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Chapter 6

Ocean Energy

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Chapter 6: Ocean Energy

CONTENTS

EXECUTIVE SUMMARY

Ocean Energy can be defined as energy derived from technologies, which utilize seawater as their motive power or harness the chemical or heat potential of seawater. Technologies for harnessing ocean energy are probably the least mature of the six principal forms of renewable energy in this Special Report but the energy resources contained in the world's oceans easily exceed present human energy requirements. Ocean energy could be used not only to supply electricity but also for direct potable water production. 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 complementary distribution. Ocean thermal energy is principally distributed in the Tropics around the Equator (0° – 35°), whilst wave energy principally occurs between latitudes of 40° - 60°. Some forms of ocean energy, notably ocean thermal energy, ocean currents, salinity gradients and, to some extent, wave energy, may generate base load electricity.

With the exception of tidal rise and fall energy, which can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, most ocean power technologies are presently immature. None can be truly characterized as commercially competitive with the other lowest cost forms of renewable energy – wind, geothermal and hydroelectric energy. Although basic concepts have been known for decades, if not centuries, ocean power 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 power technologies was rejuvenated at the start of the 2000s and some technologies – for wave and tidal current energy – have reached full-scale prototype deployments. Unlike wind turbine generators, there is presently no convergence on a single design for ocean power converters and, given the range of options for energy extraction, there may never be a single device design.

Worldwide developments of devices are accelerating with over 100 prototype wave and tidal current devices under development (US DoE, 2009). Principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major national energy utilities and investment companies. By contrast, the principal form of device developer is a private small- or medium-scale enterprise (SME). There is encouraging uptake and support from these major investors into the prototype products being developed by the SMEs.

National and regional governments are particularly supportive of ocean energy through a range of initiatives to support developments. These range from [TSU: sentence structure "from … to …", "to" missing] R&D and capital grants to device developers, performance incentives (for produced electricity), marine infrastructure development, standards, protocols and regulatory interventions for permitting, space and resource allocation. Presently the northwestern European coastal countries lead development of ocean power technologies with the North American, northwestern Pacific and Australasian countries also involved.

Environmental impacts of ocean energy converters can be forecast from maritime and other offshore industries. Ocean power technologies potentially present fewer environmental risks and thus community acceptance may be more likely than for other renewable energy developments. Social impacts are likely to be high, rejuvenating shipping and fishing industries, supplying electricity and/or drinking water to remote communities (at small-scale) or utility-scale deployments with transmission grid connections to displace aging fossil fuel generation plants. Critically, ocean power technologies do not generate greenhouse gases in operation, so they can significantly contribute to emissions reduction targets.

Although ocean energy technologies are at an early stage of development, there are encouraging signs that the capital cost of technologies (in \$/kW) and unit cost of electricity generated (in \$/kWh) will decline from their present non-competitive levels to reach the costs of wind, geothermal and hydroelectric technologies. When this occurs, the uptake of ocean energy can be expected to accelerate and ocean power technologies will create another power/water supply option for countries seeking to reduce their GHG emissions to meet internationally agreed targets for such reductions.

Ocean energy will be predominantly a utility-scale application, rather than a domestic-scale opportunity. This is particularly true for OTEC and salinity gradient plants. Small-scale, off-grid wave and tidal current technologies are likely for applications for island/remote communities and combined electricity generation/water production projects are being developed, particularly in Australia and India.

6.1 Introduction

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

- **Waves and Swells** – derived from wind energy kinetic energy input over the whole ocean,
- **Tidal Rise and Fall** – derived from gravitational forces of earth-moon-sun system,
- **Tidal and Ocean Currents** – derived from tidal energy or from wind driven / thermo-haline ocean circulation,
- **Ocean Thermal Energy Conversion (OTEC)** – derived from solar energy stored as heat in ocean surface layers and Submarine Geothermal Energy – hydrothermal energy at submarine volcanic centres,
- **Salinity Gradients** – derived from salinity differences between fresh and ocean water at river mouths (sometimes called 'osmotic power').

Aspects related to resource potential, environmental and social impacts, technology, costs and deployment are considered.

The conversion of resources available in the oceans to useful energy presents a significant engineering challenge. However, the reward may be high with many estimates of the potential energy exceeding world electricity demands (OES-IA, 2008). Even though the potential resources have been recognised for a long time, technologies for harnessing these potentials are only now becoming feasible and economically attractive, with the exception of tidal barrage systems - effectively estuarine hydro dams - of which a number of plants are operational worldwide (c. 265 MW worldwide).

6.2 Resource Potential

6.2.1 Wave Energy

Wave energy is a concentrated form of wind energy. Wind is generated by the differential heating of the atmosphere and, as it passes over the ocean, friction 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 of the resulting waves depends 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 size of the area affected by the wind (fetch). Wind-waves grow into open ocean swells by constructive interference, the difference being that wind-waves have periods of less than 10 seconds, whilst swells have greater periods.

The most energetic waves on earth are generated between 30º and 60º latitudes by extra-tropical storms (the so-called "Roaring Forties"). An attractive wave climate also occurs within ± 30º of the Equator (where trade-winds prevail most of the year): The wave energy resource is lower here but has less seasonal variability. However, doldrums occur in some Equatorial zones.

The total theoretical wave energy resource is very high (32,000 TWh; Mørk et al., 2010), roughly twice the global electrical energy consumption in 2006 (18,000 TWh; EIA, 2008). The 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.

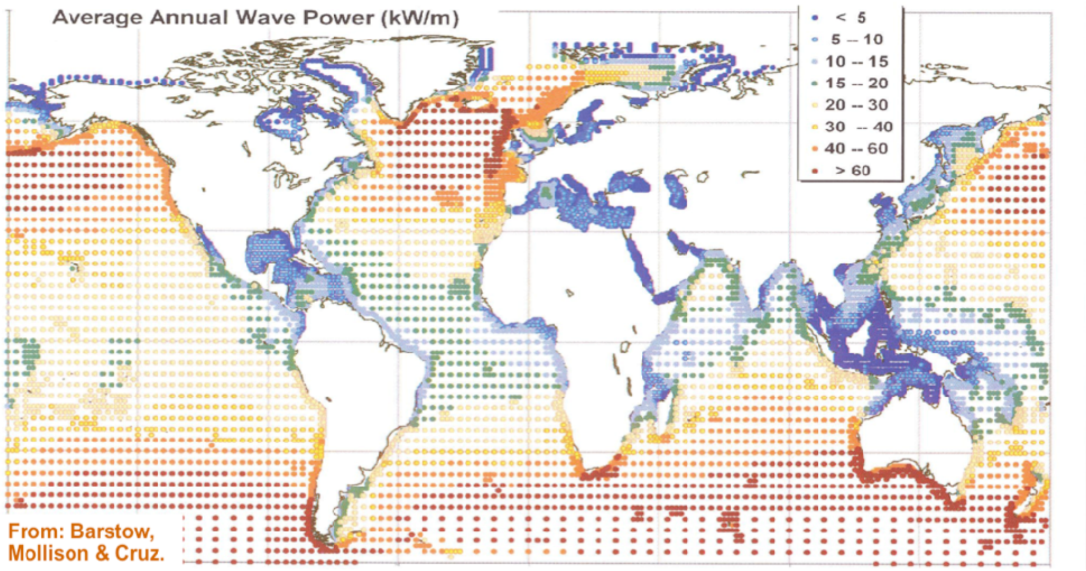

Figure 6.1: Global offshore annual wave power level distribution (Barstow, S., Mollison, D. and Cruz, J., in Cruz, 2008)

The regional distribution of the annual wave energy incident on the coasts of the respective countries or regions were obtained for areas, where theoretical wave power $P \geq 5$ kW/m and latitude $\leq \pm 66.5$ º (Table 6.1). The total annual wave energy (29,500 TWh) is a decrease of 8% from the total theoretical wave energy resource above.

Table 6.1: Regional Theoretical Wave Power (Mørk et al., 2010)

REGION	Wave Energy (TWh)
Western and Northern Europe	2,800
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300
North America and Greenland	4,000
Central America	1,500
South America	4,600
Africa	3,500
Asia	6,200
Australia, New Zealand and Polynesia	5,600
TOTAL	29,500

Swell waves travel for very long distances (i.e., tens of thousands of kilometres) with minimal energy dissipation in deep water. Swells that generated in Antarctica, Australia and New Zealand have been observed in California (e.g., Khandekar, 1989). When the water depth (h) becomes less than half the wavelength, swell waves change due to friction with the seabed (e.g., Lighthill, 1978). Bottom friction can be significant when the continental shelf is wide and the sea bottom is rough, as in the west of Scotland, where some frequency components lose half of their energy between deep water and 42 m water depth (Mollison, 1985). Shoaling causes the waves to grow in height and refraction (similar to the optical phenomenon) causes wave crests to become parallel to the bathymetric contours. This, in turn, leads to energy concentration in convex zones (e.g., close to capes) and dispersion in concave zones (e.g., in bays). Shelter by nearshore islands or by the coast itself also reduces incident energy. Waves start to break, thus dissipating their energy, when wave height H > Kh, with the constant K having values of 0.79-0.87 (Sarpkaya and Isaacson, 1981).

A range of devices is used to measure swell waves. Wave measuring buoys are used in water depth 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/ gas platforms).

Satellite-based measurements have been made regularly since 1991 by altimeters that provide measurements of significant wave height (H_s) and wave period (T) with accuracies similar to wave buoys (Pontes and Bruck, 2008). The main drawback of satellite data is the long Exact Return Period (ERP), which is between 10 and 35 days, and the corresponding large distance between adjacent tracks (0.8º to 2.8 º along the Equator). Synthetic Aperture Radar (SAR) can provide directional spectra they [TSU: that] are not useful yet for wave energy resource mapping (Pontes et al., 2009).

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 Tide Rise and Fall

Tidal rise and fall is the result of gravitational attraction of the Earth / Moon and the Sun on the ocean. In most parts of the world there are two tides a day (called ‘semi-diurnal’), whilst in other places there is only one tide a day. During the year, the amplitude of the tides varies depending on the respective positions of the Earth, the Moon and the Sun. When the Sun, Moon and Earth are aligned (at full moon and at new moon) maximum tidal level occurs (i.e., spring tides). The opposite tides, called neap tides, occur when the gravitational forces of the Moon and the Sun are in quadrature; they occur during quarter moons.

The spatial distribution of the tides varies depending on global position and also on the shape of the ocean bed, the shoreline geometry, Coriolis acceleration and atmospheric pressure. 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 may flow as the water levels on either side of the amphidromic point are not the same. 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 more details.

Locations with the highest tidal ranges are in Canada (Bay of Fundy), Western Europe (France and United Kingdom), Russia (White Sea, Sea of Okhotsk, Barents Sea), Korea, China (Yellow Sea), India (Arabic Gulf) and Australia. There is a great geographical variability in the tidal range. Some places like the Baie du Mont Saint Michel in France or the Bay of Fundy in Canada experience very high tides (respectively, 13.5 m and 17 m), while in other places (e.g., Mediterranean Sea) the tides are hardly noticeable (Shaw, 1997; Usachev, 2008). The global distribution of the M2 constituent of the tidal level, the largest semi-diurnal tidal constituent that is one half of the full tidal range, shows that the major oceans have more than one amphidromic system.

Tidal rise and fall can be forecasted with a high level of accuracy – even centuries in advance. Although the resultant power is intermittent, there is little or no hydrological risk, which is a significant advantage when compared to conventional hydro, to wind or to solar energy (Ray, 2009). The world's theoretical tidal power potential is in the range of 3 TW with 1 TW located in relatively shallow waters (Charlier and Justus, 1993). The effect of climate change on tidal rise and fall is uncertain but, in the worst case, sea level rise should only result in translation of the mean ocean level, with possible impacts linked to shoreline changes, rather than to tidal range.

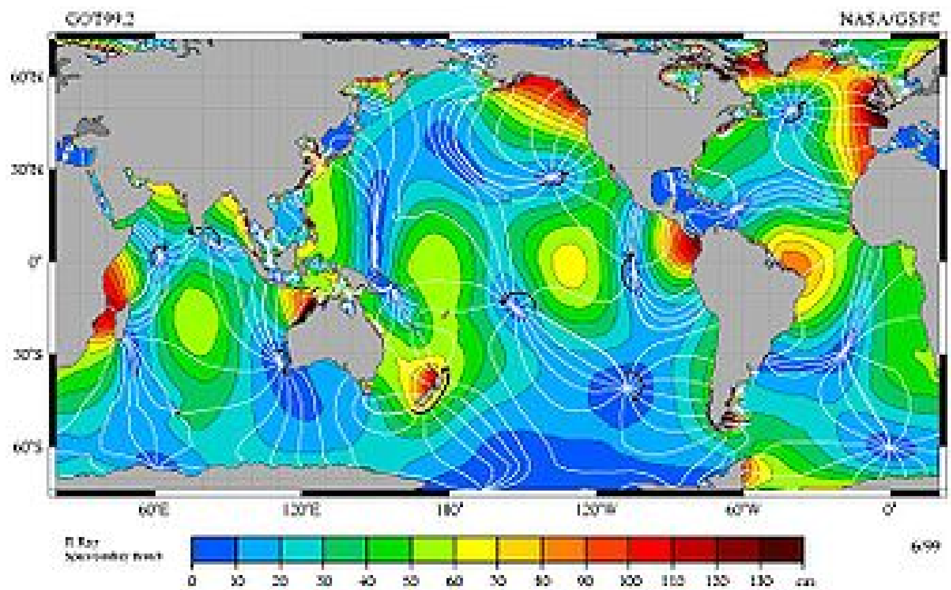

Figure 6.2 - TOPEX/Poseidon: Revealing Hidden Tidal Energy GSFC, NASA. [TSU: Source needs to be included in list of references, quotation-style needs to be adjusted.] The M2 tidal amplitude is shown in colour. White lines are cotidal lines, spaced at phase intervals of 30° (a bit over 1 hr). The amphidromic points are the dark blue areas where the cotidal [TSU: sentence incomplete]

6.2.3 Tidal Currents

Tidal currents are the ocean water mass response to tidal rise and fall. 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 sinusoidal variation of various tidal components, operating on different cycles, although these flows can be modified by short-term weather fluctuations. The potential power of a tidal current is proportional to the cube of the current velocity. For near-shore currents, i.e., in channels between mainland and islands or in estuaries, current velocity varies sinusoidally with time, the period being related to the different tidal components. Potentially commercially attractive sites require a minimum average sinusoidal current velocity greater than 1.5 ms^{-1}. Below that value (1.0 – 1.5 ms^{-1}) evaluation should be on a site-by-site basis. For non-oscillating currents, the maximum current velocity should exceed 1.0 ms^{-1}, but in the range 0.5-1.0 ms^{-1}, its practical exploitation depends on site evaluation. [TSU: references missing]

A methodology for the assessment of tidal current energy resource has been proposed (Hagerman et al., 2006). An atlas of the wave energy and tidal resource has been developed for the UK, which includes tidal current energy (UK Department of Trade and Industry, 2004). Similar atlases have been published for the European Union (CEC, 1996; Carbon Trust Marine Energy Challenge, 2004) and for far-eastern countries (CEC, 1998).

In Europe tidal energy resource is of special interest for the UK, Ireland, Greece, France and Italy. Over 106 promising locations have been identified. Using present-day technologies, these sites could supply 48 TWh/y into the European electrical grid network. China has estimated that 7,000 MW of tidal current energy are available. Locations with high potential have also been identified in the Republic of Korea, Philippines, Japan, Australia, Northern Africa and South America. [TSU: references missing]

The predictability of tidal currents and the potentially high load factor (30-60%) are important positive factors for their utilization. Sites with oscillating flows can offer capacity factors in the 40-50% range. For non-oscillating flows, this range increases to the order of 80%. [TSU: references missing]

6.2.4 Ocean Currents

In addition to nearshore tidal currents, there are also significant current flows in the open ocean. 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 ms^{-1}) to drive present-day current 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 current systems may also have potential as improvements in turbine efficiency occur.

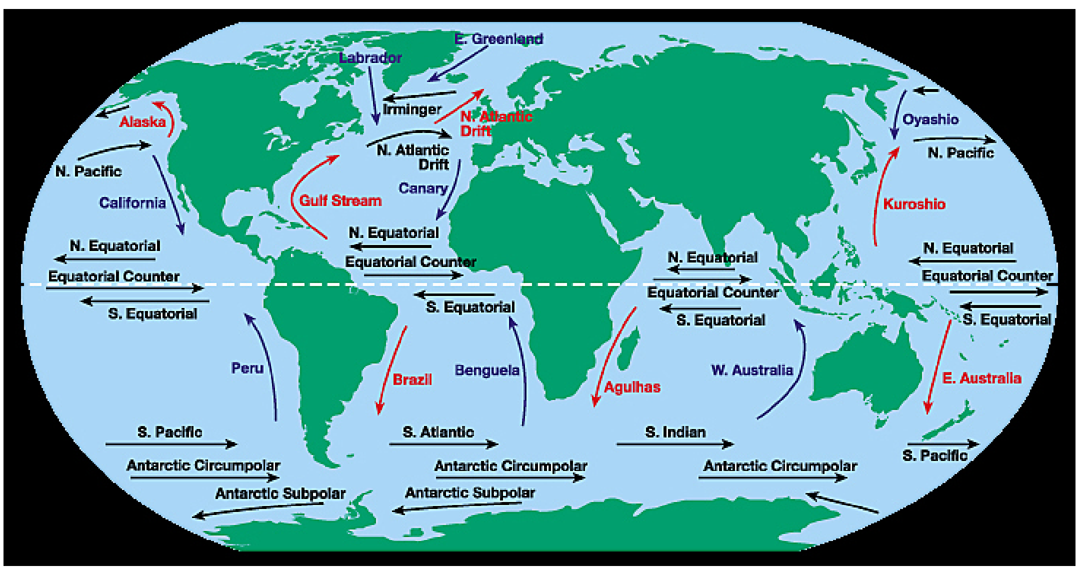

Figure 6.3: Surface ocean currents, showing warm (red) and cold (blue) systems (UCAR, 2000).

The power generation potential of the Florida Current of the Gulf Stream system was recognized decades ago (”MacArthur Workshop”; Stewart, 1974). The workshop concluded that the Florida Current had ~25 GW potential but its recommendations have languished, despite various oceanographic measurement programs confirming the potential (see Raye, 2001).

The Current has a core region, 15-30 km off the Florida coast and near surface, which represents the greatest potential for power generation. As the return flow of the Atlantic Ocean’s subtropical gyre, the Florida Current flows strongly year around, exhibiting variability on various time and space scales (Niiler & Richardson, 1973; Johns et al., 1999).

6.2.5 Ocean Thermal Energy Conversion

The most direct harnessing of ocean solar power is probably through an ocean thermal energy conversion (OTEC) plant. Among ocean energy sources, OTEC is one of the continuously available renewable resources which could contribute to base load power supply. The OTEC potential is considered to be much larger than for other ocean energy forms (UNDP, UNDESA, WEC, 2000). It also has a widespread distribution between the two tropics. An optimistic estimate of the global resource is 30,000 to 90,000 TWh (Charlier and Justus, 1993).

Only 15% of the total solar input to the ocean is retained as thermal energy, with absorption is concentrated at the top layers, declining exponentially with depth [TSU: sentence structure]. Sea surface temperature can exceed 25 °C in tropical latitudes, whilst 1 km below surface, sea temperature is between 5-10 °C. [TSU: references missing]

A minimum temperature difference of 20 °C is required to operate an OTEC power plant. [TSU: reference missing] Both coasts of Africa, the tropical west and southeastern coasts of the Americas and many Caribbean and Pacific islands have sea surface temperature of 25 – 30 °C, declining to 4 – 7 °C at depths varying from 750 to 1,000 m. An OTEC resource map showing annual average temperature differences between surface waters and the water at 1,000 meters depth shows a wide tropical area of potential 20+° C temperature differences (Figure 6.4). Almost everywhere in the Equatorial zone there is potential for installing OTEC facilities. A number of Pacific and Caribbean islands could develop OTEC plants, having an OTEC resource within one mile of their shores (UN, 1984).

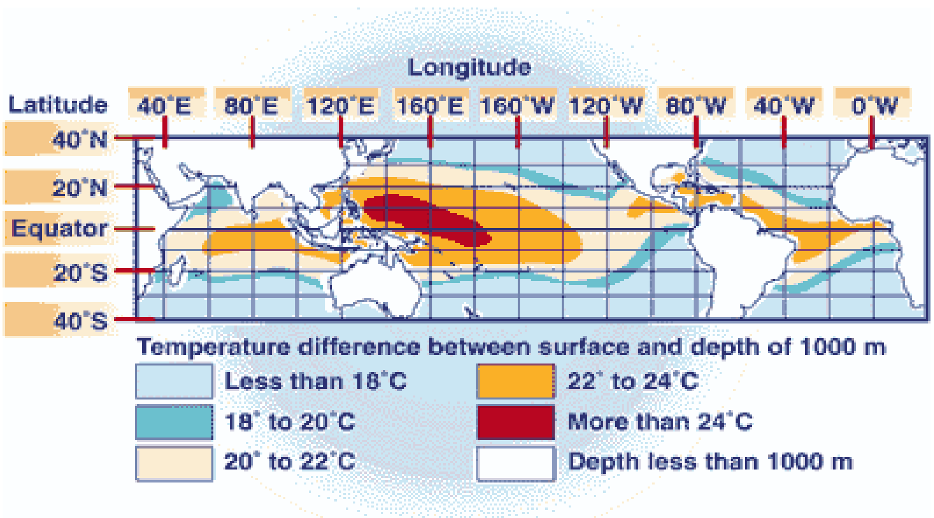

Figure 6.4: Ocean Thermal Energy Conversion Resource Map [TSU: reference missing]

6.2.6 Salinity Gradient

Since freshwater from rivers debouching into saline seawater is globally distributed, osmotic power could be generated and used in all regions - wherever there is a surplus of fresh water. Feasibility studies must be conducted before any osmotic power plant is constructed to ensure that each river discharging into the ocean can provide sufficient freshwater. Estuarine/deltaic environments are most appropriate, because of the potential for large, adjacent volumes of freshwater and seawater.

The first water quantity assessments for osmotic power potential were based on a methodology, which used average discharge and low flow discharge values. Low flow is defined as the 80th percentile of the flow regime, i.e., the low flow is exceeded 80% of the time. Freshwater extraction for electricity generation would not be possible in low flow conditions. [TSU: references missing]

Global generation capacity potential for osmotic power generation has been calculated as 1,600 – 1,700 TW (Scråmestø, personal communication, 2010). The annual generation potential has been calculated as 1,650 TWh (Scråmestø, Skilhagen and Nielsen, 2009). In Europe alone there is a potential to generate 180 TWh. Osmotic power will effectively generate base load electricity, which should make contributions to security of supply, portfolio diversity and grid strengthening.

6.3 Technology and Applications

6.3.1 Introduction

Ocean energy technologies range from the conceptual stage to the prototype stage, as few technologies have matured to commercial availability. Presently there are many technology options for each ocean energy source but, with the exception of tidal rise and fall barrages, the only one commercially available, technology convergence has not yet occurred, due to a fundamental lack of operating experience. Over the past four decades, other marine industries (primarily petroleum industry) have made significant advances in the fields of offshore materials, offshore construction, corrosion, submarine cables and communications. Ocean energy will directly benefit from these advances, rather than any new or major technological breakthrough. [TSU: references missing]

Competitive ocean energy technologies will emerge in the present decade, offering great promise beyond the near-term [TSU: references missing]. The abundance of globally distributed resources and the relatively high energy density of ocean energy resources make ocean energy a potentially widespread solution.

6.1.2 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 device motions (heaving, surging, pitching) as well as water depth and distance from shore (shoreline, near-shore, offshore).

A generic scheme for both ocean wave and tidal current consists of primary, secondary and tertiary conversion stages as shown in (Figure 6.5). The primary subsystem represents fluid-mechanical processes and feeds mechanical power to the next stage. The intermediate subsystem is a short-term storage and the power processing can be facilitated before the electrical machine is operated. The final conversion utilizes electromechanical and electrical processes.

Recent reviews have identified over 50 wave energy devices at various stages of development (Falcão, 2009; Khan and Bhuyan, 2009 and DoE, 2009). 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 will be tailored for specific site conditions.

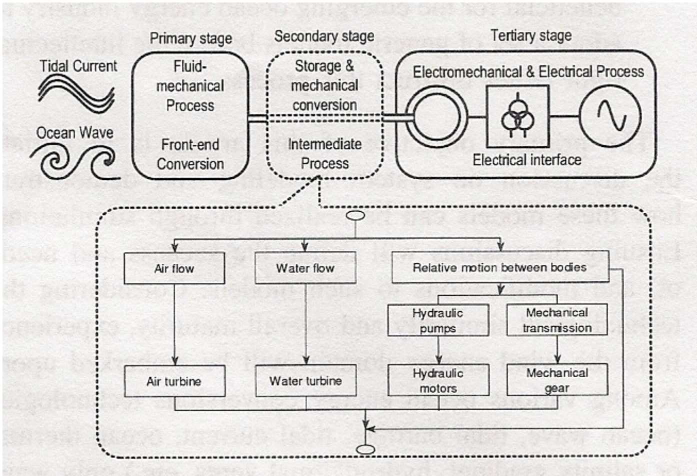

Figure 6.5: Conversion stages of ocean waves and tidal current devices (Khan et al., 2009)

Several methods have been proposed to classify wave energy systems (e.g., Falcão, 2009, Khan and Bhuyan, 2009 and DoE, 2009). The classification systems proposed by Falcão (Figure 6.6) are sorted mainly by 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.

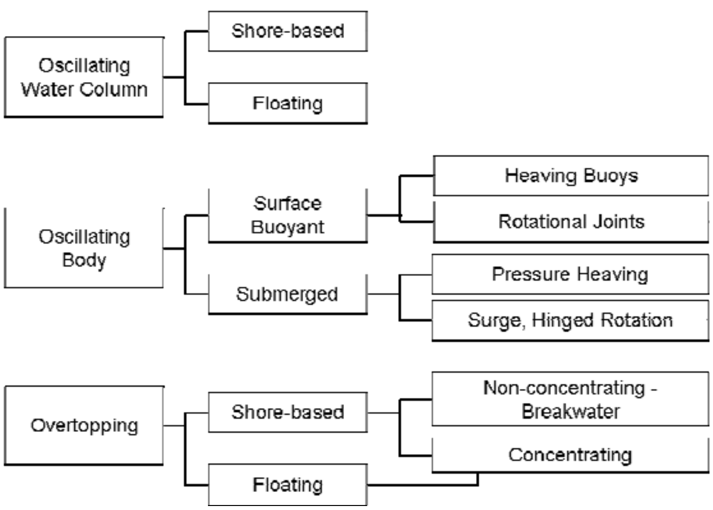

Figure 6.6: Wave energy technologies – Classification based on principles of operation (Falcão, 2009).

6.3.1.1 Oscillating Water Columns

Oscillating water columns (OWC) are wave energy converters, which use wave motion to induce different air pressure levels inside an air-filled chamber. High velocity compressed air exhausts through an air turbine, coupled to an electrical generator, which converts the kinetic energy into electricity. When the wave recedes, the airflow reverses and fills the chamber, generating another pulse of energy. The air turbine rotates in the same direction, regardless of the flow, through either its design or by 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 a floating system moored in deeper waters.

6.3.1.2 Oscillating-Body Systems

Oscillating-body (OB) wave energy conversion devices use the incident wave motion to induce differential oscillating motions between two bodies of different mass, which motions are then converted into a more usable form of energy. 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. 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.

6.3.1.3 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. The reservoir drains down through a conventional low-head hydraulic turbine. These systems can be offshore floating devices or incorporated in shorelines or man-made breakwaters.

6.3.1.4 Power Take-off Devices

In most cases, converted kinetic energy is, in turn, converted to either electricity or to a pressurized working fluid via a secondary power take-off device. Real-time wave oscillations will produce corresponding electrical power oscillations that may degrade power quality to the grid. 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. Optimal wave energy absorption involves some kind of resonance, 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.

6.3.2 Tide Rise and Fall

The development of tidal rise and fall hydropower has been usually based on estuarine developments, where a barrage encloses an estuary, which creates a single reservoir (basin) behind it and incorporates generating units. More recently, new barrage configuration has been proposed based on dual-basin mode. One of the two basins fills at high tide, whilst the other is emptied at low tide. Turbines are located between the basins. Two-basin schemes may offer highly flexible power generation availability over normal schemes, such that it is possible to generate power almost continuously. Two-basin schemes are very expensive to construct due to the extra length of barrage.

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

The conversion mechanism most widely used to produce electricity from tidal rise and fall is the bulb-turbine (Bosc, 2007). At the 240 MW power plant La Rance, these units generate in both directions (on the ebb and flood tides) and may also offer the possibility of pumping, when the tide is high, in order to increase low head storage in the basin (Andre, 1976). The 254 MW Sihwa Barrage in the Republic of Korea employs the same type of turbine.

There are some favourable sites, such as very shallowly shelving coastlines, which are well suited to tide rise and fall power plants, like the Severn Estuary in southwest England. Current feasibility studies there include options, such as barrages and tidal lagoons. Conventional tidal rise and fall power stations will generate electricity for only part of each tide cycle. Consequently, the average capacity factor for tidal power stations varies from 25% to 35% (Charlier, 2003).

6.3.3 *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. The principal difference between tidal and river/ocean current turbines is that river and ocean currents flows are unidirectional, whilst tidal turbines reverse flow direction between ebb and flood cycles. Consequently, tidal turbines can generate in both directions to provide optimum power generation.

Several classification schemes for tidal and ocean current energy systems have been proposed (Khan et al., 2000; US DOE, 2009). Usually, they are classified based on the principle-of-operation, such as axial-flow turbines (Verdant, 2009[1]), cross-flow turbines (Li and Calisal, 2010; Ponte Di Archimede, 2009[2]) and reciprocating devices (Bernitsas et al., 2006[3]), (Figure 6.7).

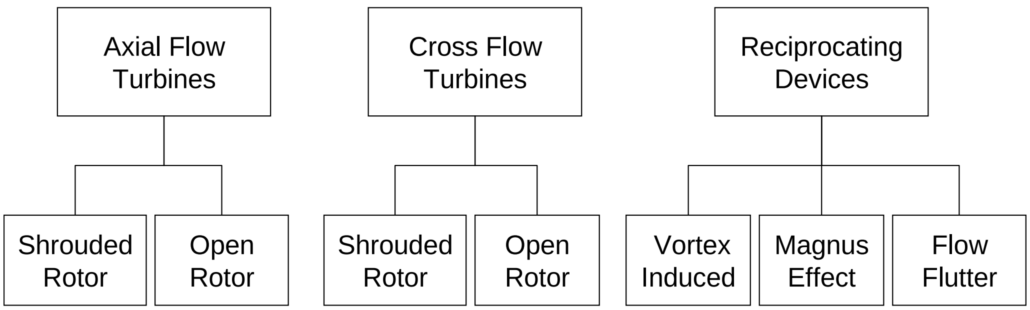

Figure 6.7: Classification of current tidal and ocean energy technologies (principles of operation) [TSU: reference missing]

Many of the water current energy conversion systems resemble wind turbine generators. However, the marine turbine designers must also take into accounts 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 flows. Axial-flow turbines will either reverse nacelle direction ~180º with each tide or, alternatively, the nacelle will have a fixed position but the rotor blades will accept flow from two directions - usually at some performance penalty.

Rotor shrouds (also known as cowlings or ducts) can enhance hydrodynamic performance by increasing the flow velocity through the rotor and reducing tip losses but the additional energy capture may not offset the cost of the shroud. The scale of water current devices in rivers and tidal currents will be driven by the external dimensions of the channel transects, in which they are installed and by navigational constraints that require minimum water clearance for vessels.

Capturing the energy of open-ocean current systems requires 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 will replace fixed bottom support structures. Alternatively they can be attached to other structures, such as offshore platforms (Van Zwieten et al., 2005; Ponte Di Archimede, 2009[4]). Whether the turbines are bottom fixed or floating, it is likely that these modules will also have hydrodynamic lifting designs to allow optimal and flexible vertical positioning (Van Zwieten et al., 2005; Venezia and Holt, 1995; Raye,

[1] www.verdantpower.com
[2] www.pontediarchimede.com
[3] http://www.vortexhydroenergy.com/
[4] http://www.pontediarchimede.it/language_us/

2001). In addition, open ocean currents will not impose a size restriction to the rotors due to lack of channel constraints. Therefore, ocean current systems may have larger rotors.

Reciprocating devices are generally based on basic fluid flow phenomena such as vortex shedding or passive and active flutter systems (usually hydrofoils), which induce mechanical oscillations in a direction transverse to the water flow. Most of these devices are in the conceptual stage of development and have not been evaluated in terms of cost or performance.

6.3.4 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, seawater is the circulating fluid - warm surface water is flash-evaporated in a partial vacuum chamber. The steam produced passes through a turbine, generating power, after which it is condensed, using cooler, deep seawater. By employing an appropriate cycle, desalinated water can be obtained as an additional product.

Closed conversion cycles offer more efficient thermal performance. A secondary working fluid, such as ammonia, propane or Freon-type is vaporized and re-condensed continuously in a closed loop to drive a turbine (Figure 6.8).

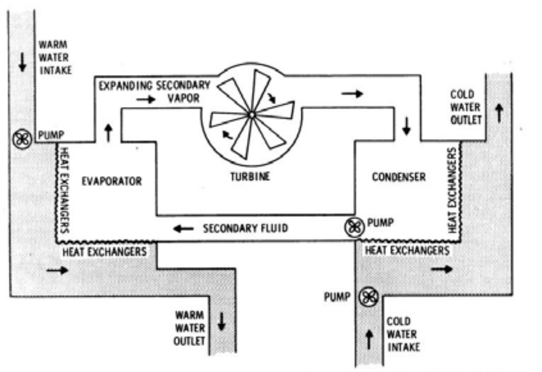

Figure 6.8: Diagram of a Closed-Cycle OTEC Plant (Charlier and Justus, 1993).

Warm seawater from the ocean surface is pumped through heat exchangers where a secondary working fluid is vaporized, causing a high pressure vapour to drive a turbine. The vapour flows to a surface condenser, 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 operating pressure. A hybrid conversion cycle combines both open and closed cycles. Steam is generated by flash evaporation and then acts as the heat source for a closed Rankine cycle, using ammonia or other working fluid.

6.3.5 Salinity Gradient

It has been known for centuries that the mixing of freshwater and seawater releases energy, therefore, a river flowing into a saline ocean releases large amounts of energy (Scråmestø et al., 2009). The challenge is to utilise this energy, since the energy released from this mixing normally results in a very small increase in the local temperature of the water. During the last few decades at least two concepts for converting this energy into electricity instead of heat have been identified, these are Reversed Electro Dialysis (RED) and Pressure Retarded Osmosis (PRO).

6.3.5.1 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 (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 (Groeman and van den Ende, 2007).

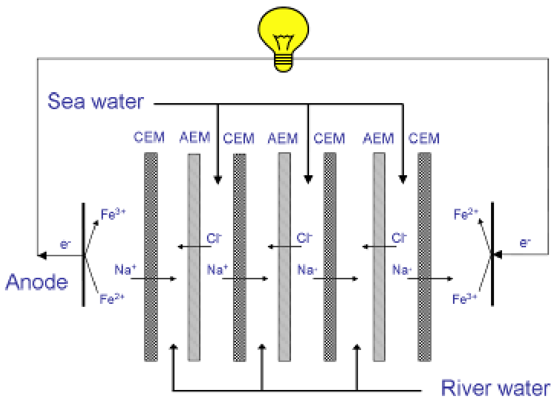

Figure 6.9: Reversed Electro Dialysis (RED) System (Groeman and Van den Ende, 2007)

6.3.5.2 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). Professor Sidney Loeb first proposed this principle in the early 1970s (Loeb and Norman, 1975).

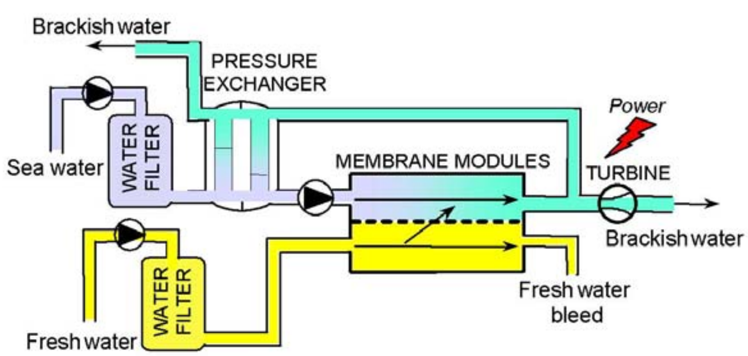

Figure 6.10: Pressure Retarded Osmosis (PRO) process (Scråmestø et al., 2009).

The osmotic power process utilises naturally occurring osmosis, caused by the difference in concentration of salt concentration between two liquids (for example, seawater and fresh water). Seawater and fresh water 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 this will be in the range of 24 to 26 bars, depending on seawater salt concentration.

Before entering the PRO membrane modules, seawater is pressurized to approximately half the osmotic pressure, about 12 - 13 bars. In the membrane module freshwater migrates through the membrane and into pressurized seawater. The resulting brackish water [TSU: is] then split in two streams. 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 Markets and Industry Development

6.4.1 Introduction

In the last 10 years marine energy technology developments have focussed on wave and tidal current technologies, probably because they are physically smaller and thus cheaper than major capital projects, such as tidal barrages and R&D projects in OTEC and salinity gradients. Presently, the only commercial ocean energy technology available is the tidal barrage, of which the best example is the La Rance Barrage in northwestern France (540 GWh/yr; de Laleu, 2009). Tidal barrages are usually large, capital-intensive constructions; complementary uses can justify development. These may include communication access, facilitating regional development, as at La Rance, or alleviation of environmental problems, such as at Sihwa Lake in Korea. [TSU: references missing]

Although some wave and tidal current devices are approaching commercial development, other technologies to develop the other ocean energy sources - ocean thermal energy conversion (OTEC), salinity gradients, ocean currents, submarine geothermal and marine biomass - are still at conceptual or early prototype stages. More than one hundred ocean power 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, at best, have reached pre-commercial prototype stage. Consequently, there is no commercial market for ocean energy technologies at present.

Some governments are using a range of initiatives and incentives to promote both ‘technology push’ and ‘market pull’ to promote and accelerate the uptake of ocean power technologies. These are fully described in section 6.4.7. The northeastern Atlantic coastal countries lead the development of the market for ocean power technologies and their produced electricity. Funding mechanisms such as the Clean Development Mechanism (CDM) or Joint Implementation (JI) projects enable developing country governments to secure additional external funding for ocean energy projects. The Sihwa barrage project in the Republic of Korea was funded, in part, by CDM finance. [TSU: references missing]

The introduction of emissions trading schemes and/or carbon taxes to promote emissions reductions may also promote uptake of ocean energy technologies, by effectively pricing in the cost of CO_2 emissions to fossil fuel technologies. This will make renewable energy technologies, such as wave and tidal stream technologies, which produce no emissions in operation, more competitive.

Since ocean energy technologies are being developed, which produce pressurized or potable water as well as or instead of electricity, markets for these products will develop in due course.

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, promoting rapid growth of industry supply chains. [TSU: references missing]

An unusual feature of ocean energy is the emergence of a loose network of national marine energy testing centres, such as the European Marine Energy Centre in Orkney – the first of a growing number of testing centres worldwide – where device developers can test their prototypes, using existing infrastructure, power purchase agreements and permits. These centres are accelerating the development of a wide range of wave and tidal current technologies. [TSU: references missing]

Industry development road maps and supply chain studies have been developed for Scotland, the United Kingdom and New Zealand (MEG, 2009; UKERC, 2008; AWATEA, 2008); the US and Canada have begun road mapping exercises. These countries have begun to assess the market potential for ocean energy as an industry development or regional development initiative. Regions supporting industry cluster development, leading to development of scalable power developments, will attract concentrations of industry development. [TSU: references missing]

There are now a series of global and regional initiatives 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:

- International Energy Agency's Ocean Energy Systems Implementing Agreement
- EquiMar – the Equitable Testing and Evaluation of Marine Energy Extraction Devices (a European Union-funded initiative to deliver a suite of protocols for evaluation of wave and tidal stream energy converters)
- WavePLAM – the WAVe Energy PLanning And Marketing project (a European industry initiative to address non-technical barriers to wave energy).

6.4.2 Wave Energy

Wave energy technologies started to be developed with appropriate scientific basis after the first oil crisis in 1974. Many different converter types have been and continue to be proposed and tested but we are still at the beginning of pre-commercial phase. It is usual to test devices at small-scale in laboratory test-tank facilities (~1:100) before the first open-sea prototype testing (1:10 – 1:4 scale). Pre-commercial testing may be at 1:2 or 1:1 scale before the final full-scale commercial version becomes commercially available. 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 the next decade. Costs of electricity from these early projects are already lower than those for solar PV and efforts such as the Marine Energy Accelerator programme (Carbon Trust, 2007) and incentivised pilot markets are intended to accelerate the cost reduction experience to make wave energy technologies commercially competitive.

A coast-attached oscillating water column device has been operational in Portugal since 1999 and a somewhat similar device (Wavegen's LIMPET device[5]) has been operating almost continuously on the island of Islay in Scotland since 2000. Offshore oscillating water column devices have been tested at prototype scale in Australia (Energetech/Oceanlinx[6]) since 2006.

The most advanced oscillating-body device is the 750 kW Pelamis Wavepower[7] attenuator device, which has been tested in Scotland and deployed in Portugal. The Portuguese devices were sold as part of a commercial project. The other near-commercial oscillating-body technology is Ocean Power Technologies' PowerBuoy[8], a small (40 – 150 kW) vertical axis device, which has been

[5] www.wavegen.co.uk
[6] www.oceanlinx.com
[7] www.pelamiswave.com
[8] www.oceanpowertechnologies.com

deployed in Hawaii, New Jersey and off the north Spanish coast. Other oscillating-body devices under development include the Irish device, Wavebob[9], and the WET-NZ device[10]. Two Danish overtopping devices have been built at prototype-scale (Wave Dragon[11] and WavePlane[12]).

6.4.3 Tide Rise and Fall

Presently, only estuary-type tidal power stations are in operation. They rely on a barrage, equipped with generating units, closing the estuary. The only industrial-scale tidal power station in the world to date 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 (South Korea) is expected to be commissioned in 2010 and will then become the largest tidal power station in the world. Sihwa power station is being retrofitted to an existing 12.7 km sea dyke that was built in 1994. The project will, when operational, generate electricity, while also improving flushing the reservoir basin to improve water quality. [TSU: references missing]

By the end of 2010, the world's installed capacity of tidal rise and fall will still be <600 MW (EDF, 2009). However, numerous projects have been identified, some of them with very large capacities, e.g., the Severn Estuary, White Sea and Sea of Okhotsk in Russia. Barrages are most common but some are tidal lagoon concepts (Figure 6.11). Total planned capacity is approximately 21.9 GW.

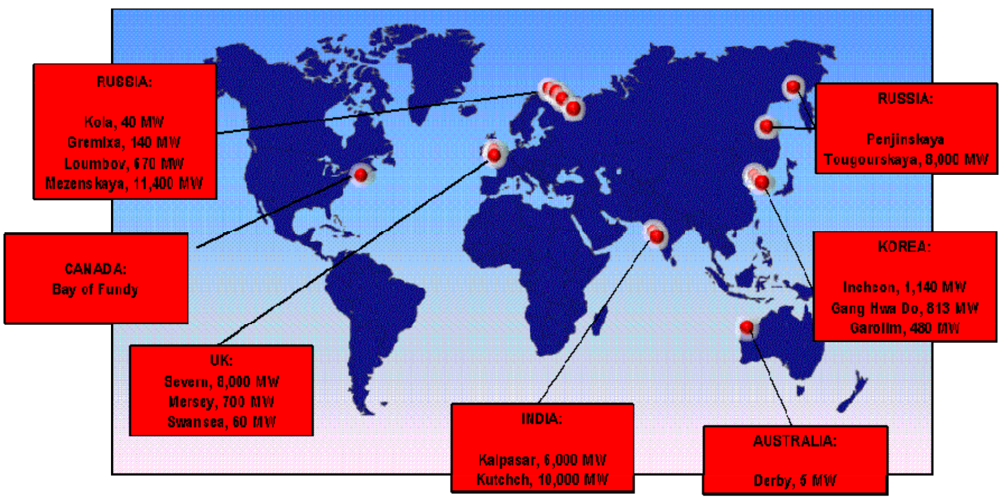

Figure 6.11: Tidal rise and fall power station proposed as of March 2009 (EDF, 2009)

6.4.4 Tidal and Ocean Currents

All tidal stream energy systems are in the proof of concept or prototype development stage, so large-scale deployment costs are not yet known. The most advanced example is the SeaGen tidal turbine, which was installed in Strangford Lough in Northern Ireland. This 'pre-commercial demonstrator' is now an accredited 'power station'. Most of these projections [TSU: context unclear] should be based on the available resources referenced in Section 6.2. From the global surveys, the best markets for tidal energy are in United Kingdom, USA, Canada, northeast Asia, and Scandinavia (EDF, 2009).

[9] www.wavebob.com
[10] www.wavenergy.co.nz
[11] www.wavedragon.net
[12] www.waveplane.com

Tidal energy has some unique attributes that may enhance its market value. Tidal stream flows are often located near population centres, where the electricity delivery is not constrained by the further requirement for long transmission lines. Being largely submarine, tidal power plants are likely to have a very low visual impact, so can be located close to populations. Tidal flows are also very predictable, which is very valuable in utility generation planning and forecasting. [TSU: references missing]

The resource for tidal current energy is not widespread, being located at specific sites where current velocities are high enough for economic viability. The threshold for this velocity is at least 1.5 ms^{-1} but not enough is known about costs and this threshold will decline as technologies improve. Generally, the global resource and, hence, markets must be large enough to support sufficient deployments and experience for the technology to reach commercial maturity. Supported markets in Scotland, Ireland, UK, France, Spain and Portugal will launch development projects through the coming decade: the experience and scale up will drive down costs to a competitive level. [TSU: references missing]

Open ocean currents, such as the Gulf Stream, are being explored for their potential. 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). They do involve much larger water volumes, promising project scale.

6.4.5 Ocean Thermal Energy Conversion

Two floating ocean thermal energy conversion (OTEC) plants have been built in India. In 2005, a short 10-day experiment was conducted using an OTEC system mounted on a barge near Tuticorin (Ravindran, 2007). A barge was moored in water 400 m deep and successfully produced fresh water at a rate of 100,000 litres per day, using an ammonia-based closed-cycle system, created in co-operation with Saga University of Japan. The design was rated at 1 MW and apparently began construction in 2000 but was never completed.

In 2005, a land-based plant, capable of producing 100,000 litres per day of freshwater was built on the island of Kavaratti, using a 350 m long cold-water intake pipe (NIOT, 2007). The location gives access to water at 400 m depth only 400 m from shore, making it an ideal site for OTEC but the current plant does not incorporate electrical generation.

A small “Mini-OTEC” prototype plant was built in US in 1979 (Vega, 1999). The plant was built on a floating barge and used an ammonia-based closed cycle system. The 28,200 rpm radial inflow turbine gave the prototype a rated capacity of 53 kW but efficiency problems with the pumps limited to only 18 kW. In 1980 another floating OTEC plant, called OTEC-1, was built. It used the same closed-cycle system and was rated at 1 MW but it was primarily used for testing and demonstration and did not incorporate a turbine. It was operational for four months during 1981, during which time issues with the heat exchanger and water pipe were studied.

During 1992, an open-cycle OTEC plant was built in Hawaii (Ocean Thermal Energy, 2007). It operated from 1993 to 1998, and it had a rated capacity of 255 kW. Peak production was 103 kW and 0.4 l/s of desalinated water. Various difficulties were encountered, including out-gassing of the seawater in the vacuum chamber, the vacuum pump and varying output from the turbine/generator.

Several OTEC power plants have been built in Japan (Kobayashi et al., 2004). A 120 kW plant was built in the republic of Nauru, which used a closed-cycle system based on Freon and a cold water pipe with a depth of 580 m. The plant operated for several months and was connected to the power grid; it produced a peak of 31.5 kW of power. In 2006 the Institute of Ocean Energy (IOES) at Saga University created a small-scale 30 kW Hybrid OTEC plant. The prototype used a mixed water/ammonia working fluid, and successfully generated electrical power.

Sea Solar Power is developing a hybrid closed-cycle/open cycle OTEC system (Sea Solar Power, 2007). The design calls for the use of a propylene-based closed cycle-system, providing 10 MW of power in a shore-based plant or 100 MW in an offshore one. A parallel open-cycle system will provide fresh water and additional generation. Although conceptual plant designs have been created, it is unclear if any development is still occurring.

6.4.6 Salinity Gradient

Osmotic power is still a concept under development (Scråmestø et al., 2009). Utility sector and research groups initiated early development of osmotic power systems but, more recently, new groups have become engaged as the industry emerges. The parallel development of related technologies, such as desalination, will benefit the osmotic power industry.

Several governments and organisations are already supporting the development itself and consideration of necessary instruments to bring this source of renewable energy to the market. [TSU: references missing]

6.4.7 Ocean Energy-Specific Policies

[TSU: references missing in this section]

Because ocean energy technologies are relatively new but could offer emissions-free electricity generation and potable water production, numerous governments have introduced policy initiatives to promote and accelerate the uptake of marine energy. These policies range from funding initiatives, incentives to specifically promote marine energy deployments, industry and market develop and other regulatory initiatives to reward developers/users of marine energy technologies.

The government initiatives fall into five main categories (Table 6.2):

- Targets for installed capacity or contribution to future supply
- Capital grants and financial incentives, including prizes
- Market incentives, including feed-in tariffs and supply obligations
- Research and testing facilities and infrastructure
- Permitting/space/resource allocation regimes, standards and protocols

Most of the countries that have ocean energy-specific policies in place are also the most advanced with respect to technology developments and deployments. Government support for ocean energy is critical to the pace at which ocean energy is developed.

There are a variety of targets both aspirational and legislated. Most ocean energy-specific targets relate to proposed installed capacity targets, which complement other targets, such as for proportional increases in renewable energy generation or renewably generated electricity. Some European countries, such as Portugal, Ireland and Germany, have preferred ‘market pull’ mechanisms, such as feed-in tariffs (i.e., performance incentives for produced electricity from specific technologies). The United Kingdom has a Renewable Obligations Certificates (ROCs) scheme, i.e., tradable certificates awarded to generators of electricity using ocean energy technologies. More recently the Scottish Executive has introduced the Saltire Prize, a prize for the first device developer to meet a cumulative electricity generation target.

Most countries offer R&D grants for renewable energy technologies but some have ocean energy-specific grant programs. The United Kingdom and, since 2008, the United States have the largest and most sophisticated programs. Capital grant programs for device deployments have been implemented by both the United Kingdom and New Zealand as ‘technology push’ mechanisms.

Table 6.2: Ocean Energy-Specific Policies (modified after Huckerby & McComb, 2009).

Policy Instrument	Country	Example Description
Aspirational Targets and Forecasts	United Kingdom Basque Country, Spain, Canada	3% of UK electricity from ocean energy by 2020 5 MW off Basque coast by 2020 14,000 MW off Canada by 2050
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
R&D programs/grants	United States	US DoE Hydrokinetic Program (capital grants for R&D and market acceleration)
Prototype Deployment Capital Grants	United Kingdom New Zealand	Marine Renewables Proving Fund (MRPF) Marine Energy Deployment Fund (MEDF)
Project Deployment Capital Grants	United Kingdom	Marine Renewables Deployment Fund (MRDF)
Feed-in Tariffs	Portugal Ireland/Germany	Guaranteed price (in $/kWh or equivalent) for ocean energy-generated electricity
Renewables Obligations	United Kingdom	ROCs scheme (tradable certificates (in $/MWh or equivalent) for ocean energy-generated electricity
Prizes	Scotland	E.g., Saltire Prize (GBP 10 million for first ocean energy device to deliver over 100 GWh of electricity over a continuous 2-year period)
Industry association support	Ireland New Zealand	Government financial support for establishment of industry associations
National Marine Energy Centres	United States	Two centres established (Oregon/Washington for wave/tidal & Hawaii for OTEC)
Marine Energy Testing Centres	Scotland, Canada and others	European Marine Energy Centre[13] and Fundy Ocean Resources Center, Canada
Offshore Hubs	United Kingdom	Wave hub, connection infrastructure for devices
Standards/protocols	International Electrotechnical Commission	Development of international standards for wave, tidal and ocean currents
Permitting Regimes	United Kingdom	Crown Estate competitive tender for Pentland Firth licences
Space/resource allocation regimes	United States	FERC/MMS permitting regime in US Outer Continental Shelf

[13] www.emec.org.uk

6.5 Environmental and Social Impacts

6.5.1 Introduction

Since all ocean energy devices produce no CO_2 during operations, they are attractive for climate change mitigation purposes. Positive effects include strengthening of regional energy supply, regional economic growth, employment and eco-tourism. Negative effects may include reduction in visual amenity and loss of access to space for competing users. Project-specific effects will be different, depending on the environment where they are located and the communities that live near them and benefit from their outputs. Once operational, projects will have fewer and more limited effects than projects in operation [TSU: sentence unclear]. Most ocean energy projects will be long-lived (25 – 100 years), so the lasting effects of their development will be important. Given the high-energy nature of the ocean environment, the effects of some ocean energy projects should be completely reversible.

The general concerns comprise the effect of deployment, operation and maintenance (O&M) and decommissioning on local flora and fauna, and to a certain extent also the alteration of the physical environment. Noise impact is another issue. In addition, cabling the power generated to shore will involve bottom disturbances, including electromagnetic field hazards for some species.

More governments are undertaking Strategic Environmental Assessments (SEAs) to assess distribution of resources and to plan for potential environmental effects of ocean energy projects. Each new project proposal must then evaluate its own specific environmental impacts.

An ocean power station of any type becomes a source of eco-tourism and attraction in its own right, providing jobs in tourism and services [TSU: references missing]. Any type of ocean energy development will require extensive social and environmental impact assessments to fully evaluate all development options. A continuing program of public and stakeholder engagement is necessary to ensure that the concerns of various parties are duly considered in the development and operation of any project.

Social benefits may be national - creation of new industries, redirection of resources from declining industries, regional - developments of industry clusters, and individual - new employment opportunities, training for new skills and development of new capabilities. For example, the [TSU: delete] Scotland could create between 1,500 – 5,300 direct jobs in ocean energy by 2020 at present rates of marine energy technological and market development (MEG, 2009).

6.5.2 Wave Energy

Public concern over the environmental impacts of wave energy technologies comes from the lack of deployment experience with various wave energy conversion technologies. Good projections can be made using data from other offshore technologies, such as oil and gas and offshore wind. Potential impacts will [TSU: add “be”] similar to those of offshore wind turbines, which have now been monitored for several years. The potential effects on bird migration routes, feeding and nesting will not be relevant to ocean power technologies and the visual impacts of marine energy converters will be negligible, except where large arrays of devices are located nearshore.

Noise and vibration are potentially important impacts that need investigation. Noise and vibration are likely to be most disruptive during deployment and decommissioning but they will be longer-lasting during operations, so require R&D to understand, eliminate or mitigate. Electromagnetic fields around devices and electrical connection/export cables that connect arrays to the shore may be problematic to sharks and rays (elasmobranchs), which use electromagnetic fields to navigate and locate prey. Chemical leakage due to abrasion (of paints and anti-fouling chemicals) and leaks, e.g., oil leaks from hydraulic power-take-off systems (PTO)) will need to be eliminated or mitigated.

Energy capture and thus downstream effects could cause changes to sedimentation (e.g., seabed scouring or sediment accumulation) as well as wave height reductions, which are a potential concern to surfers. 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.

Large-scale implementation of wave farms will have positive impacts at general and local levels. In addition to electricity generation with rather small lifecycle greenhouse gases emission, it will decrease the import of fossil fuels (in those countries that do not possess such fuels) and will increase the local work of shipyards (devices construction and/or assembling), transportation, installation and maintenance. Exclusion areas for wave farms must be allocated, therefore creating refuges, which may be a net benefit to fishery resources.

6.5.3 Tide Rise and Fall

Estuaries are complex, unique and dynamic natural environments, which 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. For an estuary-type project, construction impacts will differ depending on the construction techniques employed: a total closure of the estuary during the construction period will affect fish life and biodiversity in the estuary whereas other methods such as floating caissons sunk in place for example will be less harmful.

At the La Rance power plant, although the estuary was closed for the construction period, biodiversity comparable to that of neighbouring estuaries was restored less than 10 years after commissioning, thanks to the responsible operating mode at the power station. The environmental impacts during construction of the Sihwa tidal power plant have been very limited. [TSU: references missing]

A barrage will affect the amplitude of the tides inside the basin and modify fish and bird life and habitat, water salinity and sediment movements in the estuary. Coastal processes may be disrupted. The need to ensure a minimum head between the basin and the sea will also lengthen the slack tidal times in the basin at high and low tides. A sound operational methodology is thus critical to mitigate the environmental impacts in the estuaries. In La Rance, two tides a day are systematically maintained by the operator inside the basin, which has resulted in the rapid restoration of a “natural” biodiversity in the basin. However, sediments accumulating towards the upstream end of the basin require regular dredging. [TSU: references missing]

Offshore tidal lagoons do not produce the same type of negative impacts. Being located offshore they do not have any impact on delicate nearshore ecosystems. Obviously they will have an impact on the area covered by the new basin, but provided this area is located away from sea currents, the impacts on marine life and biodiversity may be limited.

In terms of social impact, power plants constructed to date did not require any relocation of nearby inhabitants. This should continue to be so for future projects, as it is unlikely, even in the case of pumping, that the water level in the basin would be substantially higher than the water level at very high tides. Further these basins will be artificial installations at sites not previously inhabited.

Offshore tidal lagoons may have some impacts on fishing activities but this impact should be limited for locations away from sea currents. Lagoons may even be used to develop aquaculture to breed certain species of fish adapted to calm waters.

The construction phase usually requires large numbers of workers for the civil works, with significant investment and economic benefit to local communities. [TSU: references missing]

Estuary-type projects are often associated with the creation of new and shorter routes due to the use of the top of the barrage walls as roads linking locations originally with difficult access to each other. This will be positive in terms of improvement of socio-economic conditions for local communities. It should also lead to reductions in CO_2 emissions by reducing travel distances.

6.5.4 Tidal and Ocean Currents

6.5.4.1 Tidal Currents

The environmental impacts of tidal current technologies will be similar to those of wave energy converters. Tidal current technologies are likely to be large submarine structures, although some devices have surface-piercing structures. Environmental effects will be somewhat limited because devices are located in an already energetic, moving water environment.

A key concern with tidal current technologies is that they have rotating rotor blades or flapping hydrofoils - moving parts, which may harm marine life. To date there is no evidence of harm to marine life (such as whales, dolphins and sharks) from tidal current devices and this may in part be due to slow rotation speeds (relative to escape velocities of the marine fauna) compared with ship propulsion. On the positive side, arrays of tidal current turbines may act as de facto marine reserves, effectively creating new but protected habitats for some marine life.

6.5.4.2 Ocean Currents

Full-scale commercial deployments of open-ocean current electric generating systems could present certain environmental risks (Charlier, 1993; Van Walsum, 2003). These can be grouped into four broad categories: the physical environment (the ocean itself), benthic (ocean-bottom) communities, marine life in the water column and commerce.

Ocean current systems, with sufficient velocities to be cost-effective, are all associated with wind-driven circulation systems. Generation devices will not alter this circulation or its net mass transport. For example, the equator-ward Sverdrup drift in the 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). There could, however, be some alteration in meander patterns and in upper-ocean mixing processes, because the characteristics of the boundary current depend on dissipation. These effects need to be fully evaluated prior to full site development. Modelling studies of the Florida Current, using the HYCOM high-resolution regional simulation capability, are underway to assess these potential impacts (Chassignet et al., 2009).

Open-ocean power generation systems will 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 and thus impact the attraction of sports fishing. Because underwater structures are known to become fish aggregating devices (FADs) (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).

6.5.5 Ocean Thermal Energy Conversion

Potential changes in the regional properties of seawater due to ocean thermal energy conversion (OTEC) pumping operations are a major 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 characteristics of the waters before discharge into ambient ocean water near the site. For this reason some shipboard OTEC projects, called ‘grazing’ projects, have been proposed so that the large volumes [TSU: singular] of discharged water does not have a long-term impact on the discharge site.

Under normal operating conditions, OTEC power plants will release few emissions to the atmosphere and will not adversely affect local air quality. The magnitude of possible climatic effects resulting from sea-surface temperature alterations by commercial OTEC development have not yet been ascertained and additional research on this theme is recommended.

Materials selection and design for operational flow rates, temperatures and pressures must be considered, together with aspects research on bio-fouling, corrosion and maintenance (Charlier and Justus (1993).

Marine organisms, mainly plankton and dissolved organic material, will be attracted by marine nutrients by the OTEC plant’s discharge pipe. Bacterial slimes will, which will [TSU: sentence structure] degrade heat exchanger performance, unless preventive procedures are implemented.

6.5.6 Salinity Gradient

Mixing of seawater and freshwater is a natural process that occurs all over the world. An osmotic power plant will extract the energy using this process without any significant interference with the environmental qualities of the site. Freshwater and seawater mixed in an osmotic power plant will be returned (to the sea) as brackish water, where they would have mixed naturally. Brackish water is the main waste product of the osmotic power plant but its concentrated discharge may alter the environment and result in changes for animals and plants living in the location. The impact of produced brackish water on the local marine environment will need to be monitored. Osmotic power will not produce any operational CO_2 emissions.

Assessments of the environmental optimisation and pre-environmental impact of an osmotic power plant located at an estuarine river mouth have not identified any serious obstacles. Major cities and industrial area [TSU: plural] are often sited at the mouths of major rivers, so osmotic power plants could be constructed on ‘brownfield’ sites. The plants can be constructed partly or completely underground to reduce their environmental footprint on the local environment.

6.6 Prospects for Technology Improvement, Innovation and Integration

6.6.1 Wave Energy

Wave energy technologies are still largely at a very nascent stage of development and all are pre-commercial (Falcão, 2009). Any cost or reliability projections are speculative with 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 to advance technology developments. As has happened with wind turbine generators, wave energy devices will iterate to the scale of the largest practical machine, to minimize the number of operation and maintenance (O&M) service visits, reduce installation and decommissioning costs and limit mooring requirements.

The largest cost reductions will come from maximizing power production by individual wave energy converters, even if deployed in arrays [TSU: references missing]. This will require efficient capture devices and dependable, efficient conversion systems. Performance and reliability will be top priorities for wave energy systems as commercialization and economic viability will depend on systems that require little servicing and can continue to produce energy reliably with minimal maintenance. The use of arrays will permit redundancy of single units and assist better maintenance/repair planning.

6.6.2 Tide Rise and Fall

Tidal rise and fall power projects rely on proven technologies in civil and electromechanical engineering, albeit built and operated in an estuarine, rather than a riverine environment. There are basically three areas where technology improvements can still be achieved [TSU: references missing]:

1. Development of cost-effective offshore tidal lagoons will allow the development of cost effective projects
2. Multiple tidal basins will increase the value of projects by reducing the intermittency of generation, thus allowing a better placement of the energy generated on the load curve.
3. Turbine efficiency improvements, particularly in bi-direction flows (including pumping).

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 in situ within cofferdams or pre-fabricated in caissons (steel or reinforced concrete) and floated to site.

6.6.3 Tidal and Ocean Currents

Like wave energy converters, tidal current technologies are in 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 O&M service visits, reduce installation and decommissioning costs and minimize substructure requirements.

Tidal device performance may be limited by the geometry of the specific channel transect dimensions and navigational requirements. The total tidal 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. A similar trend is well documented in the wind energy industry in the United States, where wind turbine technology developments targeted less energetic sites, creating a 20-fold increase in the available resource.

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

6.6.4 Ocean Thermal Energy Conversion

The heat exchanger system is one of the key components of closed-cycle ocean thermal energy conversion (OTEC) 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.

Evaporator and condenser units represent 20 - 40% of the plant total cost, so most research efforts are directed toward improving heat exchanger performance. Materials selection for the heat exchanger system is important. One of the best options is corrosion-resistant titanium but, due to its high cost, aluminium is substituted. This requires regularly scheduled planned maintenance. Copper-nickel alloys and stainless steel alloys are also candidate materials for the heat exchanger.

A second key component of an OTEC plant is the large diameter pipe, which carries deep coldwater to the surface. Experience obtained in the last decade with large-diameter risers for offshore oil and gas production can be easily transferred to the cold water pipe design.

A number of options are available for the closed-cycle working fluid, which has to boil at a low temperature (of warm surface water) and condense at a slightly lower temperature (of deep sea cold water). Three major candidates are ammonia, propane and a commercial refrigerant R-12/31. The main advantages are high evaporation and high thermal conductivity, especially in the liquid phase. Non-compatibility with copper alloys should be taken into account during design.

6.6.5 Salinity Gradient

The first osmotic power prototype plant became operational in October 2009 at Tofte, near Oslo in southeastern Norway. The prototype location is within an operational pulp factory, which gives good access to existing infrastructure. The location has sufficient access to seawater and fresh water from a nearby lake (Scråmestø, Skilhagen and Nielsen, 2009).

The main objective of the prototype is to confirm that the designed system can produce power on a reliable 24-hour/day production. After the start-up, initial operation and further testing, experience gained will be based on both operational changes as well as changes to the system and replacement of parts. These changes will be designed to increase the efficiency and optimise power generation. If the results of the prototype and the technology development are as expected, the R&D programme will lead to a commercial technology within a few years. [TSU: references missing]

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 pre-treatment equipment and the water inlets and outlets is needed (Scråmestø, Skilhagen and Nielsen, 2009).

6.7 Cost Trends

6.7.1 Introduction

Commercial markets are not yet driving marine energy technology development. Government-supported technology R&D and national policy incentives are the key motivation for most technology development and deployment (US DoE, 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).

Key variables that were taken into account in conducting some of the cost analysis include:

- Total installed capital cost (CAPEX),
- Reliability (i.e., operations and maintenance (O&M)),
- Annual Energy Production or Performance (AEP)[14]
- Learning curve (based on total industry wide deployment),
- Economies of scale (based on project size, production capacity),
- Impact of R&D and value engineering (innovation and implementation)

[14] This term is widely accepted in the industry, even though 'energy production' is incorrect

Table 6.3: Cost Summary for All Ocean Energy Technology Sub-types

		Current Cost Parameters[1]					Future Cost Parameters			
Source of Cost Data	Type of Ocean Energy Technology	Capex (US$/kW)	O&M Costs (US$/kW)	Discount Rate in %	Capacity Factor in %	LCOE (US¢/kWh)	LCOE (US¢/kWh)	Required Cumulative Capacity in MW	Learning Rate	Notes
Vega (2002)	OTEC	12,300	NA	-	-	0.22	-	-	-	100 MW closed-cycle, 400 km from shore
SERI (1989)		12,200	NA	-	-	-	-	-	-	40 MW plant planned at Kahe Point, Oahu
Cohen (2009)		8,000 - 10,000	NA	-	-	0.16 - 0.20	0.08 - 0.16	-	-	100 MW early commercial plant
Francis (1985)		5,000 - 11,000	NA	-	-	-	-	-	-	-
Lennard (2004)		9,400	NA	-	-	0.18 (0.11)	-	-	-	10 MW closed-cycle; LCOE in parenthesis apply if also producing potable water
SERI (1989)		7,200	NA	-	-	-	-	-	-	Onshore, open-cycle
Vega (2002)		6,000	NA	-	-	0.10	-	-	-	100 MW closed-cycle, 100 km from shore
Vega (2002)		4,200	NA	-	-	0.07	-	-	-	100 MW closed-cycle, 10 km from shore
Scråmestø et al., 2009	Salinity Gradient Power	High	-	-	70%	0.05 - 0.10	-	-	-	[TSU: LCOE are in EUR/kWh. Will be converted in US$/kWh.]
CEC (2009)	Tidal Current	-	-	-	-	0.10 - 0.30	-	-	-	Cost estimate for California
Callaghan (2006)		8,571 - 14,286	-	-	-	0.16 - 0.32	0.046	2,800	-	Prototype, cost assessment for UK
Callaghan (2006)	Wave Energy	7,679 - 16,071	-	-	-	0.21 - 0.79	-	-	-	Prototype and pre-commercial devices, cost assessment for UK
Previsic (2004)		2620	123	7.5	38%	-	0.13 (2020)	-	-	106.5 MW capacity, 213 devices x 500 kW, 20-year life, 95% availability, R&D improvement

[1] Cost estimates for OTEC technologies are in different-year dollars and cover a range of different technologies and locations. Many are also highly speculative.

6.7.2 Wave and Tidal Energy

Several cost studies have estimated costs for wave and tidal energy devices by extrapolating from available prototype cost data (BBV, 2001; Li and Florig, 2006; Previsic, 2004; Callaghan, 2006; IEA, 2008). A recent study undertaken for the California Renewable Energy Transmission Initiative showed that tidal current generation (deployed in California) would cost US$100-300/MWh (CEC, 2009)[15]. Wave and current devices are at approximately the same early stage of development. CAPEX costs will potentially decline with experience to costs achieved by other renewable energy technologies such as wind energy (Bedard et al., 2006). This can only be demonstrated by extrapolation at present, since there is limited actual operating experience. Present CAPEX estimates are derived from operating prototypes, whose costs exceed commercial devices.

The US Electric Power Research Institute (EPRI) commissioned a study 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). Costs were based on a full 20-year life, 95% availability and forecast economies of scale. Energy capture

[15] http://www.energy.ca.gov/reti/index.html.

potential would take advantage of near-term R&D improvement opportunities not yet realized but which were thought to be achievable at current CAPEX costs. The study concluded that a levelized cost of energy (LCOE) of 0.134 US$/kWh could be achieved, based upon a CAPEX cost of US$ 279 M, discount rate of 7.5%, capacity factor of 38%, and annual O&M costs of US$ 13.1 M (i.e., US$ 0.44/kWh).

In 2006 the UK Carbon Trust published the results of a survey of current costs for prototype and pre-commercial wave and tidal energy converters. Wave energy converters had CAPEX values ranging from £ 4,300 - 9,000/kW (US$ 7,679 - 16,071/kW) with a midpoint of US$ 11,875/kW (Callaghan 2006). Similarly, prototype tidal stream energy generator costs ranged from £ 4,800 - 8,000/kW (US$ 8,571 - 14,286/kW) with a midpoint of £ 6,400/kW (US$ 11,428/kW). Some current device concepts may have even greater CAPEX costs, which may be offset by future cost reductions. The same study estimated that energy from early UK wave energy farms would have LCOEs between 12 – 44 p/kWh (21.4 - 78.8 US¢/kWh) whilst early tidal stream farms had estimated LCOEs between 9 – 18 p/kWh (16.1 - 32.1 US¢/kWh). The studies did not account for economies of scale, R&D improvements or learning curve effects.

These theoretical analyses provide plausible benchmarks to demonstrate that wave energy projects could have lower LCOEs than wind energy did in the 1980s. Early wind turbines had numerous deployment problems and high 'infant mortality rates' that drove up early wind LCOE estimates, which may be avoided by early marine energy devices. The greatest uncertainties in estimating the LCOE of ocean energy are annual energy production (AEP) and operation and maintenance (O&M) costs. To achieve competitive costs, future ocean energy AEP and O&M must be estimated assuming increased efficiency and reliability.

There is also a high degree of uncertainty in estimating future CAPEX for mature, reliable systems from prototype data (Previsic et al., 2004; Buckley, 2005). Learning curve effects are an important downward cost driver for LCOE. As deployments multiply and installed capacity rises, costs reduce along the learning curve, due to natural production efficiency gains and assimilated experience. Early learning curve decline rates will be high but reduce over time. Learning curve rates for wind turbine generators ranged from 10% to 27% per doubling of installed capacity (see review of learning curve literature in Chapter 7, Table 7.8.2). Limiting this analysis to studies that span the full development of the wind industry (i.e., the three decades from 1980s to the present day), the learning curve effect converges to about 11% per doubling, without including an R&D factor (Wiser and Bolinger, 2009). Future ocean energy industries (wave, tidal current, ocean current and OTEC) could follow the same 11% learning curve as the wind industry. A CAPEX learning curve for wave and tidal current technologies, beginning with the midpoints for the CAPEX costs given by the Carbon Trust (2006), shows a rapid decline with increased installed capacity (Figure 6.12).

CAPEX costs for wave and tidal energy technologies will reduce to a range from US$ 2,600/kW to US$ 5,400/kW (average: US$ 4,000/kW), assuming worldwide deployments of 2-5 GW by 2020 and a learning rate of 11%. Electricity production from ocean energy technologies will exceed 667.5 TWh/yr from an installed capacity for all technologies of approximately 220 GW (assuming a nominal capacity factor of 35% and deployment estimates to 2050 (Table 6.4 or Chapter 10)). CAPEX costs will reduce to US$ 1,800 - 3,500, depending on the other market achievements of the individual ocean energy subtypes, assuming that aggregated energy output is roughly allocated at 50 GW per major technology subtype (Figure 6.12).

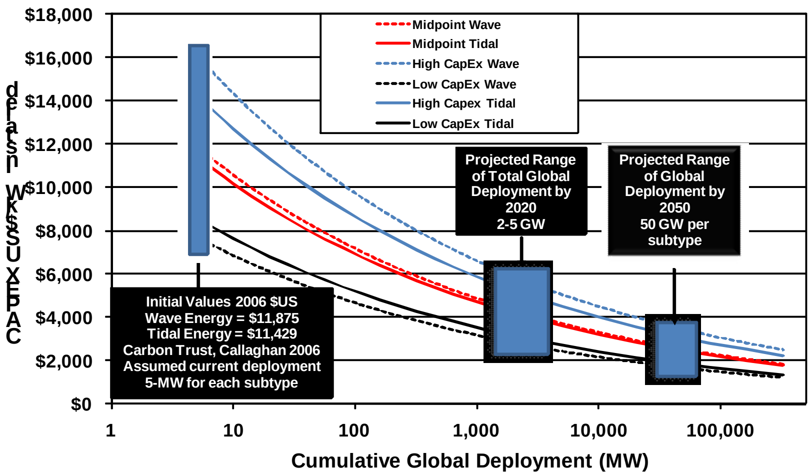

Figure 6.12: Learning curve reductions in CAPEX for wave and tidal energy devices based on current cost and 11% cost reduction per doubling of capacity (Callaghan, 2006).

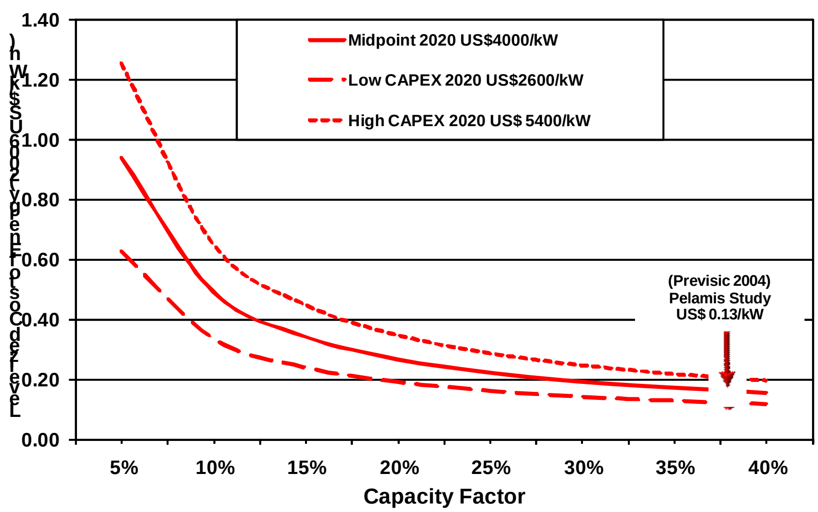

Figure 6.13: Capacity factor effect on LCOE for 2020 ocean energy CAPEX showing theoretical EPRI design, using Pelamis 500 kW machines at 38% capacity factor (Previsic, 2004).

Figure 6.13 shows projections of LCOE for wave and tidal energy as function of capacity factor, using a calculation worksheet provided by IPCC wind modelling group (Wiser, 2009). The three curves correspond to the calculated high, mid and low learning rate curves, i.e., US$ 5,600/kW, US$ 4,000/kW and US$ 2,600/kW, taken in the year 2020 (Figure 6.12). Marine devices operating with high capacity factors (i.e., 30% to 40%) can potentially generate electricity at rates competitive with other technologies. Devices must be reliable and located in a high quality wave or tidal current resource to achieve such capacity factors. Cost reductions will derive from manufacturing economies, new technology designs, knowledge and experience transfer from other industries and design modifications realized through operation and experience. All will contribute to rapid LCOE reductions. The cost and economics for open-ocean current technologies should track closely the evolution of tidal stream energy technologies. No definitive cost studies are available in the public domain for ocean current technologies.

6.7.3 Tide Rise and Fall

Tidal rise and fall 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, capital costs associated with tidal rise and fall technologies are high, when compared to other sources of energy. Innovative techniques including construction of large civil components onshore and flotation to the site will allow substantial reduction in risks and costs. Tidal rise and fall projects tend, therefore, to be large-scale, as the scale reduces the unit cost of generation.

Tidal rise and fall projects may be eligible for Clean Development Mechanism (CDM) credits, as was the case for the Sihwa project in the Republic of Korea or, as in the UK, for the award of two Renewable Obligation Certificates (ROCs) for tidal energy, worth £ 105 (US$ 191) per MWh each.

6.7.4 Ocean Thermal Energy Conversion

Because there has been no sustained field experience with commercial ocean thermal energy conversion (OTEC) operations, it is hard to predict cost trends. Costs for individual projects are presently high, so iterative development has been slow. Published cost estimates are generally high. These range from: $ 4,200/kW, $ 6000/kW and $ 12,300 for a 100 MW closed-cycle power plant (10 km, 100 km, and 400 km, respectively from shore, corresponding to $ 0.07/kWh, $ 0.10/kWh, and $ 0.22/kWh (Vega, 2002 and 2009); $ 9,400/kW or $ 0.18/kWh for a 10 MW closed-cycle pilot plant, dropping to $ 0.11/kWh, if also producing potable water (Lennard, 2004); and $ 8,000-$ 10,000/kW for an early commercial 100-MW plant, corresponding to $ 0.10 - 0.20/kWh, dropping to $ 0.08 - 0.16/kWh, once enough plants have been built; an initial 75-MWe commercial floating plant off Puerto Rico will cost approximately $600 million, will produce 600 million kWh of electricity annually for about $ 0.15/kWh (Plocek et al., 2009) [TSU: not included in Table 6.3]. These speculative estimates are in different-year dollars and cover a range of different technologies and locations.

Perhaps the most reliable current costs are the Lockheed-Martin pilot plant estimates: $32,500/kW for a 10 MW pilot plant to $10,000/kW for a commercial 100 MW plant (Cooper et al., 2009) [TSU: not included in Table 6.3]. Advances in new materials and construction techniques in other fields in recent years, however, improve OTEC economics and technical feasibility. Offshore construction experience for wind turbines, undersea electrical cables, and oil drilling platforms, in particular, will prove helpful to future OTEC installations. Potentially important work specific or directly applicable to OTEC includes a congressionally mandated U.S. Navy contract expected to be awarded soon for development of high-efficiency, low-cost heat exchangers and industry and university work on lower-cost turbines. Costs will decrease dramatically with deployments.

6.7.5 Salinity Gradient

The estimated costs of producing osmotic power, based on a number of detailed investment analyses, are expected to be in the range of Euro 50 -100 per MWh [TSU: All monetary values will be converted to 2005 US$](Scråmestø et al., 2009). Full-scale cost estimates are based on current hydropower knowledge, general desalination (reversed osmosis) engineering and a specific membrane target as a prerequisite. Capital costs are expected to be high, compared to other renewable energy sources, and dependent on development of reliable, large-scale and low-cost membranes. However, capacity factors are expected to be approximately 70% [AUTHORS: This number was inferred from the claim that osmotic power could produce twice what a wind turbine could make. Please verify and provide a reference to support this claim.], based on preliminary calculations, which will yield relatively high AEP.

6.8 Deployment Potential

[TSU: Plenary-approved heading: Potential Deployment]

Individual ocean energy technology subtypes (i.e., tidal, wave, OTEC, ocean current) were aggregated to perform the initial analyses presented in Chapter 10 (Krewitt, 2009). These aggregated values yield estimates for world ocean energy deployments - with relatively high uncertainties. Further analysis is required to break down capital costs, resource technical potential, capacity factor and regional distribution of the resource for each technology.

Technical potential for aggregated ocean energy resources were estimated to be 0.207 EJ/yr (57.5 TWh/yr) by 2020, but increasing to 2.437 EJ/yr (677.5 TWh/yr), by 2050 as new technology is introduced (see section 6.4 to obtain specific data on current installations). This is a significant proportion of the world's energy consumption. The proportion of ocean energy deployments in the world's energy use portfolio is expected to continue to grow well beyond the 2050 horizon.

Significant growth in the decade 2010 – 2020 will see a substantial increase in ocean energy's contribution to energy/electricity supply and thus climate change reductions (Table 6.4). However, the total contribution will still be small. From 2020 mature technology deployments will effectively treble the proportion of energy/electricity production, with an effective doubling for the succeeding decades. These generation figures were generated from ocean energy runs of the MESAP/PlanNet - Energy [R]evolution Scenario model (Krewitt 2009, SRREN Database 2010). This analysis is preliminary, since ocean energy has only recently been included in some IPCC scenario modelling. The magnitude and diversity of ocean energy resources indicate that ocean energy can offer significant potential for carbon emission reductions before 2050 and beyond but near-term deployments (10 years) are unlikely to have a significant impact on global climate change.

Table 6.4: Ocean Energy Deployment from MESAP/PlanNet - Energy [R]evolution Scenario

	2010		2020		2030		2040		2050	
	TWh/yr	EJ/yr	TWh/yr	EJ/yr	TWh/yr	EJ/yr	TWh/yr	EJ/yr	TWh/yr	EJ/yr
World	2.5	0.009	57.5	0.207	151.2	0.544	338.6	1.218	677.5	2.437
Brazil	0.0	0.000	0.2	0.001	0.9	0.003	1.7	0.006	2.0	0.007
China	0.0	0.000	5.0	0.018	25.0	0.090	75.1	0.270	260.2	0.936
EU	0.6	0.002	3.4	0.012	13.0	0.047	34.0	0.122	55.0	0.198
India	0.0	0.000	4.2	0.015	9.0	0.032	19.0	0.068	37.0	0.133
Japan	1.2	0.004	7.0	0.025	18.0	0.065	29.0	0.104	35.0	0.126
Russia	0.0	0.000	13.0	0.047	17.0	0.061	21.0	0.076	25.0	0.090
USA	0.70	0.0025	8.0	0.029	27.0	0.097	71.1	0.256	115.1	0.414

6.8.1 Near-term Forecasts

Most near-term deployment will be policy driven in countries where government-sponsored research programs and policy incentives have been implemented to promote ocean energy development. Some countries have proposed non-binding deployment targets and timelines to achieve prescribed ocean energy capacity. The United Kingdom government has a target of 2 GW by 2020 (UKERC, 2008). Canada, USA, Portugal and Ireland have announced, or are working on establishing, independent deployment targets in a similar timeframe. However, most countries with significant ocean resources have not yet quantified their ocean energy resource potentials and have not established national deployment goals. In general, the near-term forecast for ocean energy does not envisage a substantial contribution to near-term carbon mitigation.

6.8.2 Long-term Deployment in the Context of Carbon Mitigation

The long-term deployment potential for ocean energy is significant in terms of future carbon mitigation. Substantial technology development is expected over the next 10 years, making ocean energy's proportionate larger in longer-term scenarios. Ocean technology scenario modelling need to be refined by disaggregation into the technology sub-types, better resource and cost information. The validity of scenario model projections depends on cost and resource assumptions for individual technologies, which, to date, have had only limited actual deployments. As deployments proliferate, model inputs will improve and scenario modelling will iterate towards better accuracy.

6.8.2.1 Resource Potential

- Wave energy sites are globally dispersed over all coastal boundaries, but mid-latitude sites (30 – 60º) are more favourable. Seasonal variations are much larger in the northern hemisphere than in the southern hemisphere, an important advantage for southern hemisphere deployments. The technical resource potential is present on coasts where incident wave energy exceeds an average of 20 kW/m but may be limited to nearshore sites (< 50 km) near coastal load centres. Availability of suitable sites may become a barrier in some regions under high penetration scenarios or in populated areas with competing uses.
- Tidal rise and fall is most likely in enclosed bays, where the regional tidal range is adequate for deployment. Limited site availability may prevent widespread deployment but tidal power plants are likely to be large to capture economies of scale.
- Tidal currents energy is globally distributed but is locally limited to sites, where local bathymetry accelerates existing currents. Average current speeds must exceed 1.5 ms^{-1} for present technologies. Sites with current speeds of at least 1.0 ms^{-1} may become viable as technologies mature.
- OTEC resources are limited to tropical regions where thermal differences of c. 20º C occur in close proximity to load centres. Coasts and islands with steep gradients – to bring deep water close to shore – are ideal locations. OTEC has potential for Indian, Pacific and Caribbean coast and island sites.
- The potential of ocean currents is limited to sites where relatively fast-moving global circulation currents come reasonably close to land, e.g., Florida Gulf Stream. The technical resource is abundant and could support substantial local or regional deployment.
- The technical potential for salinity gradient technology is probably limited to large river mouths, where large volumes of fresh water debouch into the sea.

6.8.2.2 Regional Deployment

Ocean energy technology is under development in countries bordering the North Atlantic, North Pacific and Southern Ocean, where government-sponsored programmes support R&DD and deployments, whilst pro-active policy incentives to promote early-stage projects [TSU: sentence structure].

6.8.2.3 Supply Chain Issues

There are no foreseeable supply chain issues that will limit the manufacture or deployment of ocean energy devices.

6.8.2.4 Technology and Economics

Successful demonstration of ocean energy technologies are limited to electric energy generating facilities located close to shore, where power delivery and grid integration issues do not significantly exceed the knowledge base of other variable output renewable energy sources, like offshore wind. The technical performance of ocean energy technologies will improve steadily over time as experience is gained and new technologies will be able to access poorer quality resources.

Technical improvements will enhance capacity factors, give access to more remote sites and tolerance of poorer quality resources (poorer wave climates or lower average current velocities).

6.8.2.5 Integration and transmission

Ocean energy deployments are likely to occur where network/grid access is available with sufficient nearby load demand. Small-scale off-grid applications are also possible. Large-scale deployment scenarios will require forecasting capability (which may be good in some instances), matching generation variability with load demand and power quality. Variability will differ by technology from relatively steady base-load generation from [TSU: sentence incomplete]. Ocean currents, OTEC and osmotic power plants will produce base load power, whilst tidal currents and tidal rise and fall will produce cyclical but predictable generation. Even the more stochastic nature wave generation has forecastable characteristics on longer-term variability than wind or solar insulation [TSU: sentence structure].

6.8.2.6 Social and Environmental Impacts

The social and economic impacts of ocean energy projects are being evaluated as actual deployments multiply (Section 6.5). Risk analysis and mitigation, using environmental impacts assessments, will be part of early deployments. Competitive uses may preclude the availability of some good resources sites. A balanced approach to engaging energy end-users in coastal communities will be necessary, whilst maintaining a fair and responsible respect for existing coastal uses.

6.8.3 Conclusions Regarding Deployment

The preliminary estimation of aggregated ocean energy deployment presented here is the first attempt to include ocean energy in any of the IPCC scenario modelling. Ocean power technologies have promising potential to mitigate long-term climate change by offsetting GHG emissions with predicted deployments resulting in energy delivery of 2.437 EJ/yr (677.5 TWh/yr) by 2050 (based on the preliminary analysis provided by the MESAP/PlanNet - Energy [R]evolution analysis). The modelling process established here will allow future scenarios to include ocean energy to be disaggregated into individual technologies, with better performance and cost data, to provide more rigorous and accurate analyses in [TSU: the] future.

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