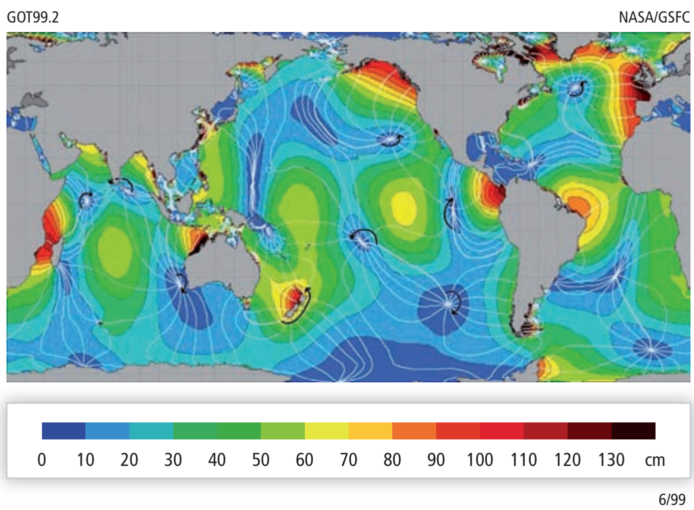


Figure 6.2 | World map of M2 tidal amplitude (NASA, 2006).

Notes: M2 is the largest (semidiurnal) tidal constituent, whose amplitude is about 60% of the total tidal range. The white lines are cotidal lines—where tides are at the same point of rising or falling, spaced at phase intervals of 30° (a bit over 1 hr). The amphidromic points are the dark blue areas where the cotidal lines meet. Tides rotate about these points where little or no tidal rise and fall occurs but where there can be strong tidal currents.

6.2.3 Tidal currents

Tidal currents are the ocean water mass response to tidal range (see Section 6.2.2). Tidal currents are generated by horizontal movements of water, modified by seabed bathymetry, particularly near coasts or other constrictions (e.g., islands). Tidal current flows result from the rise and fall of the tide; although these flows can be slightly influenced by short-term weather fluctuations, their timing and magnitude are highly predictable and largely insensitive to climate change influences.

A number of methods for the assessment of the tidal current energy resource potential have been discussed (Hagerman et al., 2006; Mackay, 2008). In the energy flux method, which is widely used, the potential power of a tidal current is proportional to the cube of the current velocity. Hence, the power density (in W/m^2) of tidal currents increases substantially with small increases in velocity. For near-shore currents such as those occurring in channels between mainland and islands or in estuaries, current velocity varies systematically and predictably in relation to the tide. In the specific case of tidal channels, however, there is a further limitation on the calculation of the overall resource (Garrett and Cummins, 2005, 2008; Karsten et al., 2008; Sutherland et al., 2008).

An atlas of wave energy and tidal current resource potential has been developed for the UK (UK Department of Trade and Industry, 2004). Similar resource estimates have been published for the EU (CEC, 1996; Carbon Trust, 2004), Canada (Cornett, 2006) and China (CEC, 1998).

In Europe, the tidal current energy resource potential is of special interest for the UK, Ireland, Greece, France and Italy. Over 106 promising locations have been identified, mostly in the UK (CEC, 1996). Using present-day state-of-the-art technologies, these sites have been estimated to have a technical potential of 48 TWh/yr (0.17 EJ/yr) (CEC, 1996). China has estimated that around 14 GW of tidal current power is available (Wang and Lu, 2009). Commercially attractive sites have also been identified in the Republic of Korea, Canada, Japan, the Philippines, New Zealand and South America.

6.2.4 Ocean currents

In addition to near-shore tidal currents, significant current flows also exist in the open ocean. These currents flow continuously in the same direction and have low variability. Large-scale circulation of the oceans is concentrated in various regions, notably the western boundary currents associated with wind-driven circulations. Some of these offer sufficient current velocities (~2 m/s) to drive present-day technologies (Leaman et al., 1987). These include the Agulhas/Mozambique Currents off South Africa, the Kuroshio Current off East Asia, the East Australian Current, and the Gulf Stream off eastern North America (Figure 6.3). Other ocean currents may also have potential for development as improvements in turbine systems occur.

The potential for power generation from the Florida Current of the Gulf Stream system was recognized decades ago. The ‘MacArthur Workshop’ concluded that the Florida Current had a technical potential of 25 GW (Stewart, 1974; Raye, 2001). It has a core region 15 to 30 km off the coast near the surface and flows strongly year-round as part of the North Atlantic Ocean subtropical gyre (Niiler and Richardson, 1973; Johns et al., 1999).

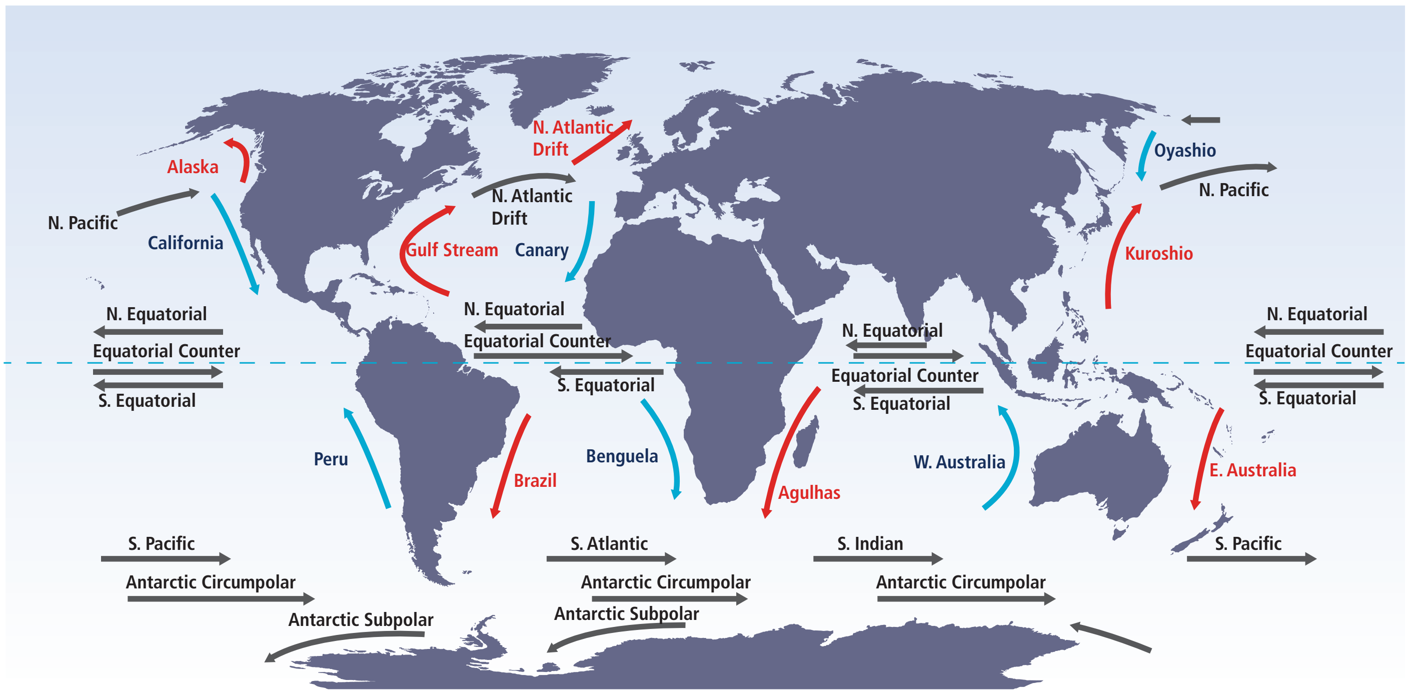


Figure 6.3 | Surface ocean currents, showing warm (red) and cold (blue) systems.

6.2.5 Ocean thermal energy conversion

About 15% of the total solar input to the ocean is retained as thermal energy, with absorption concentrated at the top layers, declining exponentially with depth as the thermal conductivity of sea water is low. Sea surface temperature can exceed 25°C in tropical latitudes, while temperatures 1 km below the surface are between 5°C and 10°C (Charlier and Justus, 1993).

A minimum temperature difference of 20°C is considered necessary to operate an OTEC power plant. Both coasts of Africa and India, the tropical west and south-eastern coasts of the Americas and many Caribbean and Pacific islands have sea surface temperature of 25°C to 30°C, declining to 4°C to 7°C at depths varying from 750 to 1,000 m. The OTEC resource map showing annual average temperature differences between surface waters and the water at 1,000-m depth shows a wide tropical area with a potential greater than 20º C temperature difference (Figure 6.4). A number of Pacific and Caribbean countries could develop OTEC plants close to their shores (UN, 1984). It seems unlikely that climate change would have a meaningful impact on the size of the global technical potential for OTEC.

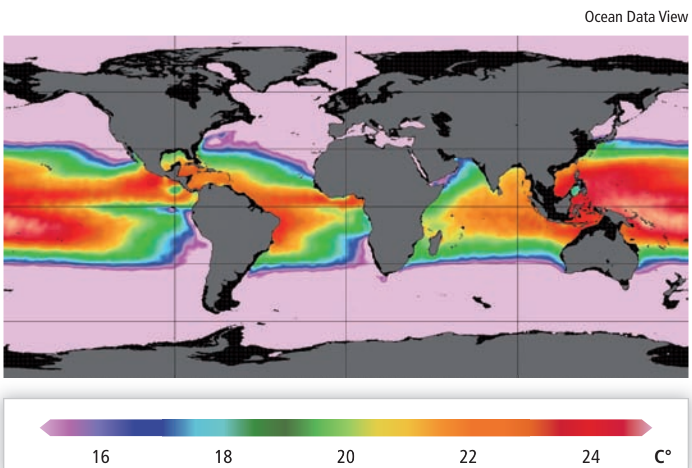


Figure 6.4 | Worldwide average ocean temperature differences (°C) between 20 and 1,000 m water depth (Nihous, 2010).

Among ocean energy sources, OTEC is one of the continuously available renewable resources that could contribute to base-load power supply (there is a slight variation from summer to winter), although compared to wave and tidal current energy, its energy density is very low.

The resource potential for OTEC is considered to be much larger than for other ocean energy forms (World Energy Council, 2000). It also has a widespread distribution between the two tropics. An optimistic estimate of the global theoretical potential is 30,000 to 90,000 TWh/yr (108 to 324 EJ/yr) (Charlier and Justus, 1993). More recently, Nihous (2007) calculated that about 44,000 TWh/yr (159 EJ/yr) of steady-state power may be possible. Up to 88,000 TWh/yr (318 EJ/yr) of power could be generated from OTEC without affecting the ocean's thermal structure (Pelc and Fujita, 2002).

6.2.6 Salinity gradients

The mixing of freshwater and seawater releases energy as heat. Harnessing the chemical potential between the two water sources, across a semi-permeable membrane, can capture this energy as pressure, rather than heat, which can then be converted into useful energy forms.

Since freshwater from rivers discharging into saline seawater is globally distributed, osmotic power could be generated and used in all regions wherever there is a sufficient supply of freshwater. River mouths are most appropriate, because of the potential for large adjacent volumes of freshwater and seawater.

Recently, the technical potential for power generation was calculated as 1,650 TWh/yr (6 EJ/yr) (Scråmestø et al., 2009). Salinity gradients could potentially generate base-load electricity, if cost-effective technologies can be developed.

6.3 Technology and applications

6.3.1 Introduction

The current development status of ocean energy technologies ranges from the conceptual and pure R&D stages to the prototype and demonstration stage, and only tidal range technology can be considered mature. Presently there are many technology options for each ocean energy source and, with the exception of tidal range barrages, technology convergence has not yet occurred. Over the past four decades, other marine industries (primarily offshore oil and gas) have made significant advances in the fields of materials, construction, corrosion, submarine cables and communications. Ocean energy is expected to directly benefit from these advances.

Competitive ocean energy technologies could emerge in the present decade, but only if significant technical progress is achieved. Ocean energy technologies are suitable for the production of both electricity and potable water, whilst OTEC can also be used to provide thermal energy services (e.g., seawater cooling for air conditioners). A general overview is given in Krishna (2009).

6.3.2 Wave energy

Many wave energy technologies representing a range of operating principles have been conceived, and in many cases demonstrated, to convert energy from waves into a usable form of energy. Major variables include the method of wave interaction with respective motions (heaving, surging, pitching) as well as water depth (deep, intermediate, shallow) and distance from shore (shoreline, near-shore, offshore). Efficient operation of floating devices requires large motions, which can be achieved by resonance or by latching, that is, with hold/release of moving parts until potential energy has accumulated.

A generic scheme for characterizing ocean wave energy generation devices consists of primary, secondary and tertiary conversion stages (Khan et al., 2009). The primary interface subsystem represents fluid-mechanical processes and feeds mechanical power to the next stage. The secondary subsystem can incorporate direct drive or include short-term storage, so that power processing can be facilitated before the electrical machine is operated. The tertiary conversion utilizes electromechanical and electrical processes.

Recent reviews have identified more than 50 wave energy devices at various stages of development (Falcão, 2009; Khan and Bhuyan, 2009; US DOE, 2010). The dimensional scale constraints of wave devices have not been fully investigated in practice. The dimension of wave devices in the direction of wave propagation is generally limited to lengths below the scale of the dominant wavelengths that characterize the wave power density spectrum at a particular site. Utility-scale electricity generation from wave energy will require device arrays, rather than larger devices and, as with wind turbine generators, devices are likely to be chosen for specific site conditions.

Several methods have been proposed to classify wave energy systems (e.g., Falcão, 2009; Khan and Bhuyan, 2009; US DOE, 2010). The classification system proposed by Falcão (2009) (Figure 6.5) is based mainly upon the principle of operation. The first column is the genus, the second column is the location and the third column represents the mode of operation as outlined in the subsections below. A small number of prototype devices based upon novel uses of electro-polymers and bulging tubes fall outside of this classification scheme.

6.3.2.1 Oscillating water columns

Oscillating water columns (OWC) are wave energy converters that use wave motion to induce varying pressure levels between the air-filled chamber and the atmosphere (Falcão et al., 2000; Falcão, 2009). High-velocity air exhausts through an air turbine coupled to an electrical generator, which converts the kinetic energy into electricity (Figure 6.6, top left). When the wave recedes, the airflow reverses and fills the chamber, generating another pulse of energy (Figure 6.6, top right). The air turbine rotates in the same direction, regardless of the flow, through either its design or variable-pitch turbine blades. An OWC device can be a fixed structure located above the breaking waves (cliff-mounted or part of a breakwater), it can be bottom mounted near shore or it can be a floating system moored in deeper waters.

6.3.2.2 Oscillating-body systems

Oscillating-body (OB) wave energy conversion devices use the incident wave motion to induce oscillatory motions between two bodies; these motions are then used to drive the power take-off system (Falcão,

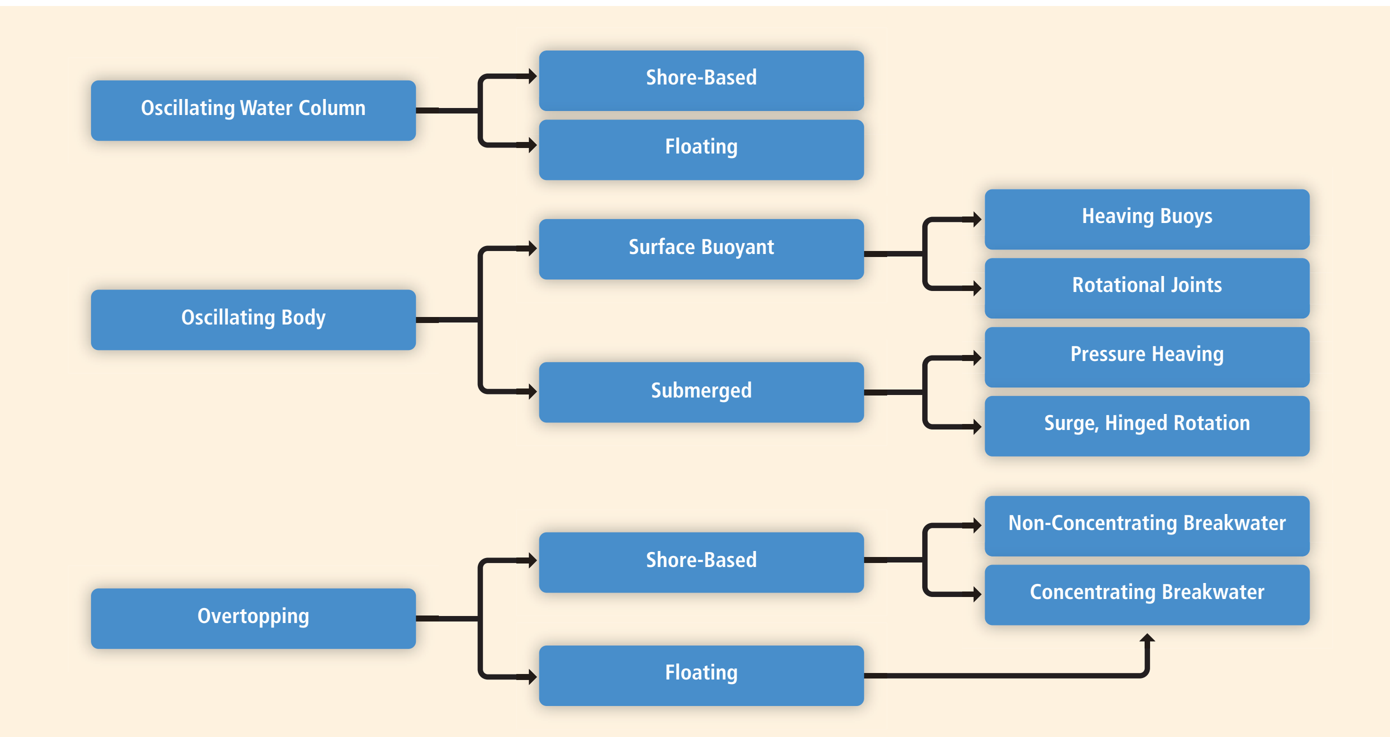


Figure 6.5 | Wave energy technologies: Classification based on principles of operation (Falcão, 2009).

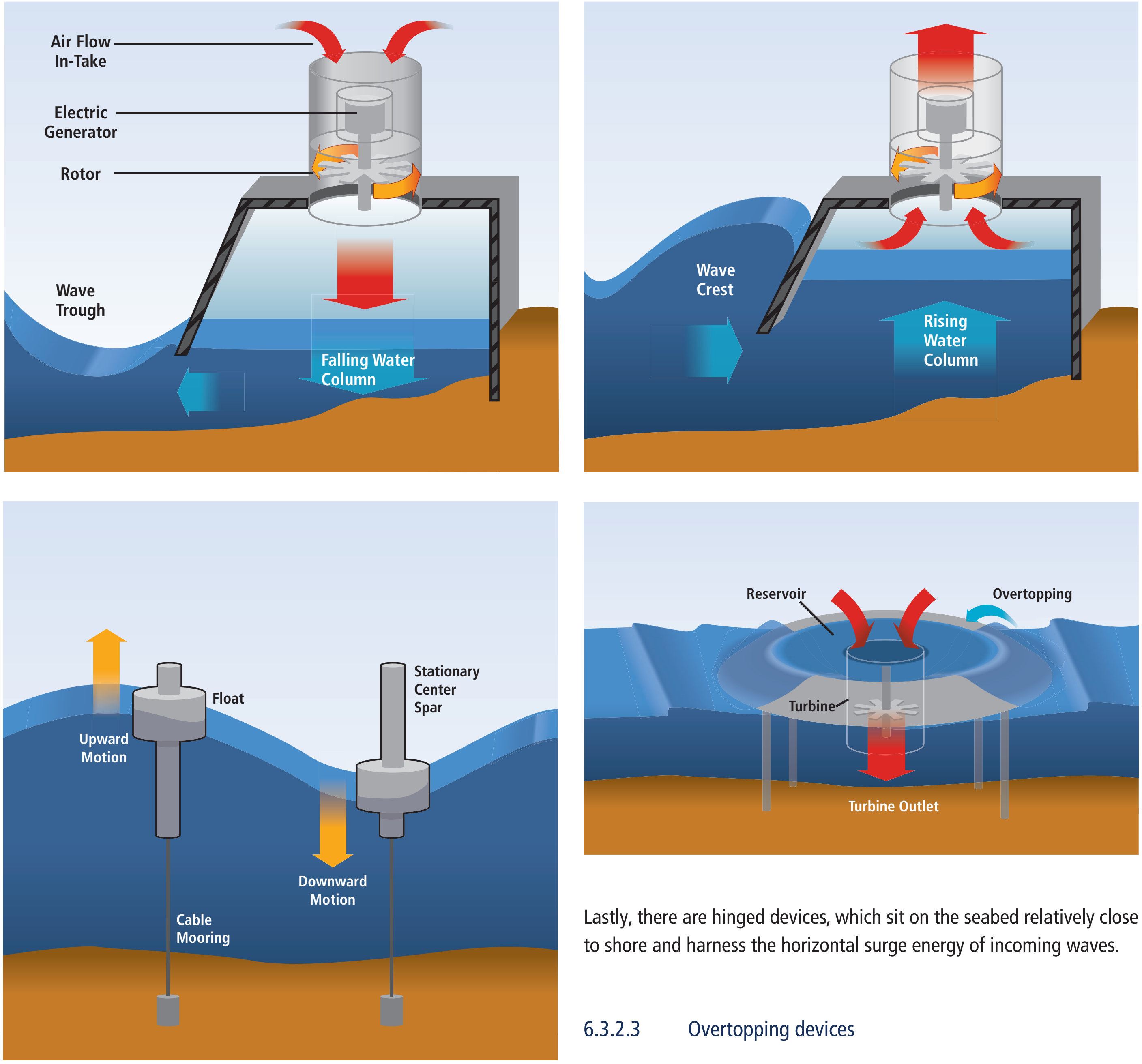


Figure 6.6 | Wave energy converters and their operation: (top, left and right) oscillating water column device; (bottom left) oscillating body device; and (bottom right) overtopping device (design by the National Renewable Energy Laboratory (NREL)).

2009). OBs can be surface devices or, more rarely, fully submerged. Commonly, axi-symmetric surface flotation devices (buoys) use buoyant forces to induce heaving motion relative to a secondary body that can be restrained by a fixed mooring (Figure 6.6, bottom left). Generically, these devices are referred to as 'point absorbers', because they are non-directional. Another variation of floating surface device uses angularly articulating (pitching) buoyant cylinders linked together. The waves induce alternating rotational motions of the joints that are resisted by the power take-off device. Some OB devices are fully submerged and rely on oscillating hydrodynamic pressure to extract the wave energy. Lastly, there are hinged devices, which sit on the seabed relatively close to shore and harness the horizontal surge energy of incoming waves.

6.3.2.3 Overtopping devices

An overtopping device is a type of wave terminator that converts wave energy into potential energy by collecting surging waves into a water reservoir at a level above the free water surface (Falcão, 2009). The reservoir drains down through a conventional low-head hydraulic turbine. These systems can be offshore floating devices or incorporated into shorelines or man-made breakwaters (Figure 6.6, bottom right).

6.3.2.4 Power take-off systems

Power take-off systems are used to convert the kinetic energy, air flow or water flow generated by the wave energy device into a useful form, usually electricity. There are a large number of different options depending upon the technology adopted and these are fully described in Khan and Bhuyan (2009). Real-time wave oscillations will produce corresponding electrical power oscillations that may degrade power quality from a single device. In practice, some method of short-term energy storage (durations of seconds) may be needed to smooth energy delivery. The cumulative power generated by several devices will be smoother than from a single device, so device arrays are likely to be common. Most oscillating-body devices use resonance to derive optimal energy absorption, which requires that the geometry, mass or size of the structure must be linked to wave frequency. Maximum power can only be extracted by advanced control systems.

6.3.3 Tidal range

The development of tidal range hydropower has usually been based on estuarine developments, where a barrage encloses an estuary, which creates a single reservoir (basin) behind it and incorporates conventional low-head hydro turbines. Alternative barrage configurations have been proposed based on multiple-basin operations. Basins are filled and emptied at different times with turbines located between the basins. Multi-basin schemes may offer more flexible power generation availability over normal schemes, such that it is possible to generate power almost continuously.

The most recent advances focus on offshore basins (single or multiple) located away from estuaries, called 'tidal lagoons', which offer greater flexibility in terms of capacity and output with little or no impact on delicate estuarine environments.

This technology uses commercially available systems and the conversion mechanism most widely used to produce electricity from tidal range is the bulb-turbine (Bosc, 1997). The 240 MW power plant at La Rance in northern France has bulb turbines that can generate in both directions (on the ebb and flood tides) and also offer the possibility of pumping, when the tide is high, in order to increase storage in the basin at low head (Andre, 1976; De Laleu, 2009). The 254 MW Sihwa Barrage in the Republic of Korea, which is nearing completion, will employ ten 25.4 MW bulb turbines in a single flood tide mode (Paik, 2008).

Some favourable sites, such as very gradually sloping coastlines, are well suited to tidal range power plants, such as the Severn Estuary between southwest England and South Wales. Current feasibility studies there include options such as barrages and tidal lagoons. Conventional tidal range power stations will generate electricity for only part of each tide cycle. Consequently, the average capacity factor for tidal power stations has been estimated to vary from 25 to 35% (Charlier, 2003); ETSAP (2010b), meanwhile, reports a capacity factor range of 22.5 to 28.5%.

6.3.4 Tidal and ocean currents

Technologies to extract kinetic energy from tidal, river and ocean currents are under development, with tidal energy converters the most common to date. River current devices are covered in Chapter 5. The principal difference between tidal and river/ocean current turbines is that river and ocean currents flows are unidirectional, whilst tidal currents reverse flow direction between ebb and flood cycles. Consequently, tidal current turbines have been designed to generate in both directions.

Several classification schemes for tidal and ocean current energy systems have been proposed (Khan et al., 2009; US DOE, 2010). Usually they are classified based on the principle of operation, such as axial-flow turbines, cross-flow turbines and reciprocating devices (Bernitsas et al., 2006, see Figure 6.7). Some devices have multiple turbines on a single device (Figure 6.8, top left). Axial-flow turbines (Figure 6.8, top left) operate about a horizontal axis whilst cross-flow turbines may operate about a vertical axis (Figure 6.8, bottom left and right) or a horizontal axis with or without a shroud to accentuate the flow.

Many of the water current energy conversion systems resemble wind turbine generators. However, marine turbine designers must also take into account factors such as reversing flows, cavitation and harsh underwater marine conditions (e.g., salt water corrosion, debris, fouling, etc). Axial flow turbines must be able to respond to reversing flow directions, while cross-flow turbines continue to operate regardless of current flow direction. Axial-flow turbines will either reverse nacelle direction about 180º with each tide or, alternatively, the nacelle will have a fixed position but the rotor blades will accept flow from both directions. Rotor shrouds (also known as cowlings or ducts) enhance hydrodynamic performance by increasing the flow velocity through the rotor and reducing tip losses. To be economically beneficial, the additional energy capture must offset the cost of the shroud over the life of the device.

Reciprocating devices (not illustrated) are generally based on basic fluid flow phenomena such as vortex shedding or passive and active flutter systems (usually hydrofoils), and normal hydrofoils (e.g., tidal sails), which induce mechanical oscillations in a direction transverse to the water flow.

Most of these devices are in the conceptual stage of development, although two prototype oscillating devices have been trialled at open sea locations in the UK (Engineering Business, 2003; TSB, 2010).

The development of the tidal current resource will require multiple machines deployed in a similar fashion to a wind farm, thus the turbine siting is important especially in relation to wake effects (Peyrard et al., 2006).

Capturing the energy of open-ocean current systems is likely to require the same basic technology as for tidal flows but some of the infrastructure involved will differ. For deep-water applications, neutrally buoyant turbine/generator modules with mooring lines and anchor systems may replace fixed bottom support structures. Alternatively, they can be attached to other structures, such as offshore platforms (VanZwieten et al., 2005). These modules will also have hydrodynamic lifting designs to allow optimal and flexible vertical positioning (Venezia and Holt, 1995; Raye, 2001; VanZwieten et al., 2005). In addition, open ocean currents

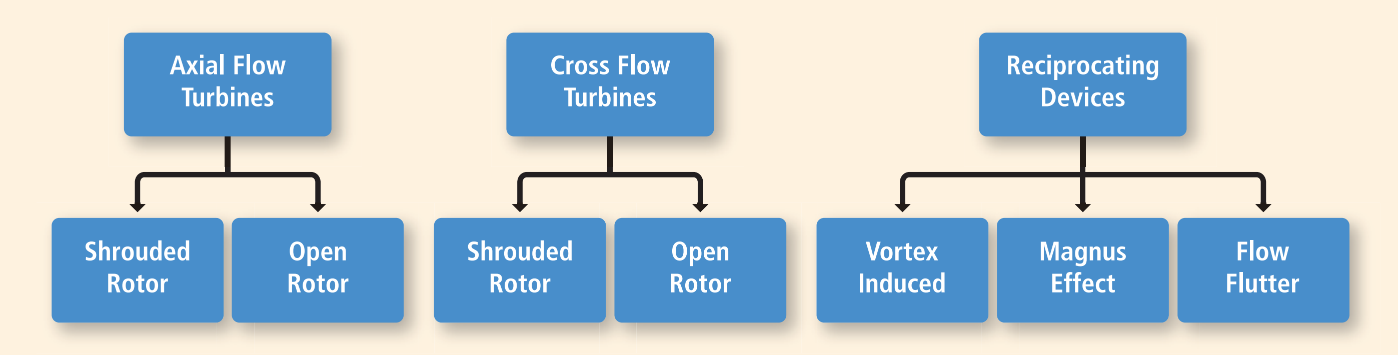
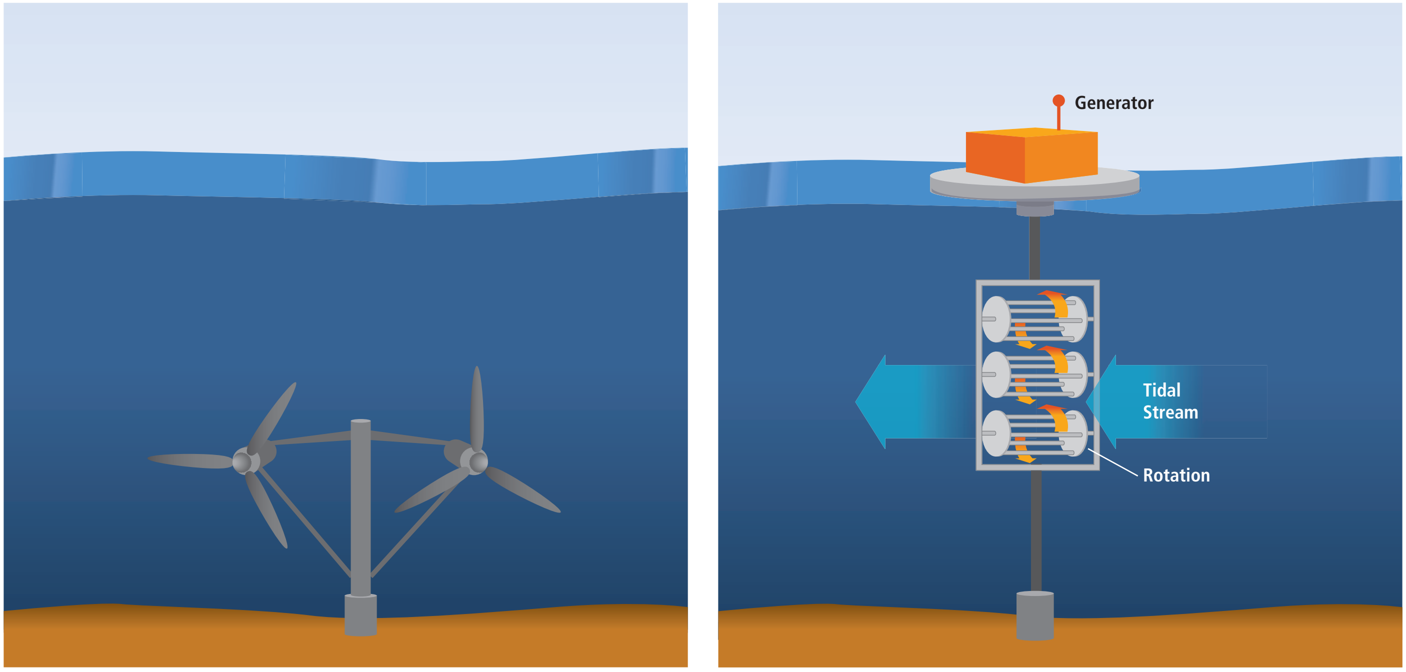


Figure 6.7 | Classification of current tidal and ocean energy technologies (principles of operation).



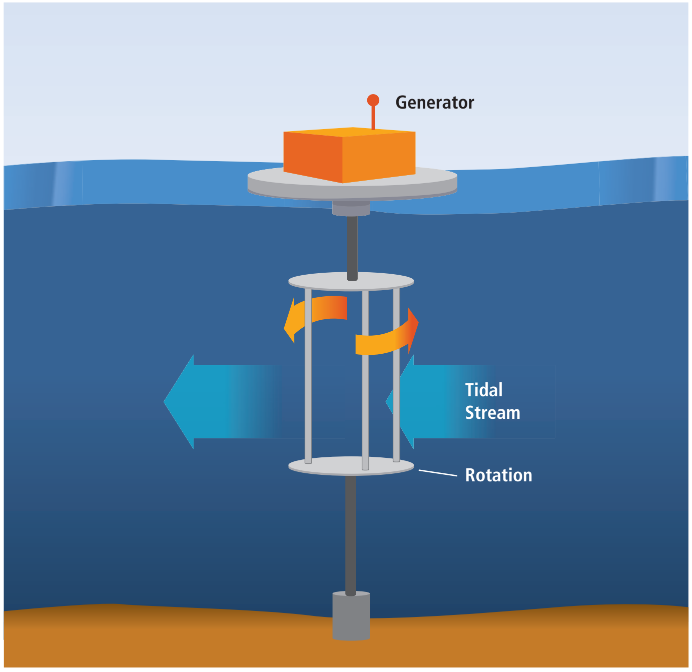


Figure 6.8 | Tidal current energy converters and their operation: twin turbine horizontal axis device (top left); cross-flow device (top right); and vertical axis device (bottom left) (design by NREL).

will not impose a size restriction on the rotors due to lack of channel constraints and therefore, ocean current systems may have larger rotors.

6.3.5 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) plants have three conversion schemes: open, closed and hybrid (Charlier and Justus, 1993). In the open conversion cycle, about 0.5% of the warm surface seawater is flash-evaporated in a vacuum chamber. This steam is the cycle's working fluid, which passes through a power-generating turbine before being condensed by deep cold seawater. Desalinated water can be obtained as an additional product by employing an appropriate cycle.

Closed conversion cycles offer more efficient thermal performance, with warm seawater from the ocean surface being pumped through heat exchangers to vaporize a secondary working fluid (such as ammonia, propane or chlorofluorocarbon (CFC)) creating a high-pressure vapour to drive a turbine. The vapour is subsequently cooled by seawater to return it to a liquid phase. Closed-cycle turbines may be smaller than open-cycle turbines because the secondary working fluid operates at a higher pressure.

A hybrid conversion cycle combines both open and closed cycles, with steam generated by flash evaporation acting as the heat source for a closed Rankine cycle, using ammonia or another working fluid.

Although there have been trials of OTEC technologies, problems have been encountered with maintenance of vacuums, heat exchanger bio-fouling and corrosion issues. However, there are a large number of potential by-products, including hydrogen, lithium and other rare elements, which enhance the economic viability of this technology.

Ocean thermal energy can also be used for seawater air conditioning, thereby providing thermal energy services (Nihous, 2009).

6.3.6 Salinity gradients

The mixing of freshwater and seawater, such as where a river flows into a saline ocean, releases energy and causes a very small increase in local water temperature (Scråmestø et al., 2009). Reversed electro dialysis (RED) and pressure-retarded osmosis (PRO) are among the concepts identified for converting this heat into electricity. This form of energy conversion is often called osmotic power and the first 5 kW PRO pilot power plant was commissioned in Norway in 2009.

6.3.6.1 Reversed electro dialysis

The RED process harnesses the difference in chemical potential between two solutions. Concentrated salt solution and freshwater are brought into contact through an alternating series of anion and cation exchange membranes (AEM and CEM) (Figure 6.9). The chemical potential difference generates a voltage across each membrane; the overall potential of the system is the sum of the potential differences over the sum of the membranes. The first prototype to test this concept is being built in the Netherlands (van den Ende and Groeman, 2007).

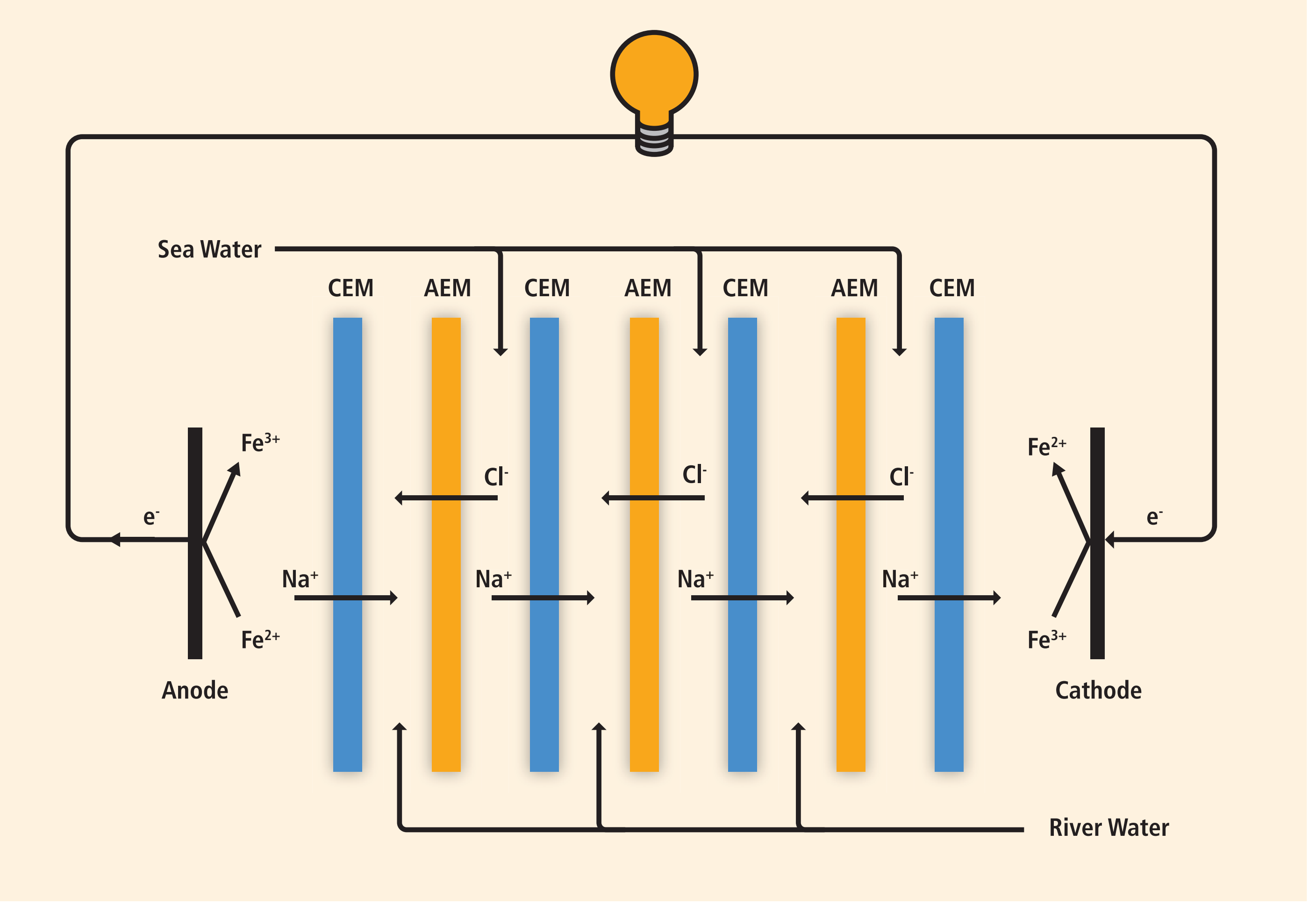


Figure 6.9 | Reversed electro dialysis (RED) system (van den Ende and Groeman, 2007).

Notes: CEM = cation exchange membrane; AEM = anion exchange membrane, Na = sodium, Cl = Chlorine, Fe = iron.

6.3.6.2 Pressure-retarded osmosis

Pressure-retarded osmosis (PRO), also known as osmotic power, is a process where the chemical potential is exploited as pressure (Figure 6.10) and was first proposed in the 1970s (Loeb and Norman, 1975).

The PRO process utilizes naturally occurring osmosis caused by the difference in salt concentration between two liquids (for example, seawater and freshwater). Seawater and freshwater have a strong tendency to mix and this will occur as long as the pressure difference between the liquids is less than the osmotic pressure difference. For seawater and freshwater the osmotic pressure difference will be in the range of 2.4 to 2.6 MPa (24 to 26 bar), depending on seawater salinity.

Before entering the PRO membrane modules, seawater is pressurized to approximately half the osmotic pressure, about 1.2 to 1.3 MPa (12 to 13 bar). In the membrane module, freshwater migrates through the membrane and into pressurized seawater. The resulting brackish water is then split into two streams (Scråmestø et al., 2009). One-third is used for power generation (corresponding to approximately the volume of freshwater passing through the membrane) in a hydropower turbine, whilst the remainder passes through a pressure exchanger in order to pressurize the incoming seawater. The brackish water can be fed back to the river or into the sea, where the two original sources would have eventually mixed.

6.4 Global and regional status of market and industry development

6.4.1 Introduction

Since the 1990s, R&D projects on wave and tidal current energy technologies have proliferated, with some now reaching the full-scale pre-commercial prototype stage. Presently, the only full-size and operational ocean energy technology available is the tidal barrage, of which the best example is the 240 MW La Rance Barrage in northwestern France, completed in 1966 (540 GWh/yr; De Laleu, 2009). The 254 MW Sihwa Barrage (South Korea) is due to become operational in 2011. Technologies to develop the other ocean energy sources—ocean thermal energy conversion (OTEC), salinity gradients and ocean currents—are still at the conceptual, R&D or early prototype stages. Currently, more than 100 different ocean energy technologies are under development in over 30 countries (Khan and Bhuyan, 2009).

6.4.1.1 Markets

Apart from tidal barrages, all ocean energy technologies are conceptual, undergoing R&D or in the pre-commercial prototype stage. Consequently, there is virtually no commercial market for ocean energy technologies at present.

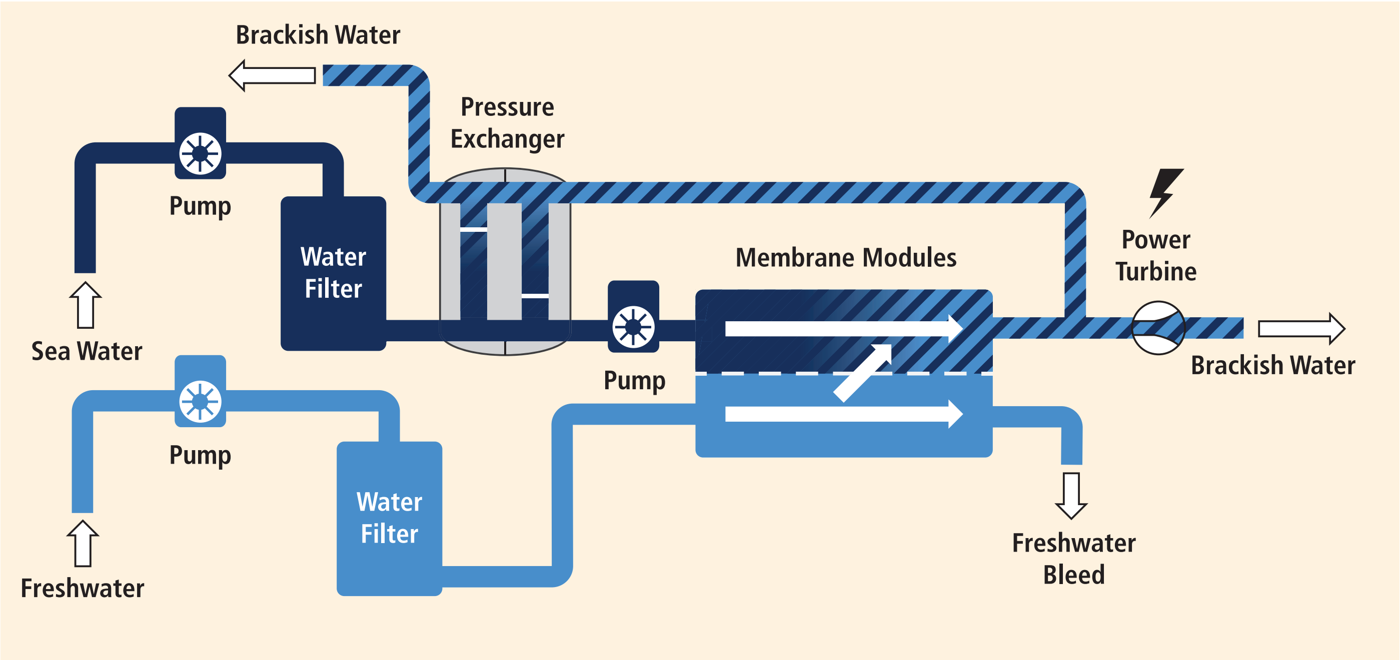


Figure 6.10 | Pressure-retarded osmosis (PRO) process (Scråmestø et al., 2009).

Some governments are using a range of initiatives and incentives to promote and accelerate the implementation of ocean energy technologies. These are described in Section 6.4.7. The north-eastern Atlantic coastal countries lead the development of the market for ocean energy technologies and their produced electricity. Funding mechanisms such as the Clean Development Mechanism (CDM) or Joint Implementation (JI) projects enable governments to secure additional external funding for ocean energy projects in developing nations. The Sihwa barrage project in the Republic of Korea was funded, in part, by CDM finance (UNFCCC, 2005).

Since there are ocean energy technologies being developed that produce pressurized or potable water as well as, or instead of, electricity, they may be able to compete in the market for water.

6.4.1.2 Industry development

As the marine energy industry moves from its present R&D phase, capacity and expertise from existing industries, such as electrical and marine engineering and offshore operations, will be drawn in, encouraging rapid growth of industry supply chains. The industry is presently underpinned by a large number of independent, entrepreneurial companies with limited investment from the finance sector. Large utility investment in device developments has become more commonplace in the last 10 years and some governments have recognized the skills and knowledge transfer benefits from other industries.

An unusual feature of ocean energy is the emergence of an international network of national marine energy testing centres, which includes the European Marine Energy Centre[1] (EMEC) in Scotland—the first of a growing number of testing centres worldwide—where device developers can reduce the costs of testing their prototypes by using existing infrastructure, particularly the offshore cable, power purchase agreements and permits. These centres are accelerating the development of a wide range of wave and tidal current technologies by effectively allowing device developers to share the costs of device prototype testing.

Industry development road maps and supply chain studies have been developed for Scotland, the UK and New Zealand (AWATEA, 2008; Mueller and Jeffrey, 2008; MEG, 2009). The USA (Thresher, 2010) and Ireland (SEAI, 2010) have completed road mapping exercises and Canada has begun road mapping exercises. Similar road maps have been produced for the EU countries (EOEA, 2010) and European marine energy science research (ESF MB, 2010). These countries have begun to assess the market potential for ocean energy as an industry or regional development initiative. Regions supporting industry cluster development, leading to scalable power developments, seek to attract concentrations of industry.

A series of global and regional initiatives now exist for collaborative development of ocean energy markets and industry. These are assisting in the development of international networks, information flow, removal of barriers and efforts to accelerate marine energy uptake. The presently active initiatives include the following:

- The International Energy Agency's Ocean Energy Systems Implementing Agreement.[2] This initiative has members from the developing countries who can see an opportunity for the transfer of knowledge to exploit their local ocean energy resources.
- The Equitable Testing and Evaluation of Marine Energy Extraction Devices (EquiMar). This EU-funded initiative intends to deliver a suite of protocols for the evaluation of wave and tidal stream energy converters.[3]
- The Wave Energy PLanning And Marketing (WavePLAM) project. This European industry initiative addresses non-technical barriers to wave energy.[4]

6.4.2 Wave energy

Wave energy technologies started to be developed after the first oil crisis in 1974. Many different converter types have been, and continue to be, proposed and tested but they are still at the pre-commercial phase. Recently, governments and developers have begun to use Technology Readiness Levels to guide their structured development of marine energy devices (Holmes and Nielsen, 2010). It is usual to test devices at a small scale in laboratory test-tank facilities (1:15 to 1:50 scale) before the first open-sea prototype testing (1:4 to 1:10 scale). Pre-commercial testing may be at half or full scale. Presently only a handful of devices have been built and tested at full scale. Pre-commercial trials of individual modules and small arrays began in recent years and are expected to accelerate through this decade. Given the early stage of development, the costs for wave energy are relatively high, but significant potential for cost reductions exist. Programmes such as the Marine Energy Accelerator programme (Callaghan, 2006) and incentives for pilot markets are intended to accelerate the cost reduction experience to seek to make wave energy technologies commercially competitive in the future.

A coast-attached oscillating water column device has been operational in Portugal since 1999 (Falcão et al., 2000; Aqua-RET, 2008) and a somewhat similar device (Voith Hydro Wavegen's LIMPET device)[5] has been operating almost continuously on the island of Islay in Scotland since 2000. Two offshore oscillating water column devices have been tested at prototype scale in Australia (Energetech/Oceanlinx)[6] since 2006

1 See www.emec.org.uk for Centre description.

2 See www.iea-oceans.org for description of activity.

3 See www.equimar.org for description of project outcomes.

4 See www.waveplam.eu for description of project outcomes.

5 See www.wavegen.co.uk for description of technology.

6 See www.oceanlinx.com for description of technology.

(Denniss, 2005) and Ireland (the OE Buoy)[7]. An oscillating water column device was operational off the southern coast of India between 1990 and 2005, when several experiments on the power modules were conducted and wave-powered desalination was demonstrated (Ravindran et al., 1997; Sharmila et al., 2004).

The most maturely developed oscillating-body device is the 750 kW Pelamis Wavepower[8] attenuator device, which has been tested in Scotland and deployed in Portugal. The Portuguese devices were sold as part of a commercial demonstration project. The other near-commercial oscillating-body technology is Ocean Power Technologies' PowerBuoy,[9] a small (40 to 250 kW) vertical axis device, which has been deployed in Hawaii, New Jersey and on the north Spanish coast. Other oscillating-body devices under development include the Irish device, Wavebob,[10] the WET-NZ device[11] and the Brazilian hyperbaric converter (Estefen et al., 2010).

Two Danish overtopping devices have been built at prototype scale and deployed at sea (Wave Dragon[12] and WavePlane[13]). Finally, two surge devices have been tested. Aquamarine Power[14] deployed its first full-scale 'Oyster' unit at EMEC in November 2009, whilst AW Energy (Finland) will deploy its Waveroller[15] surge device off the coast of Portugal.

6.4.3 Tidal range

Presently, only estuary-type tidal power stations are in operation. They rely on a barrage, equipped with generating units, closing the estuary. Though the technology itself is mature, the only utility-scale tidal power station in the world is the 240 MW La Rance power station, which has been in successful operation since 1966. Other smaller projects have been commissioned since then in China, Canada and Russia. The 254 MW Sihwa barrage is expected to be commissioned in 2011 and will then become the largest tidal power station in the world. The Sihwa power station is being retrofitted to an existing 12.7 km sea dyke that was built in 1994. The project will generate electricity whilst also improving flushing in the reservoir basin to improve water quality.

By the end of 2011, the world's installed capacity of tidal range power will still be less than 600 MW, assuming that the Sihwa power plant comes on line. However, numerous projects have been identified, some of them with very large capacities, including in the UK (Severn Estuary), India, Korea and Russia (the White Sea and Sea of Okhotsk). Total installed capacity under consideration is approximately 43.7 GW, or 64.05 TWh/yr (233 PJ/yr) (Kerr, 2007).

6.4.4 Tidal and ocean currents

There are probably more than 50 tidal current devices at the proof-of-concept or prototype development stage, but large-scale deployment costs are yet to be demonstrated. The most advanced example is the SeaGen[16] 1.2 MW capacity tidal turbine, which was installed in Strangford Lough in Northern Ireland and has delivered electricity into the electricity grid for more than one year. An Irish company, Open Hydro,[17] has tested its open-ring turbine at EMEC in Scotland, and more recently in Canada (Bay of Fundy). A number of devices have also been tested in China (Zhang and Sun, 2007).

Two companies have demonstrated horizontal axis turbines at full scale: Hammerfest Strom[18] in Norway and Atlantis Resources Corporation[19] in Scotland, whilst Ponte di Archimede[20] has demonstrated a vertical-axis turbine in the Straits of Messina (Italy). Finally, Pulse Tidal Limited[21] demonstrated a reciprocating device off the Humber Estuary in the UK in 2009.

The resource for tidal current energy is not widespread, with potentially economically viable sites located where tidal current velocities are accelerated around headlands or through channels between islands. Potential sites have been identified in Europe (particularly Scotland, Ireland, the UK and France), China, Korea, Canada, Japan, the Philippines, Australasia and South America. A number of development projects will begin during the present decade: experience and scale-up in these projects is expected to drive down costs.

Open ocean currents, such as the Gulf Stream, are being explored for development. Because they are slower moving and unidirectional, harnessing open ocean currents may require different technologies from those presently being developed for the faster, more restricted tidal stream currents (MMS, 2006). No pilot or demonstration plants have been deployed to date. Given the scale of open ocean currents, which involve much larger water volumes than tidal currents, there is a promise

7 See www.oceanenergy.ie/index.html for description of technology.

8 See www.pelamiswave.com for description of technology.

9 See www.oceanpowertechnologies.com for description of technology.

10 See www.wavebob.com for description of technology.

11 See www.wavenergy.co.nz for description of technology.

12 See www.wavedragon.net for description of technology.

13 See www.waveplane.com for description of technology.

14 See www.aquamarinepower.com for description of technology.

15 See www.aw-energy.com for description of technology.

16 See www.marinecurrentturbines.com for description of technology.

17 See www.openhydro.com/home.html for description of technology.

18 See www.hammerfeststrom.com for description of technology.

19 See www.atlantisresourcescorporation.com for description of technology.

20 See www.pontediarchimede.it/language_us for description of technology.

21 See www.pulsetidal.co.uk/our-technology.html for description of technology.

of significant project scale if technologies can be developed to harness the lower-velocity currents.

6.4.5 Ocean thermal energy conversion[22]

Presently only a small number of OTEC test facilities have been trialled globally. A small 'Mini-OTEC' prototype plant was tested in the USA in 1979. Built on a floating barge, the plant used an ammonia-based closed-cycle system with a 28,200 rpm radial inflow turbine. Although the prototype had a rated capacity of 53 kW, pump efficiency problems reduced its output to 18 kW. A second floating OTEC plant (OTEC-1) using the same closed-cycle system but without a turbine was built in 1980. Rated at 1 MW, it was primarily used for testing and demonstration, including studies of issues with the heat exchanger and water pipe, during its four months of operation in 1981.

In 1982 and 1983 in the Republic of Nauru, a 120-kW plant that used a Freon-based closed-cycle system and a cold water pipe to a depth of 580 m was operated for several months. It was connected to the electric grid and generated a peak of 31.5 kW of power.

An open-cycle OTEC plant was built in Hawaii in 1992 that operated between 1993 and 1998, with peak production of 103 kW and 0.4 l/s of desalinated water. Operational issues included seawater out-gassing in the vacuum chamber, problems with the vacuum pump, varying output from the turbogenerator and the connection to the electrical grid.

In 1984, India designed a 1 MW ammonia-based closed-cycle OTEC system. Construction began in 2000 but could not be completed due to difficulties in deployment of the long cold water pipe (Ravindran and Raju, 2002). A 10-day experiment was conducted on the same barge off Tuticorin in 2005, and desalination using ocean thermal gradients was demonstrated in shallower depths.

By the early 2000s, Japan had tested a number of OTEC power plants (Kobayashi et al., 2004). In 2006, the Institute of Ocean Energy at Saga University built a prototype 30-kW hybrid OTEC plant that uses a mixed water/ammonia working fluid and continues to generate electrical power.

Larger-scale OTEC developments could have significant markets in tropical maritime nations, including the Pacific Islands, Caribbean Islands, Central American and African nations, if the technology develops to the point of being a cost-effective energy supply option.

6.4.6 Salinity gradients

Salinity gradient power is still a concept under development (Scråmestø et al., 2009), with two research/demonstration projects under development, using two different technology concepts (Section 6.3.6). The parallel development of related technologies, such as desalination, is expected to benefit the development of osmotic power systems.

Research into osmotic power is being pursued in Norway, with a prototype becoming operational in 2009 (Statkraft, 2009) as part of a drive to deliver a commercial osmotic power plant. At the same time, the RED technology has been proposed for retrofitting to the 75-year-old Afsluitdijk dike in the Netherlands (Willemse, 2007).

6.4.7 Impact of Policies[23]

Presently the north-western European coastal countries lead development of ocean energy technologies, with the North and South American, north-western Pacific and Australasian countries also involved. Ocean energy technologies could offer emission-free electricity generation and potable water production, and a number of governments have introduced policy initiatives to promote and accelerate the uptake of marine energy. Chapter 11 gives more details of policies and initiatives that promote renewable energy technology uptake. Some of these policies and initiatives are applied to ocean energy and fall into six main categories:

1. Capacity or generation targets;
2. Capital grants and financial incentives, including prizes;
3. Market incentives;
4. Industry development;
5. Research and testing facilities and infrastructure; and
6. Permitting/space/resource allocation regimes, standards and protocols.

Generally, the countries that have ocean energy-specific policies in place are also the most advanced with respect to technology developments and deployments, and given the early state of the technology, government support for ocean energy is likely to be critical to the pace at which technologies and projects are developed.

There are a variety of targets both aspirational and legislated. Most ocean energy-specific targets relate to proposed installed capacity, complementing other general targets, such as for proportional increases in other RE generation. Some European countries, such as Portugal and Ireland, have preferred 'market pull' mechanisms, such as feed-in tariffs (i.e., additional payments for produced electricity from specific technologies), whilst the UK and the Scottish Government have utilized enhanced banded Renewable Obligations Certificates schemes, that is, tradable certificates awarded to generators of electricity using ocean energy technologies. The Scottish Government introduced the Saltire Prize in 2008, which is a prize for the first device developer to meet a cumulative electricity generation target of 100 GWh over a continuous two-year period.

22 The contents of Section 6.4.5 are primarily derived from Vega (1999) and Khan and Bhuyan (2009) except where stated.

23 Non-technology-specific policy issues are covered in Chapter 11 of this report.

Most countries offer R&D grants for RE technologies but some have ocean energy-specific grant programs. The UK has had the longest, largest and most comprehensive programs, though the US Federal Government has increased investment significantly since 2008. Capital grant programs for device deployments have been implemented by both the UK and New Zealand as 'supply push' mechanisms but both countries have a range of policy instruments in place (Table 6.2). Note that Table 6.2 shows only examples of ocean energy policies existing at the end of 2010.

6.5 Environmental and Social Impacts[24]

6.5.1 Lifecycle greenhouse gas emissions

Ocean energy does not directly emit CO_2 during operation; however, GHG emissions may arise from different aspects of the lifecycle of ocean energy systems, including raw material extraction, component manufacturing, construction, maintenance and decommissioning. A comprehensive review of lifecycle assessment (LCA) studies published

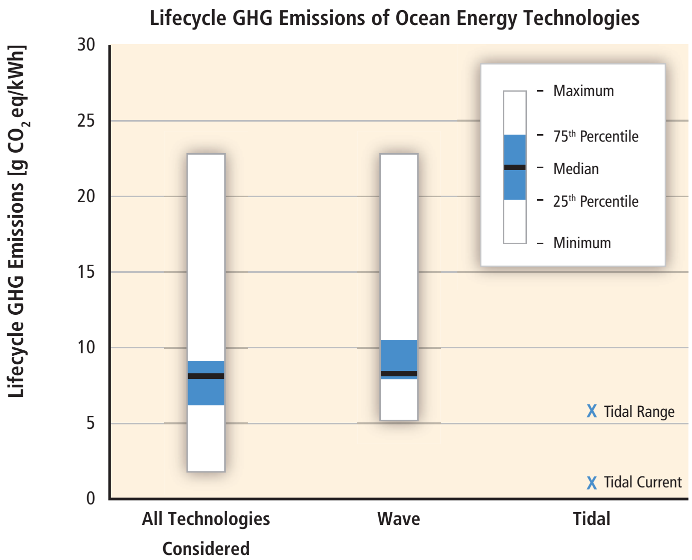
Table 6.2 | Examples of ocean energy-specific policies (modified from Huckerby and McComb, 2008).

Policy Instrument	Country	Example Description
Capacity or Generation Targets		
Aspirational Targets And Forecasts	UK Spain (Basque Government) Canada	3% of UK electricity from ocean energy by 2020 5 MW off Basque coast by 2020 Canada is developing a roadmap for 2050 (Ocean Renewable Energy Group)[1]
Legislated Targets (Total Energy Or Electricity)	Ireland Portugal	Specific targets for marine energy installations 500 MW by 2020 off Ireland 550 MW by 2020 off Portugal
Capital Grants and Financial Incentives		
R&D Programs/Grants	USA China	US Department of Energy Wind & WaterPower Program (capital grants for R&D and market acceleration) High Tech Research & Development Programme (#863)
Prototype Deployment Capital Grants	UK New Zealand China	Marine Renewables Proving Fund Marine Energy Deployment Fund Ocean Energy Major Projects
Project Deployment Capital Grants	UK	Marine Renewables Deployment Fund
Prizes	Scotland	Saltire Prize (GBP 10 million for first ocean energy device to deliver over 100 GWh of electricity over a continuous two-year period)
Market Incentives		
Feed-In Tariffs	Portugal Ireland/Germany	Guaranteed price (in $/kWh or equivalent) for ocean energy-generated electricity
Tradable certificates and Renewables Obligation	UK	Renewable Obligation Scheme - tradable certificates (in $/MWh or equivalent) for ocean energy-generated electricity
Industry Development		
Industry & Regional Development Grants	Scotland, UK and others	Cluster developments
Industry Association Support	Ireland New Zealand	Government financial support for establishment of industry associations
Research and Testing Facilities and Infrastructure		
National Marine Energy Centres	USA	Two centres established (Oregon/Washington for wave/tidal and Hawaii for OTEC/wave)
Marine Energy Testing Centres	Scotland, Canada and others	European Marine Energy Centre[2] and Fundy Ocean Research Centre for Energy, Canada[3]
Offshore Hubs	UK	Wave hub, connection infrastructure for devices
Permitting/Space/Resource Allocation Regimes, Standards And Protocols		
Standards/Protocols	International Electrotechnical Commission	Development of international standards for wave, tidal and ocean currents
Permitting Regimes	UK	Crown Estate competitive tender for Pentland Firth licences
Space/Resource Allocation Regimes	USA	Department of Interior permitting regime in US Outer Continental Shelf

Notes: 1. See www.oreg.ca for description of roadmap. 2. See www.emec.org.uk for description of Centre. 3. See www.fundyforce.ca for description of Centre.

24 A comprehensive assessment of social and environmental impacts of all RE sources covered in this report can be found in Chapter 9.

since 1980 suggests that lifecycle GHG emissions from wave and tidal energy systems are less than 23 g CO_2eq/kWh, with a median estimate of lifecycle GHG emissions of around 8 g CO_2eq/kWh for wave energy (Figure 6.11). (Note that the distributions shown in Figure 6.11 do not represent an assessment of likelihood; the figure simply reports the distribution of currently published literature estimates passing screens for quality and relevance. See Annex II for further description of the literature search methods and list of references.)



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

Figure 6.11 | Estimates of life-cycle GHG emissions of wave and tidal range technologies (unmodified literature values, after quality screen). See Annex II for details of literature search and citations of literature contributing to the estimates displayed.

Insufficient studies have been conducted on wave and tidal range devices to determine whether there are any significant differences between them regarding GHG emissions; studies of tidal and ocean current, ocean thermal energy conversion and salinity gradient devices that pass the quality screens are lacking. Further LCA studies to increase the number of estimates for all ocean energy technologies are needed. Regardless, in comparison to fossil energy generation technologies, the lifecycle GHG emissions from ocean energy devices appear low.

6.5.2 Other environmental and social impacts

Ocean energy projects may be long-lived, more than 25 years in general and over 100 years for tidal barrages (Sustainable Development Commission, 2007), so the long-term effects of their development need to be considered. While the transfer of experience from other offshore technologies (such as oil and gas operations and offshore wind energy) may be appropriate, the lack of experience in deploying and operating ocean energy technologies means that there is presently little information regarding their local environmental or social impacts.

In 2001, the British Government concluded that "the adverse environmental impact of wave and tidal energy devices is minimal and far less than that of nearly any other source of energy, but further research is required to establish the effect of real installations" (House of Commons, 2001). At the same time, some European and North American governments are undertaking strategic environmental assessments to plan for the potential environmental effects of ocean energy projects, which would typically include the effects of deployment scale, design, installation, operation and maintenance (O&M) and decommissioning on the physical and biological environment. Any type of large-scale ocean energy development is likely to require extensive social and environmental impact assessments to fully evaluate all development options. A description of potential environmental effects is given by Boehlert and Gill (2010).

Besides climate change mitigation, possible positive effects from ocean energy may include avoidance of adverse effects on marine life by virtue of reducing other human activities in the area around the ocean devices, and the strengthening of energy supply and regional economic growth, employment and tourism. As one example, it has been estimated that Scotland has the possibility to create between 630 and 2,350 jobs in ocean energy by 2020 (AEA Technology & Poyry Energy Consulting, 2006). In another example, ocean energy systems have become tourist attractions in their own right, providing jobs in tourism and services (e.g., La Rance tidal barrage: Lang, 2008; De Laleu, 2009).

Negative effects may include a reduction in visual amenity and loss of access to space for competing users, noise during construction, and other limited specific impacts on local ecosystems. Project-specific effects will vary, depending on the specific qualities of the project, the environment where the project will be located and the communities that live near it. Technology-specific strategies, such as mobile OTEC plants that limit concentrated environmental effects, are one approach to mitigating possible negative impacts. The specific environmental and social impacts of ocean energy technologies will depend in part on the technology in question and so the following sections describe the potential impacts for each energy source in turn.

6.5.2.1 Wave energy

The environmental impacts of wave energy technologies are difficult to assess due to the lack of deployment experience. The potential effects will vary by technology and location, but may include competition for space, noise and vibration, electromagnetic fields, disruption to biota and habitats, water quality changes and possible pollution. Pilot projects and pre-commercial deployments are likely to generate useful data on potential environmental effects and their mitigation.

The visual impacts of wave energy converters are likely to be negligible, since most devices are partially or completely submerged, except where large arrays of devices are located near shore. For the same reason, the potential effects on bird migration routes, feeding and nesting are expected to be negligible.

Deploying wave devices may have effects similar to other existing marine structures, although the extent of some effects may be smaller than for existing uses (see Boehlert et al., 2007). Noise and vibration are likely to be most disruptive during construction and decommissioning, while electromagnetic fields around devices and electrical connection/export cables that connect arrays to the shore may be problematic to sharks, skates and rays (elasmobranchii) that use electromagnetic fields to navigate and locate prey. Chemical leakage due to abrasion (of paints and anti-fouling chemicals) and leaks, for example, oil leaks from hydraulic power take-off systems are potential impacts. All of these effects will require R&D to understand, eliminate or mitigate. Energy capture and thus downstream effects could cause changes in sedimentation (e.g., seabed scouring or sediment accumulation) as well as wave height reductions. Wave energy farms could reduce swell conditions at adjacent beaches and modify wave dynamics along the shoreline. These aspects can be assessed through numerical and tank testing studies.

In addition to electricity generation with low lifecycle GHG emissions, the possible benefits of wave energy include industry stimulation for local shipyards (device construction and/or assembly), transportation, installation and maintenance. In addition, exclusion areas for wave farms may create wildlife refuges, which may be a net benefit to fishery resources (House of Commons, 2001).

6.5.2.2 Tidal range

Estuaries are complex, unique and dynamic natural environments that require very specific and careful attention. The impacts on the natural environment have to be addressed for both the construction phase and for future operations and decommissioning.

Construction impacts will differ depending on the construction techniques employed, with some long-term effects being positive for species diversity and abundance (Retiere and Kirby, 2006). At the La Rance power plant, although the estuary was closed for the construction period, biodiversity comparable to that of neighbouring estuaries was reportedly restored less than 10 years after commissioning (De Laleu, 2009). Other construction methods, such as floating caissons being submerged in place, may further reduce short- and longer-term impacts (Lang, 2008). The environmental impacts during construction of the Sihwa tidal power plant have been very limited, in large part because the barrage into which the plant has been inserted already existed.

Operation of a barrage will affect the amplitude and timing of the tides inside the basin, and modify fish and bird life and habitat, water salinity and sediment movements in the estuary (Bonnot-Courtois, 1993). Some of these impacts can be mitigated through adopting appropriate operational practices: for example, the La Rance barrage maintains two tides a day inside the basin, which has resulted in the restoration of a 'natural' biodiversity in the basin. However, sediments accumulating towards the upstream end of the basin require regular dredging.

Construction and operation of offshore tidal lagoons is less likely to have adverse impacts on delicate near-shore ecosystems; however, it will impact the area covered by the new lagoon.

With respect to social impacts, tidal range projects constructed to date have not required any relocation of nearby inhabitants, and this should continue to be so for future projects. Moreover, the construction phase will generate local employment opportunities and associated benefits for local communities. Following construction, barrages may provide new and shorter road transport routes along the top of the barrage walls, and this also may improve the socioeconomic conditions for local communities.

6.5.2.3 Tidal and ocean currents

Tidal currents
Tidal current technologies are likely to involve large submarine structures, although some devices have surface-piercing structures. Environmental effects may be somewhat limited because devices will be located in already energetic, moving water environments, which have low species diversity and abundances.

While current technologies have moving parts (rotating rotor blades or flapping hydrofoils) that may harm marine life, there is no evidence to date of harm from tidal current devices to marine life, such as whales, dolphins, seals and sharks. This may be due in part to the limited number and duration of device deployments, but it may also be due to slow rotation speeds (relative to escape velocities of the marine fauna) compared with ship propulsion.

Ocean currents
Possible impacts from full-scale commercial deployments of ocean current energy systems can be grouped into four broad categories: the physical environment (the ocean itself); benthic (ocean-bottom) communities; marine life in the water column; and competing uses for marine space (Charlier and Justus, 1993; Van Walsum, 2003).

Physical effects on the ocean are expected to be limited: ocean current energy devices will not be of sufficient scale to alter ocean circulation or net mass transport. For example, the equatorward drift in wind-driven circulation, for which western boundary currents are the poleward return flow, is independent of the basin's dissipative mechanisms (e.g., Stommel, 1966). Systems could, however, alter meander patterns and upper-ocean mixing processes. These effects need to be fully evaluated prior to full site development. Modelling studies of the Florida Current are underway to assess these potential impacts (Chassignet et al., 2007).

Open-ocean energy generation systems are likely to operate below the draught of even the largest surface vessels, so hazards to commercial navigation will be minimal. Submarine naval operations could be impacted, although the stationary nature of the systems will make avoidance relatively simple. Underwater structures may affect fish habitats and behaviour. Because underwater structures are known to become fish aggregating devices (Relini et al., 2000), possible user conflicts, including line entanglement issues, must be considered. Associated alterations to pelagic habitats, particularly for large-scale installations, may become issues as well (Battin, 2004).

6.5.2.4 Ocean thermal energy conversion

Potential changes in the regional properties of seawater due to OTEC pumping operations may be an environmental concern. Large volumes of cold deep water and warm shallow water will be pumped to the heat exchangers and mixed. Mixing will modify the temperature and nutrient characteristics of the waters before discharge into ambient ocean water near the site. For this reason, shipboard (or 'grazing') OTEC projects have been proposed so that the large volumes of discharged water do not have a long-term impact on the discharge site (Nihous and Vega, 1993). Discharging the water at depth may minimize the environmental effects, but no robust evidence is currently available (Marti, 2008).

Under normal operating conditions, OTEC power plants will release few emissions to the atmosphere and will not adversely affect local air quality. Plankton (and perhaps food web) growth could occur as nutrient-rich deepwater effluents are released; this might only occur if sufficient light is also available at the stabilized plume depth (generally deeper than the discharge depth). Marine organisms, mainly plankton will be attracted by marine nutrients in the OTEC plant's discharge pipe, which can cause biofouling and corrosion (Panchal, 2008).

6.5.2.5 Salinity gradients

The mixing of seawater and freshwater is a natural process in estuarine environments (van den Ende and Groeman, 2007), and salinity gradient power plants would replicate this process by mixing freshwater and seawater before returning the brackish water to the ocean. Though normal brackish water is the main waste product, its concentrated discharge may alter the environment and have impacts on animals and plants living in the location.

Major cities and industrial areas are often sited at the mouths of major rivers, so power plants could be constructed on 'brown-field' sites. The plants could also be constructed partly or completely underground to reduce the visual impact on the local environment.

6.6 Prospects for technology improvement, innovation and integration[25]

As emerging technologies, ocean energy devices have the potential for significant technological advances. Not only will device-specific R&D and deployment be important to achieving these advances, but technology improvements and innovations in ocean energy converters are also likely to be influenced by developments in related fields. Rapidly growing deployments of offshore wind power plants, for example, may lead to the possibility of wave or tidal current projects being combined with them to share infrastructure (Stoutenburg et al., 2010). Similarly some breakwater-attached wave energy converters may benefit from synergies with new construction used for other purposes such as the Mutriku plant, Portugal (Torre-Enciso et al., 2009) and in China (Liu et al., 2009).

Integration of ocean energy into wider energy networks will need to recognize the widely varying generation characteristics arising from the different resources. For example, electricity generation from tidal stream resources shows very high variability over one to four hours, yet extremely limited variability over monthly or longer time horizons (Sinden, 2007). By comparison, hour-to-hour variability of wave energy tends to be lower than that of wind power, and many times lower than that of tidal stream power, while retaining significant seasonal and interannual variability (Sinden, 2007). These patterns of resource availability have implications for the large-scale integration of ocean energy into electricity networks (see Chapter 8), and on the requirements for, and utilization of, transmission capacity.

6.6.1 Wave energy

Wave energy technologies are still largely at an early stage of development and all are pre-commercial (Falcão, 2009). Any cost or reliability projections have a high level of uncertainty, because they require assumptions to be made about optimized systems that have not yet been proven at or beyond the prototype level. 'Time in the water' is critical for prototype wave devices, so developers can gain enough operating experience. Demonstrated survivability in extreme conditions will be required to advance technology developments. As has happened with wind turbine generators, wave energy devices are expected to evolve to the scale of the largest practical machine. This will minimize the number of aggregate O&M service visits, reduce installation and decommissioning costs and limit mooring requirements.

Cost reductions may in part arise from maximizing power production by individual wave energy converters, even if deployed in arrays, and from manufacturing and installation experience. This will likely require

25 Section 10.5 offers a complementary perspective on drivers of and trends in technological progress across RE technologies. Chapter 8 deals with other integration issues more widely.

efficient capture devices and dependable, efficient conversion systems, together with dedicated manufacturing and installation infrastructure.

6.6.2 Tidal range

Tidal range power projects rely on proven hydropower technologies built and operated in an estuarine environment. There are basically three areas where technology improvements can still be achieved: development of offshore tidal lagoons may allow the implementation of cost-effective projects (Friends of the Earth, 2004); multiple tidal basins may increase the value of projects by reducing the variability and even allowing base-load or dispatchable electricity (Baker, 1991); and turbine efficiency improvements (e.g., Nicholls-Lee et al., 2008), particularly in bi-directional flows (including pumping), may reduce overall costs of electricity delivery.

Technologies may be further improved, for instance, with gears allowing different rotation speeds for the turbine and the generator or with variable frequency generation, allowing better outputs. Power plants may be built onsite within cofferdams or be pre-fabricated in caissons (steel or reinforced concrete) and floated to the site.

6.6.3 Tidal and ocean currents

Like wave energy converters, tidal and ocean current technologies are at an early stage of development. Extensive operational experience with horizontal-axis wind turbines may give axial flow water current turbines a developmental advantage, since the operating principles are similar. Future water current designs are likely to increase swept area (i.e., rotor diameter) to the largest practical machine size to increase generation capacity, minimize the number of aggregate O&M service visits, reduce installation and decommissioning costs and minimize substructure requirements. A key area for R&D is likely to be in the development of deployment and recovery equipment, since periods of slack water in tidal channels can be very brief. The same applies to O&M requirements.

The total tidal and ocean current energy resource could be increased, if commercial threshold current velocities can be reduced. Tidal energy device optimization will follow a path of increasingly large turbines in lower flow regimes (BWEA, 2005). A similar trend is well documented in the wind energy industry in the USA, where wind turbine technology developments targeted less energetic sites, creating a 20-fold increase in the available resource (Wiser and Bolinger, 2010).

As with wave energy, performance and reliability will be top priorities for future tidal and ocean current energy arrays, as commercialization and economic viability will depend on systems that need minimal servicing, thus producing power reliably without costly maintenance. New materials that resist degradation caused by corrosion, cavitation, water absorption and debris impact could reduce operational costs.

6.6.4 Ocean thermal energy conversion

OTEC is also at an early stage of development. The heat exchanger system is one of the key components of closed-cycle ocean thermal energy conversion power plants. Evaporator and condenser units must efficiently convert the working fluid from liquid to gaseous phase and back to liquid phase with low temperature differentials. Thermal conversion efficiency is highly dependent on heat exchangers, which can cause substantial losses in terms of power production and reduce economic viability of systems (Panchal, 2008). Evaporator and condenser units represent 20 to 40% of the total plant cost, so most research efforts are directed towards improving heat exchanger performance. A second key component of an OTEC plant is the large diameter pipe, which carries deep, cold water to the surface (Miller, 2010). Experience obtained in the last decade with large-diameter risers for offshore oil and gas production can be transferred to the cold water pipe design.

A number of options are available for the closed-cycle working fluid, which has to boil at the low temperature of ocean surface water and condense at the lower temperature of deep sea water. Three major candidates are ammonia, propane and a commercial refrigerant R-12/31.

6.6.5 Salinity gradients

The first osmotic power prototype plant became operational in October 2009 at Tofte, near Oslo in south-eastern Norway. The location has sufficient access to seawater and freshwater from a nearby lake (Scråmestø et al., 2009).

The main objective of the prototype is to confirm that the designed system can produce power reliably 24 hours per day. The plant will be used for further testing of technology developed to increase the efficiency. These activities will focus on membrane modules, pressure exchanger equipment and power generation (i.e., the turbine and generator). Further development of control systems, water pretreatment equipment and the water inlets and outlets is needed (Scråmestø et al., 2009).

The developers of the Dutch RED system have identified the Afsluitdijk causeway in the Netherlands, which separates the salty North Sea from the less brackish Lake Ijsselmeer, as the potential site for a 200 MW power plant (Ecofys, 2007). Further R&D will focus on material selection for effectiveness of the membranes and the purification of the water flows.

6.7 Cost trends[26]

6.7.1 Introduction

Commercial markets are not yet driving marine energy technology development. Government-supported R&D and national policy incentives are the key motivation for most technology development and deployment (IEA, 2009). The cost of most ocean energy technologies is difficult to assess, because very little fabrication and deployment experience is available for validation of cost assumptions. Table 6.3 shows the best available data for some of the primary cost factors that affect the levelized cost of electricity (LCOE)[27] delivered by each of the ocean energy subtypes.

In most cases these cost and performance parameters are based on sparse information due to the lack of peer-reviewed reference data and actual operating experience, and in many cases therefore reflect estimated cost and performance assumptions based on engineering knowledge. Present-day investment costs were found in a few instances but are based on a small sample of projects and studies, which may not be representative of the entire industry. However, these parameter sets can be used to assess the overall validity of the levelized cost values published in the non-peer-reviewed literature and—to some extent—the validity and likelihood of the underlying assumptions. This is done by recalculating the LCOE based on a standard methodology outlined in Annex II and the above input data for 3, 7 and 10% discount rates and then comparing the results to previously published data. Focusing on the three ocean energy technologies for which full parameter sets are shown in Table 6.3, Figure 6.12 presents the resulting LCOE values.

Callaghan (2006) calculates LCOEs in the range of US cents$_{2005}$ 21 to 79/kWh for wave energy, which are broadly in line with the values based on the data set in Table 6.3 and shown in Figure 6.12. The EPRI study (Previsic, 2004), assessing one particular project design, is more optimistic. Besides, Callaghan (2006) calculates the LCOE for tidal current technology in the range of US cents$_{2005}$ 16 to 32/kWh. Similar LCOE values for tidal current of US cents$_{2005}$ 1 to 3/kWh are also obtained by the California Energy Commission (2010), but based on investment costs of approximately USD$_{2005}$ 2,000 to 3,000/kW that are envisaged for the year 2018, which are much lower than those estimated by Callaghan (2006) and ETSAP (2010b) for current conditions (see Table 6.3). A consistent set of input data and resulting LCOE are contained in ETSAP (2010b). The medium LCOE values that it found for wave energy, tidal range and tidal current projects are US cents$_{2005}$ 36, 24 and 31/kWh, respectively, for a 10% discount rate. The ETSAP (2010b) values for both wave and tidal current technology are at the low end of the range determined on the basis of the data in Table 6.3 for the 10% discount rate. The calculated LCOE values for tidal range shown in Figure 6.12 are based exclusively on the input data from ETSAP (2010b) and are in line with those reported by ETSAP.

The LCOE presented in Sections 1.3.2 and 10.5 and included in Annex III only include tidal range systems as this was the only ocean technology that had reached commercial maturity.

Future cost estimates come with an even larger degree of uncertainty and should be considered highly speculative. One of the methods, however, that can be used to derive possible future cost is based on the concept of learning. The accumulation of experience from increased deployment of new technologies usually leads to cost reductions. Empirical studies have quantified the link between cumulative deployment and cost reductions yielding so-called learning rates.[28] Applying such learning rates that have been found for technologies broadly similar to ocean energy allows estimation of future cost under certain deployment scenarios. Several estimates of the future costs of ocean energy technologies have been published. The underlying deployment scenarios and detailed cost assumptions, however, remain largely unclear. The following subsections assess some of the published future cost estimates by examining the conditions under which those cost levels can be achieved.

6.7.2 Wave and tidal current energy

Some studies have estimated costs for wave and tidal current energy devices by extrapolating from available prototype cost data (Binnie Black & Veatch, 2001; Previsic, 2004; Callaghan, 2006; Li and Florig, 2006).

Wave and tidal current devices are at approximately the same early stage of development. Investment costs could potentially decline with experience to costs achieved by other RE technologies such as wind energy (Bedard et al., 2006). This can only be demonstrated by extrapolation from a few limited data, since there is limited actual operating experience. Present investment cost estimates were derived from single prototypes, whose costs are likely to be higher than more mature future commercial versions. Some O&M cost data appears in Table 6.3, for both wave and tidal current energy, but it should be acknowledged that this data was extrapolated from a limited amount of operating data.

26 Discussion of costs in this section is largely limited to the perspective of private investors. Chapters 1 and 8 to11 offer complementary perspectives on cost issues covering, for example, costs of integration, external costs and benefits, economy-wide costs and costs of policies.

27 LCOE is a widely used measure that allows for a comparison of the cost of alternative ways of generating electricity. The concept of levelized costs and the methodology used to calculate them is explained in Annex II of the report. However, even from the perspective of a private investor the LCOE is not the sole determinant of the value of a particular project. Risks associated with a particular project and the timing of electricity generation, for instance, are further relevant factors, to name just a few.

28 An overview of the theory and empiricism of learning can, for instance, be found in Section 10.5. Several technology chapters also provide information on technology-specific assessments of learning effects.

Table 6.3 | Summary of core available cost and performance parameters for all ocean energy technology subtypes.

Ocean Energy Technology	Investment costs (USD_{2005}/kW) [i]	Annual O&M Costs (USD_{2005}/kW)	Capacity Factor (CF)[ii] (%)	Design Life[iii] (years)
Wave	6,200–16,100[iv,v,vi]	180[v, vi]	25–40[v,vi]	20
Tidal Range	4,500–5,000[vi]	100[vi]	22.5–28.5[vi]	40[vii]
Tidal Current	5,400–14,300[iv,vi]	140[vi]	26–40[vi]	20
Ocean Current	N/A	N/A	N/A	20
Ocean Thermal	4,200–12,300[viii]	N/A	N/A	20
Salinity Gradient	N/A	N/A	N/A	20

Notes and References:

i. Cost figures for ocean thermal technologies are in different year-dollars.

ii. Capacity factors are estimated based on technology and resource characteristics, not on actual in-the-field hardware experience.

iii. Design life estimates are based on expert knowledge. A standard assumption is to set the design lifetime of an ocean energy device to 20 years.

iv. Callaghan (2006). Higher ranges of investment cost based on this source.

v. Previsic (2004) published a assessment of future cost based on 213 x 500 kW Pelamis wave energy converters with investment cost of USD_{2005} 2,620/kW, annual O&M cost of USD_{2005} 123/kW and additional retrofit cost after 10 years of USD_{2005} 264/kW. Assumed CF was 38%; the design lifetime 20 years.

vi. ETSAP (2010b). Lower ranges of investment cost for wave, tidal range and tidal current are all based on this source. Note that ETSAP (2010a) estimated that investment cost could be as low as USD_{2005} 5,200/kW for wave and as low as USD_{2005} 4,500/kW for tidal current technology. Later in the same year, however, ETSAP (2010b) adjusted its estimates for both wave and tidal stream technologies up significantly to the lower bounds stated in the table, while the estimated investment cost for tidal barrages remained stable. With respect to CFs, the more recent source (ETSAP, 2010b) is more optimistic. The ranges stated in the table are based on both references.

vii. Tidal barrages resemble hydropower plants, which in general have very long design lives. There are many examples of hydropower plants that have been in operation for more than 100 years, with regular upgrading of electromechanical systems but no major upgrades of the most expensive civil structures (dams, tunnels etc). Tidal barrages are therefore assumed to have a similar economic design lifetime as large hydropower plants that can safely be set to at least 40 years (see Chapter 5).

viii. Cost estimates for ocean thermal technologies are in different-year dollars and cover a range of different technologies and locations. Most are for plants of 100 MW size. Many are highly speculative (see, e.g., Francis, 1985; SERI, 1989; Vega, 2002; Lennard, 2004; Cohen, 2009). The most current costs available for OTEC come from Lockheed-Martin, which estimates investment costs at USD 32,500/kW for a 10 MW pilot plant, which shrink to an estimated USD 10,000/kW for a commercial 100 MW plant (Cooper et al., 2009).

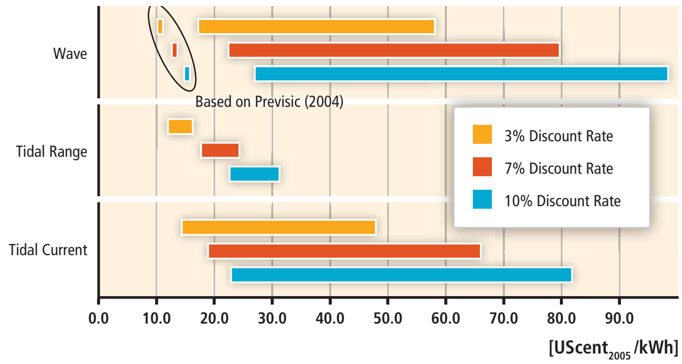


Figure 6.12 | LCOE of wave energy, tidal range and tidal current technology based on primary cost and performance parameters drawn from various studies and listed in Table 6.3.

One of the few studies that provides analysis on future costs was commissioned by the Electric Power Research Institute (EPRI) in the United States to examine theoretical commercial-scale project costs, using Pelamis wave energy converters off the California coast (Previsic, 2004). Overall plant size was assumed to be 213 x 500 kW devices (106.5 MW). The LCOE was calculated based on a 20-year design life and 95% availability. Energy capture technical potential was assumed to take advantage of near-term R&D improvement opportunities not yet realized but which were thought to be achievable at current assumed investment costs. The study concluded that an LCOE of US $cents_{2005}$ 13.4/kWh could be achieved, based upon an investment cost of USD_{2005} 279 million (USD_{2005} 2,620/kW), a discount rate of 7.5%, a capacity factor of 38% and annual O&M costs of USD_{2005} 13.1 million (USD_{2005} 123/kW/yr), with an assumed retrofit cost of USD_{2005} 28.1 million (USD_{2005} 264/kW) after 10 years.

In 2006 the UK Carbon Trust (Callaghan, 2006) published the results of a survey of current costs for prototype and pre-commercial wave and tidal energy converters from which much of the investment cost data was derived. Wave energy converters had investment costs ranging from USD_{2005} 7,700 to 16,100/kW with a midpoint of USD_{2005} 11,875/kW. Similarly, prototype tidal current energy generator costs ranged from USD_{2005} 8,600 to 14,300/kW with a midpoint of USD_{2005} 11,400/kW. Some tidal current device concepts may have even greater investment costs. The same study estimated that energy from early UK wave energy farms would have LCOEs of between US $cents_{2005}$ 21 and 79/kWh, whilst early tidal current farms had estimated LCOEs of between US $cents_{2005}$ 16 and 32/kWh. The Carbon Trust studies did not account for economies of scale, R&D improvements or learning curve effects (Callaghan, 2006).

A recent study undertaken for the California RE Transmission Initiative showed that tidal current generation (deployed in California) would cost US $cents_{2005}$ 1 to 3/kWh (Klein, 2009).

The theoretical analyses for wave energy devices appear to provide plausible benchmarks to demonstrate that near-term wave energy projects might have LCOEs comparable to wind energy in the 1980s. It is less clear how the LCOE levels published by the Callaghan (2006) and Klein (2009) could be achieved, unless the costs were lower or the performance parameters were significantly better than the ranges published. The greatest uncertainties in estimating the LCOE for ocean energy are in the long-term estimation of capacity factor and O&M costs, which require operational data to determine. To achieve economically competitive LCOE estimates, capacity factors near 40%, excellent availability (near 95%) and high efficiency commensurate with mature technology must be assumed for wave energy converters (Previsic, 2004; Buckley, 2005).

Learning curve effects could be an important downward cost driver for LCOE but have a high degree of uncertainty due to lack of industry experience from which to extrapolate. As deployments multiply, costs could be reduced due to learning that is derived from natural production efficiency gains, assimilated experience, economies of scale and R&D innovations. Learning rates for wind power plants over a three-decade span from the early 1980s to 2008 have been estimated at 11%, without including an R&D factor (Wiser and Bolinger, 2009). As a first-order estimate, ocean energy industries (except tidal range, which is already comparatively mature) could follow the same 11% learning curve.[29] Beginning with the midpoints for the investment costs given by Callaghan (2006), such a learning rate implies a decline in investments costs of nearly three times corresponding to approximately nine capacity doublings from 2010 capacity levels (Figure 6.13).

Investment costs for wave and tidal current energy technologies under this scenario reduce to a range from USD_{2005} 2,600 to 5,400/kW (average: USD_{2005} 4,000/kW), assuming worldwide deployments of 2 to 5 GW by 2020. Note that this level of deployment is likely to be highly dependent on sustained policies of the UK, the USA, Canada and other ocean technology countries.

Figure 6.14 shows projections of the LCOE for wave and tidal current energy in 2020 as a function of capacity factor and investment costs, using the methods summarized in Annex II, and with other assumptions as used earlier in calculating LCOE values.

Figure 6.14 shows the possible impact of the capacity factor on LCOE but is included for illustrative purposes only. These results are based on only a single reference (Callaghan, 2006) and the previous learning curve analysis applied to estimate possible 2020 costs given a deployment rate of 2 to 5 GW. The three curves correspond to the calculated high, middle and low investment cost curves, that is, USD_{2005} 5,600, 4,000 and 2,600/kW, estimated for the year 2020.

Figure 6.14 further shows that, if wave and tidal current devices can be developed to operate with capacity factors in the range of 30 to 40% at the above level of investment cost (USD_{2005} 2,600 to 5,600/kW), they can potentially generate electricity at rates comparable with some of the other renewable technologies. Devices must be reliable and located in a high-quality wave or tidal current resource to achieve such capacity factors. Realization of the necessary investment cost levels may require cost reductions that could potentially be derived from manufacturing economies, new technology designs, knowledge and experience transfer from other industries and design modifications realized through operation and experience.

Although no definitive cost studies are available in the public domain for ocean current technologies, the cost and economics for open-ocean current technologies may have attributes similar to tidal current technologies.

6.7.3 Tidal range

Tidal barrages are considered the most mature of the ocean energy technologies reviewed in this report, since there are a number of examples of sustained plant operation, although very little data on cost was available. Tidal barrage projects usually require a very high capital investment, with relatively long construction periods. Civil construction in the marine environment—with additional infrastructure to protect against the harsh sea conditions—is complex and expensive. Consequently, investment costs associated with tidal range technologies are high when

29 The 11% learning rate is based on wind energy market analysis and is only used in making preliminary projections of ocean energy's future cost potential. Actual learning rates are not yet known. Theoretical and empirical literature on learning as a driver of cost reductions is presented in Section 10.5.2

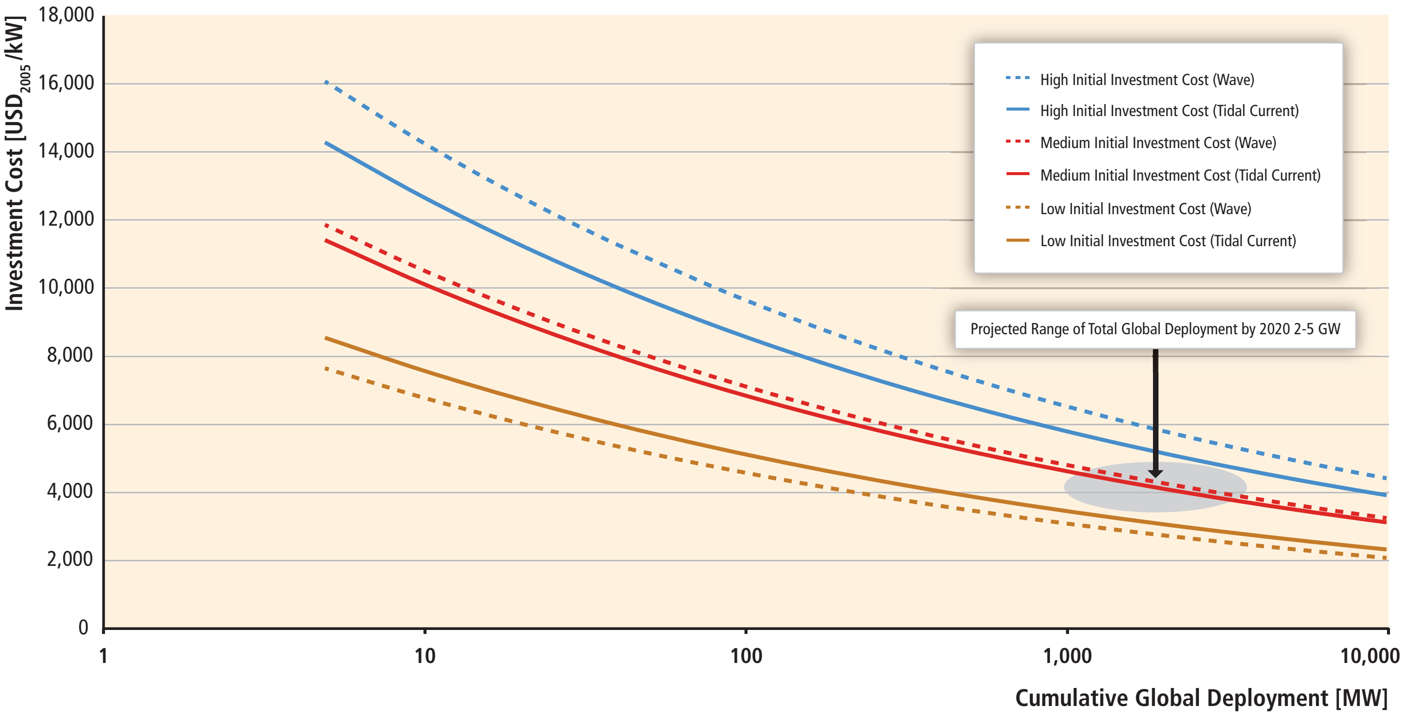


Figure 6.13 | Potential reductions in investment costs for wave and tidal current energy devices based on estimated current cost (Callaghan, 2006) and 11% cost reduction per doubling of cumulative installed capacity (Wiser and Bolinger, 2009).

Note: Initial deployments are assumed to be 5 MW for both subtypes.

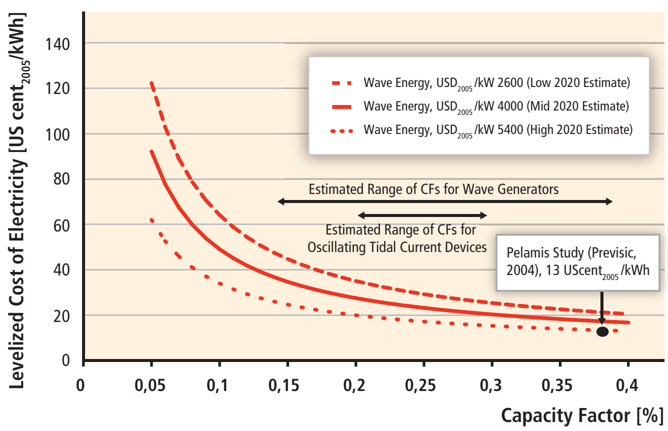


Figure 6.14 | Capacity factor effect on LCOE for estimated 2020 wave and tidal current investment costs. The data point showing the EPRI conceptual design, using Pelamis 500 kW machines at 38% capacity factor, is based on Previsic (2004).

compared to other sources of energy. Innovative techniques, including construction of large civil components onshore and flotation to the site, are expected to allow for substantial reductions in risks and costs. To date, tidal barrage projects have been larger in scale than other ocean energy projects, as the scale reduces the unit cost of generation.

Tidal barrage costs were estimated to be between USD_{2005} 4,500 and 5,000/kW with O&M costs of approximately USD_{2005} 100/kW/yr (ETSAP, 2010b). The design life of a tidal range energy project is expected to exceed 20 years and can be compared to hydroelectric facilities, which can reach economic lives of 40 to 100 years or more.

6.7.4 Ocean thermal energy conversion

There has been no long-term, sustained field experience with OTEC technologies, so it is difficult to predict current costs and future trends. Investment costs for individual projects are high, so technology development has been slow. Published cost estimates are presented in Table 6.4. These cost estimates are presented to provide some insight about what has been documented to date. They do not imply that OTEC technologies have achieved significant maturity. The figures presented have not been converted to 2005 USD, so they appear in different-year dollars and cover a range of different technologies and locations. Many are also highly speculative.

The most current costs available for OTEC come from Lockheed-Martin, which estimates investment costs at USD 32,500/kW for a 10 MW pilot plant, which drop to an estimated USD 10,000/kW for a commercial 100 MW plant (Cooper et al., 2009).

Advances in new materials and construction techniques in other fields in recent years may improve OTEC economics and technical feasibility.

Table 6.4 | Published investment costs and LCOE for OTEC pilot projects and concepts.

Source of Cost Data	Investment Cost (USD/kW)	LCOE (US cents/kWh)	Notes
Vega (2002)	12,300	22	100 MW closed-cycle, 400 km from shore
SERI (1989)	12,200	—	40 MW plant planned at Kahe Point, Oahu
Cohen (2009)	8,000–10,000	16–20	100 MW early commercial plant
Francis (1985)	5,000–11,000	—	—
Lennard (2004)	9,400	18 [11]	10 MW closed-cycle; LCOE in brackets apply if also producing potable water
SERI (1989)	7,200	—	Onshore, open-cycle
Vega (2002)	6,000	10	100 MW closed-cycle, 100 km from shore
Vega (2002)	4,200	7	100 MW closed-cycle, 10 km from shore
Plocek et al. (2009)	8,000	15	Estimate for 75 MW commercial floating plant off Puerto Rico

Note: LCOEs listed in this table are from the published literature. Underlying assumptions are not always known. Neither investment cost nor LCOE have been converted to 2005 USD.

6.7.5 Salinity gradients

Salinity gradient technologies are immature and current costs are not available. Statkraft has estimated that the future LCOE for salinity gradients power may fall in the same range as other more mature renewable technologies, such as wind, based on their current hydropower knowledge, general desalination (reverse osmosis) engineering and a specific membrane technology. Achieving competitive costs will, however, be dependent on the development of reliable, large-scale and low-cost membranes. Statkraft estimates that investment costs will be much higher than other RE technologies, but that capacity factors could be very high, with 8,000 hours of operation annually (Scråmestø et al., 2009).

6.8 Potential deployment[30]

Ocean energy may offer the potential for long-term carbon emissions reduction but is unlikely to make a significant short-term contribution before 2020 due to its nascent stage of development. In 2009, additionally installed ocean capacity was less than 10 MW worldwide (Renewable UK, 2010), yielding a cumulative installed capacity of about 300 MW (REN21, 2010) at present.

6.8.1 Deployment scenarios with ocean energy coverage

Until about 2008, ocean energy was not considered in any of the major energy scenario modelling activities worldwide and therefore its potential impact on future world energy supplies and climate change mitigation is just now beginning to be investigated. As such, the results of the published scenarios literature as it relates to ocean energy are sparse and preliminary, reflecting a wide range of possible outcomes.

Specifically, scenarios for ocean energy deployment are considered in only three major sources here: Energy [R]evolution (E[R]) (Teske et al., 2010), IEA World Energy Outlook (WEO) (IEA, 2009), and IEA Energy Technology Perspectives (ETP) (IEA, 2010). Multiple scenarios were considered in the E[R] and the ETP reports and a single reference scenario was documented in the WEO report. Note that the E[R] Reference scenario is based on the WEO 2009 Reference case and therefore deployment levels until 2030 are very close (Teske et al., 2010). The main characteristics of the considered scenarios, including the deployment levels of ocean energy are summarized in Table 6.5.

The treatment of ocean energy in each of these scenarios reflects a very preliminary state of analysis. In most cases, the inputs have not been fully validated and may not represent the diverse characteristics of the multiple ocean energy resource technologies. In most scenarios, all ocean energy technologies are represented as a single aggregate. This approach is taken out of convenience, and because relevant disaggregated data (e.g., detailed resource assessments with global coverage) are limited (see Chapter 10.2.4 for a more detailed discussion). Many of the technologies are still at an early stage of development and do not have fully established estimates for current and future investment cost, O&M cost, and capacity factors, or even technical potential. Disaggregation into the technology subtypes in future scenario studies may provide further insight into the possible role of ocean energy, but doing so would require a level of data fidelity that does not yet exist for ocean energy technologies.

Regardless of the limitations of the existing scenarios, they do provide a first-order analysis of possible ocean energy technology deployments from which to build a more refined analysis. Specifically, the scenarios indicate a wide range of possible deployments for ocean energy from a conservative baseline case presented by the IEA WEO 2009 to the most aggressive Advanced E[R] scenario, which assumes an 80% CO_2 emissions reduction by 2050.

30 Complementary perspectives on potential deployment based on a comprehensive assessment of numerous model-based scenarios of the energy system are presented in Chapter 10 and Sections 10.2 and 10.3 of this report.

Table 6.5 | Main characteristics of medium- to long-term scenarios from major published studies that include ocean energy.

		Deployment TWh/yr (PJ/yr)				GW	
Scenario	**Source**	**2010**	**2020**	**2030**	**2050**	**2050**	**Notes**
Energy [R]evolution - Reference	(Teske et al., 2010)	N/A	3 (10.8)	11 (36.6)	25 (90)	N/A	No policy changes
Energy [R]evolution	(Teske et al., 2010)	N/A	53 (191)	128 (461)	678 (2,440)	303	Assumes 50% carbon reduction
Energy [R]volution - Advanced	(Teske et al., 2010)	N/A	119 (428)	420 (1,512)	1943 (6,994)	748	Assumes 80% carbon reduction
WEO 2009	(IEA, 2009)	N/A	3 (10.8)	13 (46.8)	N/A	N/A	Basis for E[R] reference case
ETP BLUE map 2050	(IEA, 2010)	N/A	N/A	N/A	133 (479)	N/A	Power sector is virtually decarbonized
ETP BLUE map no CCS 2050	(IEA, 2010)	N/A	N/A	N/A	274 (986)	N/A	BLUE Map Variant – Carbon capture and storage is found to not be possible
ETP BLUE map hi NUC 2050	(IEA, 2010)	N/A	N/A	N/A	99 (356)	N/A	BLUE Map Variant – Nuclear share is increased to 2000-GW
ETP BLUE Map hi REN 2050	(IEA, 2010)	N/A	N/A	N/A	552 (1,987)	N/A	BLUE Map Variant – Renewable share is increased to 75%
ETP BLUE map 3%	(IEA, 2010)	N/A	N/A	N/A	401 (1,444)	N/A	BLUE Map Variant – Discount rates are set to 3% for energy generation projects.

6.8.2 Near-term forecasts

Most near-term ocean energy deployment will likely be policy driven in those countries where government-sponsored research programs and policy incentives have been implemented to promote ocean energy (IEA, 2009). In those cases, near-term forecasts for ocean energy deployment may be related to any country-specific deployment targets that have been established for ocean energy. Some countries have, in fact, proposed non-binding deployment targets and timelines to achieve prescribed ocean energy capacity. The UK government has a target of 2 GW by 2020 (Mueller and Jeffrey, 2008). Canada, the USA, Portugal and Ireland are working on establishing deployment targets for a similar timeframe. Most countries with significant ocean resources have not yet quantified their resource potentials, however, and have not established national deployment goals. And, in those countries that have established ocean energy goals, those goals are rarely obligatory.

Regardless of the drivers for near-term deployment, in general, the near-term forecasts for ocean energy among the scenarios reviewed in this chapter and summarized in Table 6.5 do not envisage a substantial contribution to near-term carbon mitigation. From the scenarios shown in Table 6.5, the near-term (2020) deployment for ocean energy ranges from 3 to 119 TWh/yr (10.8 to 428 PJ/yr), with the highest case being the Advanced E[R] scenario. This wide range reflects the high degree of uncertainty embodied in the scenario assumptions, as well as the different frames of the analysis as the reference case is intended to be a business-as-usual case in which new policies are not enacted, whereas the ambitious Advanced E[R] scenario seeks to dramatically reduce carbon emissions.

6.8.3 Long-term deployment in the context of carbon mitigation

The potential for ocean energy supply to make contributions to the mitigation of climate change is expected to increase to more significant levels in the longer term. By 2050, the deployment scenarios indicated in Table 6.5 range from the Reference E[R] case of only 25 TWh/yr (90 PJ/yr) to the Advanced E[R] case of 1,943 TWh/yr (6,994 PJ/yr). Since ocean energy technologies are presently at an early stage of development, current deployments are very limited. Significant deployments are not forecast until after 2030, though commercial deployments would be expected to continue well beyond the 2050 modelling horizon.

To achieve these higher levels of deployment in the longer term, a variety of possible challenges to the growth of ocean energy deserve discussion.

Resource potential: Resource potential assessments for ocean energy are at a preliminary stage. Nonetheless, even the highest estimates for long-term (2050) ocean energy supply (7 EJ/yr) presented above are well within the theoretical and technical potential for the resource, suggesting that—on a global basis, at least—technical potential is unlikely to be a limiting factor to ocean energy deployment. As presented earlier, OTEC may have the highest technical potential of the available ocean energy options, but even excluding OTEC, the technical potential for ocean energy has been found to exceed 7 EJ/yr. Moreover, though the available literature is limited, the impact of climate change on the technical potential for ocean energy is anticipated to be modest. Regardless, certain regional limitations to resource supply are possible. Wave energy sites are globally dispersed over all coastal boundaries, for example, but the availability of mid-latitude sites (30° to 60°) with lower levels of seasonal variation, adequate incident wave energy, and that are close to load centres may become a barrier in some regions under high penetration scenarios or in populated areas with competing uses. Similarly, limited site availability may prevent widespread deployment of tidal power plants, tidal current energy and ocean current energy beyond certain areas, while OTEC and salinity gradient opportunities are also not equally distributed globally.

Regional deployment: Whether the more ambitious levels of deployment considered in Table 6.5 are feasible will depend, in part, on whether locations of ocean energy resource potential are correlated with areas that demand ocean energy services. Wave and tidal energy technologies are under development in countries bordering the North Atlantic and North Pacific, as well as Australasia, where government-sponsored programmes support R&D and deployments, with pro-active policy incentives to promote early-stage projects. OTEC projects are likely to be developed off the coasts of tropical islands and states. Tidal current, ocean current and salinity gradient projects are most likely to be limited to specific locations where resource quality is strong. These locations are likely to become more numerous and widespread as the efficiencies of these technologies mature. Overall, while technical potential is not anticipated to be a primary global barrier to ocean energy deployment, resource characteristics will require that local communities in the future select among multiple available ocean technologies to suit local resource conditions.

Supply chain issues: Wave, tidal current and some other ocean energy technologies require a sophisticated O&M infrastructure of sufficient scale to be cost effective. Different technologies require different support vessels due to differences in insertion and extraction methods. Until there is a critical mass of deployment for some of the ocean technologies, lack of sufficient infrastructure could be a significant barrier to industry growth. Some benefits may be realized from offshore wind energy development, which may contribute to this infrastructure requirement (in terms of deployment vessels, moorings and export cable access) in advance of significant ocean energy deployment.

Technology and economics: All ocean energy technologies, except tidal barrages, are conceptual, undergoing R&D, or are in the pre-commercial prototype and demonstration stage. The technical performance of ocean energy technologies is anticipated to improve steadily over time as experience is gained and new technologies are able to access poorer quality resources. Technical improvements can reduce capital costs, enhance efficiency, reduce O&M requirements and enhance capacity factors, giving access to sites that are more remote and providing improved methods for harnessing poorer-quality resources. Concurrently with these technical improvements, the LCOE for ocean energy technologies should decline. Whether the technical advances lead to sufficient associated cost reductions to enable broad-scale deployment of ocean energy is the most critical uncertainty in assessing the future role of ocean energy in meeting ambitious long-term deployment targets.

Integration and transmission: The integration of ocean energy into wider energy networks will need to recognize the widely varying generation characteristics arising from the different resources. These patterns of resource availability have implications for the large-scale integration of ocean energy into electricity networks (see Chapter 8), and on the requirements for, and utilization of, transmission capacity, including the need for and value of offshore transmission networks. To effectively manage the variability of some ocean energy sources at higher levels of deployment may require similar technical and institutional solutions as considered for wind and solar photovoltaic technologies, specifically, forecasting capability, increased system-wide flexibility, grid connection standards, demand flexibility and bulk energy storage. Other ocean energy technologies, on the other hand, have characteristics that may be similar to base-load or even partially dispatchable thermal generators, thereby not imposing concerns about operational integration, though new transmission infrastructure may still be required.

Social and environmental impacts: The social and environmental impacts of ocean energy projects are being evaluated as actual deployments multiply. Risk analysis and mitigation, using environmental impact assessments, will be essential components of early deployments. Competitive uses may preclude the availability of some high-quality sites, and environmental and ecological concerns are likely to impact deployment locations as well. A balanced approach to engaging coastal communities will be necessary, whilst maintaining a fair and responsible respect for existing coastal uses and ocean ecologies. That some forms of ocean energy have high levels of environmental reversibility may make them attractive for future development, but the early stage of ocean energy deployment creates uncertainty about the degree to which social and environmental concerns might eventually constrain development.

6.8.4 Conclusions regarding deployment

This preliminary presentation of scenarios that describe alternative levels of ocean energy deployment is among the first attempts to review the potential role of ocean energy in the medium- to long-term scenarios literature with the intention of establishing the potential contribution of ocean energy to future energy supplies and climate change mitigation. As shown by the limited number of existing scenarios, ocean energy has the potential to help mitigate long-term climate change by offsetting GHG emissions, with projected deployments resulting in energy delivery of up to 1,943 TWh/yr (~7 EJ/yr) by 2050. Other scenarios have been developed indicating deployment as low as 25 TWh/yr (0.9 EJ/yr) from ocean energy. The wide range in results is based in part on uncertainty about the degree to which climate change mitigation will drive energy sector transformation, but for ocean energy, is also based on inherent uncertainty as to when and if various ocean energy technologies will become commercially available at attractive costs. To better understand the possible role of ocean energy in climate change mitigation, not only will continued technical advances be necessary, but the scenarios modelling process will need to increasingly incorporate the range of potential ocean energy technology subtypes, with better data for resource potential, present and future investment costs, O&M costs and anticipated capacity factors. Improving the availability of the data at global and regional scales will be an important ingredient to improve coverage of ocean energy in the scenarios literature (see also Section 10.2.4).

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