Introduction to Ocean Renewable Energy

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Overview

It has been estimated that the world's oceans contain at least 10 TW of renewable energy potential, comprising wave & tidal energy, ocean thermal energy conversion (OTEC), ocean current, and salinity gradient energy. However, these resources remain largely untapped – currently there is around 500 MW (0.005%) of installed ocean renewable energy capacity throughout the world, and this largely comprises of tidal range energy. This volume of Comprehensive Renewable Energy discusses various aspects of the ocean renewable energy resource and the technologies suitable for ocean energy conversion, covering wave & tidal energy, ocean currents, OTEC, and salinity gradient energy. In this introduction to the volume, I briefly introduce the nature and potential of these five main ocean renewable energy resources, with further details found in subsequent chapters of this Volume.

Keywords: Wave energy, Ocean currents, OTEC, Salinity gradients, Tidal energy

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Contents

1. Introduction

Covering 71% of the Earth's surface, and with a mean water depth exceeding 3 km, one of the largest potential sources of energy conversion surrounds us – the ocean. Excluding offshore wind (which is covered by Volume 2), the ocean offers five main forms of energy conversion, each with the potential to generate electricity at significant scale:

- Wave energy
- Ocean currents
- Ocean thermal energy conversion (OTEC)
- Salinity gradients
- Tidal energy

Although the feasibility of each of these forms of energy conversion has been proven, none of these resources has yet been exploited at significant scale, one of the most prohibitive factors being cost. The majority of these resources ultimately derive from the Sun (e.g. wave energy is due to momentum transferred from the wind – a result of uneven heating of the Earth's surface), but one of the most predictable forms of ocean energy, tidal energy, has its origins in the tide generating forces, dominated by the coupled Earth-Moon system (in conjunction with the Sun). However, tidal energy is highly variable, characterized by diurnal or semi-diurnal cycles, in addition to fortnightly (spring-neap) cycles. In contrast, OTEC and ocean current resources are relatively constant and, although possibly more technically challenging and more expensive than tidal energy to exploit (since the resource is in deeper water and generally further offshore), could facilitate integration of ocean energy power plants into electricity grids which require firm 'baseload' power.

Although more details can be found in the subsequent chapters of this volume, I here introduce these various forms of ocean energy conversion, focussing on their nature and potential, but also including details of commercial progress. It is difficult to categorize and hence logically order the sequence of their introduction, but I begin with the most stochastic 'weather-dependent' ocean renewable energy resource – wave energy, followed by ocean currents (also largely driven by westerlies and trade winds). I then introduce OTEC (which exploits vertical temperature gradients in the ocean), then salinity gradient energy (which exploits horizontal salinity gradients where rivers meet the sea). Finally, I introduce the most predictable form of ocean renewable energy – tidal energy, driven by the coupled Earth-Moon system (and the Earth's rotation), in conjunction with the gravitational influence of the Sun.

2. Wave energy

As with wind energy (which leads to the generation of surface wind waves), wave energy is a stochastic form of renewable energy.

2.1. Nature of wave energy

Although waves in the natural environment occur over a wide range of scales, from capillary waves with periods of less than 0.1 s, to trans-tidal waves with periods of over 24 h, the waves that are suitable for wave energy conversion generally have wave periods of between 1-25 s, and corresponding wave lengths of around 5-200 m (Fig. 1).

Wave energy occurs when momentum from the wind field is transferred into the ocean. Locally, for example at the centre of a storm, wind waves are generated, and the energy of the sea is characterized by a wide range of wave frequencies. Further from the storm, the wave frequencies disperse, and the sea may be characterized by a local (wind) component in addition to a swell component that represents energy from the distant storm. Indeed, on a calm day you may have noticed that there are often long period waves present, representing swell. Information on the wave energy distribution can be presented in the form of a wave energy spectrum, where the wave energy (related to the amplitude squared) is plotted against each wave frequency. Fig. 2 shows an example of a wave energy spectrum from the west coast of Scotland, showing a peak wave period of around 9 s, but also a range of wave periods between 2-16 s.

Waves propagate in the ocean at a speed that is a function of the water depth and wave frequency. The relationship between these three variables is described by the dispersion equation

$$\sigma^2 = gk\tanh(kh) \tag{1}$$

where $\sigma = 2\pi/T$ is the angular frequency (T is wave period), g is acceleration due to gravity, h is water depth, and $k = 2\pi/L$ is the wavenumber (L is wave length). As you can see from Eq. 1, provided water depth is not a limiting

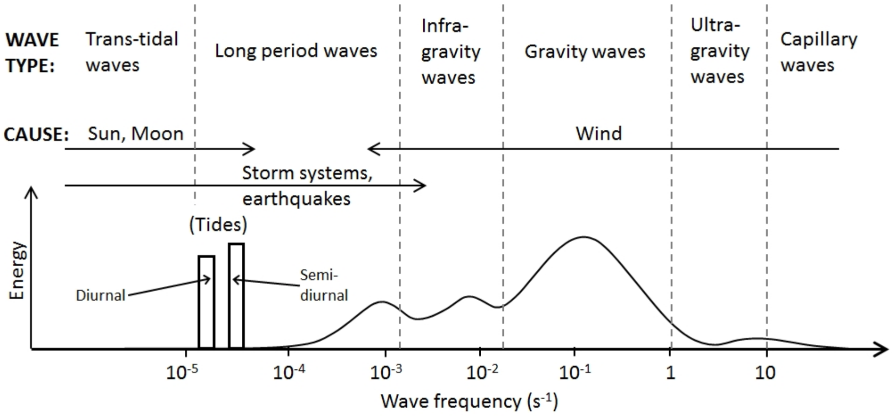

Figure 1: Scales of surface waves.

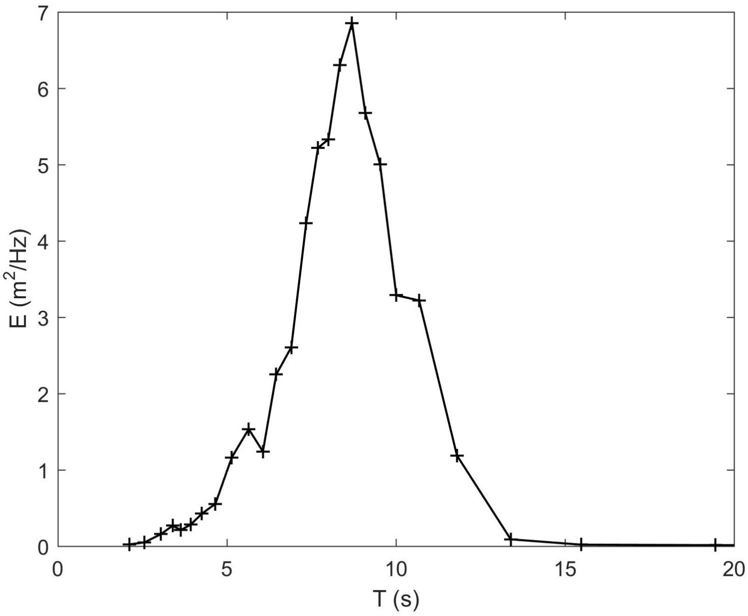

Figure 2: One dimensional wave spectrum from Blackstone wave buoy, west coast of Scotland, 2nd June 2019, 15:30. Data from `https://www.cefas.co.uk/cefas-data-hub/wavenet/`

factor (i.e. in deep water where the wave length is much less than the water depth), then $\tanh(kh) = 1$ and the phase speed (c) becomes

$$c = \frac{g}{\sigma} = \frac{gT}{2\pi} \tag{2}$$

i.e. the phase speed depends only on the wave period, and hence long period (low frequency) waves propagate faster than short period (high frequency) waves. Therefore, when waves generated at the centre of a storm propagate away from their source, the longer period (longer wave length) waves propagate fastest. For example, if a wave buoy is sited 1000 km from the centre of a storm in the Southern Ocean, the longer period waves will be detected first. Since wave energy travels at the *group velocity* (which is half the phase speed in deep water), a 14.8 s wave would take 12 h to arrive at the observation station, whereas a 7.4 s wave would take 24 h – an example of dispersion (Eq. 1). Note that in shallow water, where the wave length is much greater than the water depth, $\tanh(kh) = kh$ and Eq. 1 simplifies to $c = \sqrt{gh}$ – the same result as a tidal wave (Section 6).

Waves contain equal proportions of potential energy (due to the displacement of the free surface) and kinetic energy (due to wave orbital motion), and the total energy E is

$$E = \frac{\rho g H^2}{8} \tag{3}$$

where H is wave height and ρ is water density. Wave power P (assuming deep water conditions, i.e. where $L \ll h$) is

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{4}$$

where H_s is the significant wave height (the mean height of the largest one-third of waves in a record) and T_e is the energy wave period; therefore larger amplitude and longer period waves are more attractive for electricity generation.

2.2. Wave energy potential and commercial progress

The global wave energy resource has been estimated as around 2 TW [1], but this is a mean estimate (wave energy varies considerably over time), and it is not practical to exploit all regions, for example a large amount of the resource is far offshore, such as in the Southern Ocean. However, there is a significant resource adjacent to many coastal regions, such as along the south coast of Australia, the west coast of the US, and the west coasts of Ireland and Scotland.

There are various types of wave energy converter (WEC), but two of the most popular are the *wave attenuator* and the *surface point absorber*. An attenuator, the most publicized example of which is Pelamis, is a long floating device that is aligned with the direction of wave propagation. The device converts the energy of waves into electricity by constraining the motion along its length. Since the attenuator is aligned with the direction of wave propagation, it is more suited to environments where the wave direction is relatively consistent, for example in the coastal zone where waves refract, and tend to propagate normal to the coastline. In contrast, a point absorber can convert the energy from waves travelling in multiple directions. These are therefore more suited to environments, possibly further offshore, where wave direction is more variable. Other types of WEC, particularly those that are shore-attached, include oscillating water column and overtopping devices [2].

The European Marine Energy Centre (EMEC) was established in Orkney (north of Scotland) in 2003. Although EMEC has now expanded to 13 sites suited to either tidal or wave energy conversion, the full scale wave test site at Billia Croo to the west of Orkney opened first, and the Pelamis 750, the world's first grid-connected floating wave energy device, began testing in 2004. Various iterations of Pelamis, an attenuator device, were subsequently developed and tested, culminating in the P2 device (also rated at 750 kW). Pelamis went into administration in 2014, but did manage to deliver over 250 MWh of electricity to the UK grid, and valuable lessons were gained and communicated through extensive testing. The publicly available power matrix of Pelamis is often used in technical wave energy resource assessments [e.g. 1].

Early prototype point absorber technologies made use of heaving buoys that reacted against a fixed frame of reference, such as the sea bed. However, this creates difficulties due to the relatively large distance between the sea surface and sea bed, and so most point absorbers now developed are two-body systems, in which energy is converted from the relative motion between two bodies oscillating differently [3]. The Wavebob, developed in Ireland, converts the relative axial motion between two co-axial axisymmetric buoys into electrical energy through a high pressure oil system. A 1/4 scale device has been tested in Galway Bay, in the west coast of Ireland, but unfortunately the company closed down in 2013 due to funding difficulties. Another two-body point absorber is the PowerBuoy, developed by the US-based Ocean Power Technologies. Rated at around 3 kW, the device is targeted more towards creating an uninterruptable power supply, for example to provide power to offshore communication platforms, rather than grid integration. This is an interesting area of development for wave energy projects and devices, since a much higher levelized cost of energy is more suited to the provision of electricity offshore (which is of order \$1000/MWh) compared to domestic electricity prices (more of order \$100/MWh).

3. Ocean current energy

Large scale ocean currents such as the Gulf Stream have been fairly well popularized, but along the western boundaries of ocean basins, these ocean currents are intensified into 'Western Boundary Currents', which have significant energy conversion potential.

3.1. Nature of the ocean current resource

Winds are generated by uneven solar heating, in combination with the Earth's rotation. As air moves towards the subtropics ($23.5^\circ - 35^\circ$ latitude), it descends over the oceans, creating semi-permanent circulation features known as subtropical highs. In the Northern Hemisphere, for example, these high pressure systems are located over the North Pacific and North Atlantic oceans. Anticyclonic wind systems circulate around these subtropical highs, leading to the westerlies and easterlies (trade winds) that have been exploited in ocean exploration and trading since the fifteenth century. Friction between the wind and the ocean surface drives ocean surface currents, and hence corresponding ocean gyre systems, with the currents generally concentrated in the upper 400 m of the water column.

Surface currents located on the western side of the subtropical gyres, known as western boundary currents, are faster than their eastern boundary counterparts (Fig. 3). One reason for the westward intensification of boundary currents is related to the strengthening of the Coriolis effect with latitude. The Coriolis effect is stronger at the higher latitudes of the westerlies than in the lower latitudes of the trade winds. Transport of surface waters toward the western boundary of the ocean basins causes the ocean-surface slope to be steeper on the western side (versus eastern side) of a gyre (in either hemisphere). A steeper ocean-surface slope translates into a faster geostrophic flow on that side of the gyre.

In contrast to the high temporal variability that characterizes the wave energy resource (Section 2), these relatively fast flowing (generally around $1 - 1.5$ m/s – see Fig. 3) ocean currents are relatively persistent. Since variability is relatively low, western boundary currents could be a fairly reliable ocean renewable energy resource. Further, since ocean currents pass fairly close to land masses (as western boundary currents), for example the Agulhas Current flows along the east coast of Africa, and the Gulf Stream flows through the Straits of Florida (Florida Current), devices that convert the kinetic energy of ocean currents into electricity could be feasible for grid integration, further facilitated by the fact that the currents have low variablity. However, the core of the ocean current resource tends to be relatively far from shore (e.g. > 20 km) and in relatively deep water (e.g. > 500 m) [4], and so extraction of the resource will be expensive and technically challenging. Western boundary currents transport vast volumes of water, for example the Aghulas Current has a mean transport of around 70 Sv (1 Sverdrup = 10^6 m^3/s) [5]. Therefore, from a practical perspective, it is unlikely that extraction, even at significant scale, would affect the resource itself, in contrast, for example, to tidal energy extraction that tends to be focussed in narrow channels (Section 6).

3.2. Ocean current energy potential and commercial progress

Globally, the theoretical ocean current energy resource has been estimated as around 0.5 TW [6], with the Florida Current alone representing $20 - 25$ GW, which reduces to $1 - 4$ GW if realistic technical constraints are imposed [4]. The former figure ($20 - 25$ GW) is particularly interesting, as this is approximately the mean demand for electricity for the state of Florida.

To convert the kinetic energy that resides in western boundary currents into electricity, turbines would need to be designed with characteristics that can overcome a number of technical challenges. The resource is stronger closer to the water surface (accounting for navigational constraints), but water depths at suitable locations will be $200 - 500$ m, and regions with a suitable energy density are relatively far from shore. For the latter constraint, devices will

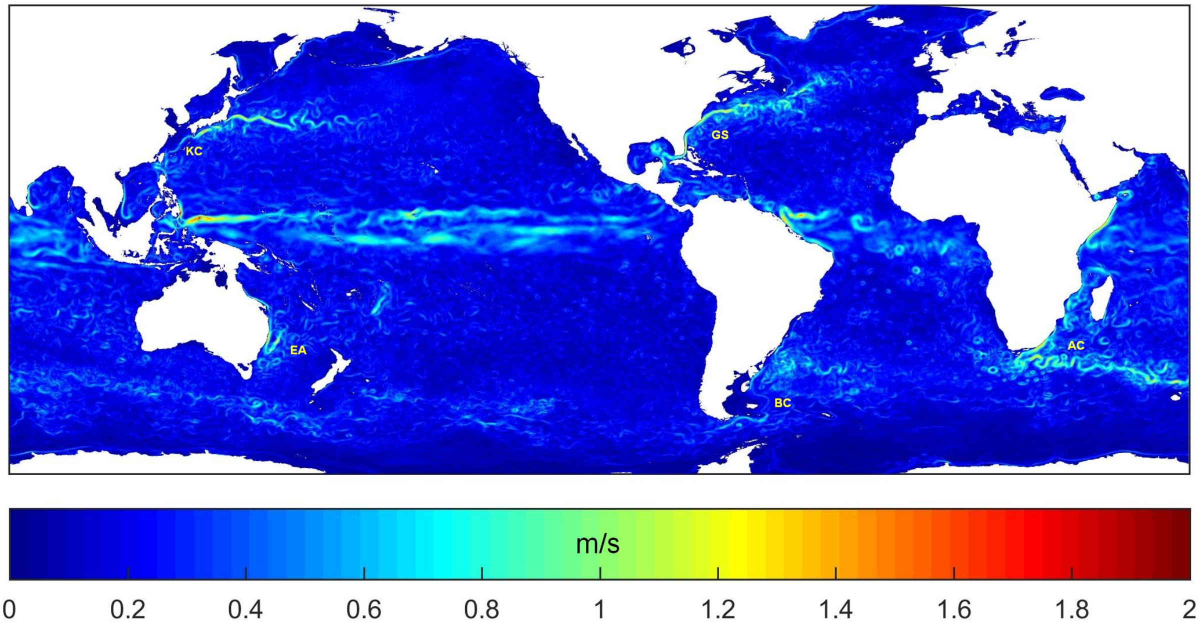

Figure 3: The five main western boundary currents, shown as mean current speed (m/s) in January 2015 at 50 m water depth. KC=Kuroshio Current; EA=East Australia Current; GS=Gulf Stream; BC=Brazil Current; AC=Agulhas Current. Data from HYCOM global reanalysis.

need to be suitably robust to minimize maintenance periods, and for this, in general, simplicity is important. One aspect that will help here is the fact that the ocean currents, in contrast to tidal energy for example, are generally uni-directional, and so neither a yawing mechanism is required, nor turbines where the blades must be designed to extract energy during different phases of a tidal cycle. Clearly in such water depths, the devices must be floating, yet tethered to the sea bed – design criteria that are not uncommon in the tidal energy and offshore wind industries. Several designs for ocean current devices have been proposed, of which three are prominent. Two of these are of the horizontal axis configuration: Aquantis C-Plane and the three-bladed Kuroshio Current prototype [7]. Another design is particularly novel – the Minesto Deep Green 'kite', which is tethered to the sea bed, and travels in a figure-of-eight trajectory, increasing the local velocity at the turbine which is placed on the kite itself. However, apart from some limited prototype testing, there is virtually zero exploitation of the ocean current energy resource to date.

4. Ocean thermal energy conversion (OTEC)

Ocean thermal energy conversion (OTEC) refers to technology that can produce electricity by exploiting the temperature difference between deep cold ocean water and warm tropical surface waters.

4.1. Nature of the OTEC resource

The temperature of the ocean is fixed at the sea surface by heat exchange with the atmosphere. There is a latitudinal variation in the incoming energy from the Sun at the Earth's surface, and indeed the average incoming energy from the Sun is about four times higher at the equator compared to the poles. In contrast, the average infrared radiation heat loss to space is relatively constant with latitude. As a result, there is a net input of heat to the Earth's surface into the tropical regions, and this is where we find the warmest surface seawater. Heat is subsequently transferred from the tropics to high latitudes by ocean currents and winds in the atmosphere.

Cold water has a higher density than warm water; therefore cold dense water sinks to the bottom of ocean basins, below the less dense warmer surface water. Combined with the wind-driven surface flow (Section 3), the sinking and transport of cold water creates a complex pattern of ocean circulation, informally referred to as the 'global conveyor belt'. Since surface waters are warmer at the tropics, there is a large temperature difference between the surface and deep water at low latitudes (for example 24°C over the uppermost 1000 m – Fig. 4). In contrast, at mid- and high-latitudes, there is a much lower temperature difference, for example 13°C over the uppermost 1000 m at mid-latitudes during the summer, reducing to just 5°C in winter. It is possible to exploit this vertical temperature gradient in a process known as ocean thermal energy conversion (OTEC).

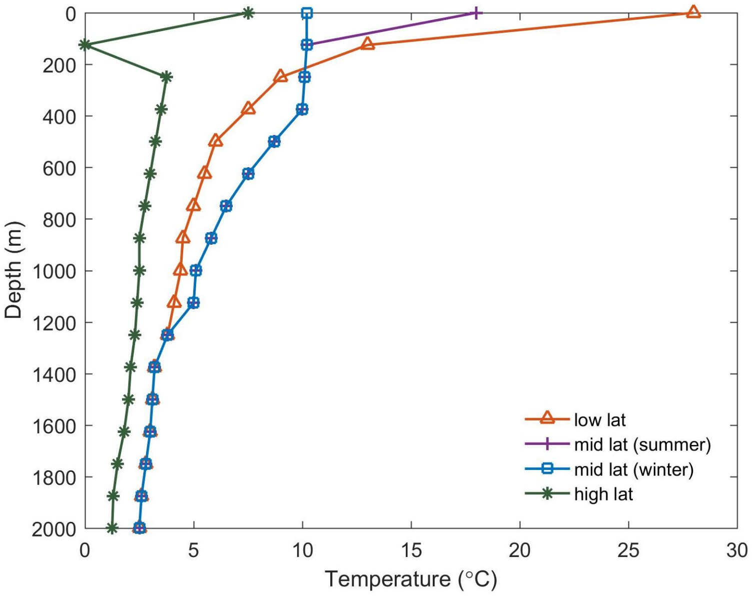

Figure 4: Typical temperature profiles in the ocean at low, mid, and high latitudes. Mid latitude data is shown for both summer and winter periods. Data from NOAA.

4.2. OTEC potential and commercial progress

Although warm tropical sea water at 24°C is at too low a temperature to boil water (to produce steam and drive a turbine), other working fluids, such as ammonia, have much lower boiling points – therefore a closed cycle OTEC power plant uses ammonia as the 'working fluid'. This working fluid circulates around a closed loop as shown in Fig. 5. Warm water from the sea surface flows through a heat exchanger, causing the working fluid to boil and vaporize. This vaporized fluid flows through a turbine, which turns a generator that converts the energy into electricity. Upon leaving the turbine, the working fluid needs to be cooled so that it can be reused, otherwise the efficiency of the system would drop significantly. Cold water pumped from the deep ocean flows through a second heat exchanger that cools the working fluid to its original temperature, ready to enter the cycle again. The cold water from the deep ocean, now at a slightly elevated temperature, is discharged into the ocean. The warm water from the ocean surface, at a slightly reduced temperature, is discharged into the upper ocean. An alternative to the closed cycle OTEC power plant is an open cycle power plant, where the sea water itself is used as the working fluid.

Although OTEC is limited to low latitudes, its potential is huge – the International Renewable Energy Agency (IRENA) has been estimated that the OTEC resource could be as high as 30 TW [8], and this would make it, by far, the largest of the ocean energy resources. However, despite the resource potential, commercial progress has been modest (Fig. 6). Although operational plants are around the 100 kW scale, those sites that are planned are around the 10 – 20 MW scale. More insights into OTEC are provided in Chapter 8.XX of this volume.

5. Salinity gradient energy

Where rivers meet the ocean, there is a large gradient in salinity, and it is possible to exploit this *salinity gradient* to produce electricity.

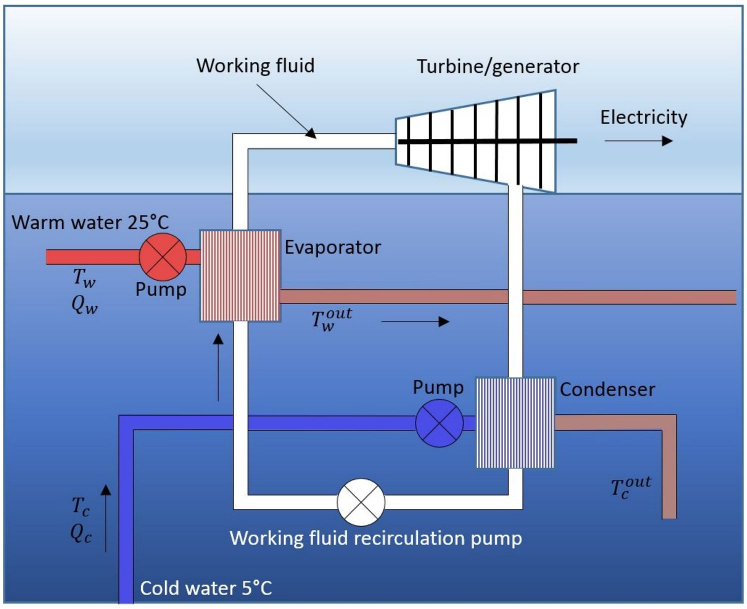

Figure 5: OTEC closed cycle. Reproduced from Neill and Hashemi [2].

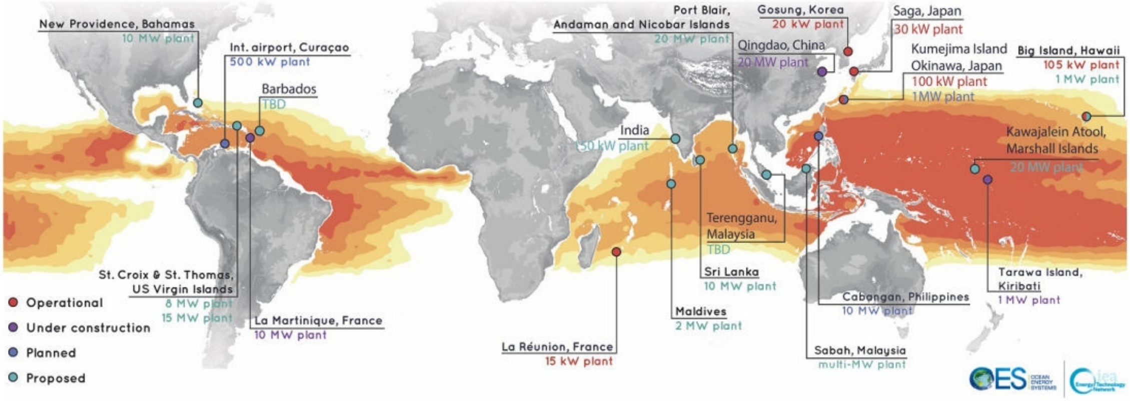

Figure 6: OTEC projects around the world. (Image kindly provided by the OTEC Foundation.)

5.1. Nature of salinity gradient energy

Salinity gradient power is the energy that is available for conversion due to the difference in salt concentration between two fluids, generally fresh and salt water, i.e. where a river flows into the sea [9]. River discharge varies vastly, depending on catchment size, soil type, weather conditions, the amount of rainfall, land use and slope. By far the largest river discharge in the world is the Amazon in South America, which has a mean discharge of 209,000 m^3/s (the second globally ranked river – the Congo – has an annual mean discharge of 41,200 m^3/s); however, there are around 140 rivers around the world with a mean discharge that exceeds 2000 m^3/s (`https://en.wikipedia.org/wiki/List_of_rivers_by_discharge`). River water has a salinity close to zero, whereas the mean salinity of seawater is around 35 ‰ (parts per thousand). There are two main salinity energy conversion technologies – pressure retarded osmosis (PRO) and reversed electro dialysis (RED), but both are based on separating the river and sea water by a semi-permeable membrane. By placing water of differing salt content either side of this membrane, the water (solvent) will flow through the membrane from the region of high water potential (region of lower salt concentration) to a region of low water potential (region of higher salt concentration) – a process known as osmosis. In PRO – the simplest of the two technologies – the flux of fresh water through the membrane towards the sea water increases the pressure inside the sea water chamber. The pressure is then used to spin a turbine and turn a generator.

5.2. Salinity gradient potential and commercial progress

Globally, the technical salinity gradient resource has been estimated as 647 GW [9]. However, many technological barriers must be overcome to achieve even a fraction of this value, the most challenging of which is the efficiency of the membrane technology [2]. A 10 kW PRO pilot plant in Tofte (Norway) was opened in 2009, consisting of 2000 m^2 of membrane. A 50 kW RED pilot plant, opened in 2013, has been constructed on a causeway in the Netherlands (the Afsluitdijk) that separates fresh water from sea water in the Wadden Sea. It is noteable that none of the major river sources have yet been exploited by salinity gradient technologies.

6. Tidal energy

All of the ocean energy sources in the previous sections are based, largely, on the Sun (e.g. uneven heating of the Earth leading to winds and hence waves). However, one resource relies predominantly on the Moon – tidal energy.

6.1. Nature of tidal energy

Although the reasons we have tides are complex and multi-faceted, involving a discussion of tide generating forces and the Coriolis force[1], it is sufficient at this stage to state that due to the coupled Earth-Moon system, in combination with the Earth's rotation and the Sun's gravity, we experience tides on Earth. The tides on Earth are predominantly semi-diurnal (two tides per day), but in many regions of the Earth the tides are either diurnal (one tide per day) or 'mixed' – a combination of semi-diurnal and diurnal tides. The tides are a predictable rise and fall in sea level, generally occurring twice per day, but also with variations over longer timescales, for example a larger tidal range is experienced during spring tides, and a smaller tidal range during neap tides one week later. This represents one of the most important challenges to tidal energy, since most of the energy is available during springs, and very little during neaps.

The analysis and prediction of tides can be explained by considering a number of tidal constituents – the principal ones are shown in Table 1. In regions that are strongly semi-diurnal, i.e. the majority of the world's oceans, the M2 tidal constituent on its own represents mean tidal conditions. In contrast, M2 + S2 is a spring tide, and M2 − S2 is a neap tide. The global distribution of M2 tidal amplitudes (Fig. 7) shows that there are a few regions in the world with high tidal range, such as the NW European Shelf Seas, NW Australia, the Patagonian shelf, and regions of Canada. In these regions, it is possible to convert the potential energy of the tidal range into electricity through tidal barrages or tidal lagoons [10]. This aspect of tidal energy – tidal range power plants – is covered in detail in Chapter 8.XX. In contrast, the tides also manifest as tidal currents, and again these are very strong in some regions, such as through tidal channels and around headlands. This aspect of tidal energy – tidal stream energy – is covered in detail in Chapter 8.XX.

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[1] Details are provided in Chapter 8.XX of this volume.

Symbol	Name	Speed (°/h)	Period (h)	Amplitude relative to M2
O1	Lunar diurnal	13.943	25.819	0.26
K1	Lunisolar diurnal	15.041	23.935	0.37
N2	Larger lunar elliptic semi-diurnal	28.44	12.658	0.21
M2	Principal lunar semi-diurnal	28.984	12.421	1
S2	Principal solar semi-diurnal	30	12	0.35

Table 1: Some of the most important diurnal and semi-diurnal tidal constituents. The amplitude of each tidal constituent relative to M2 is calculated using mean amplitudes extracted from TPXO9 global tidal atlas for water depths less than 200 m (representative of shelf sea regions), between latitudes 66.5°S and 66.5°N.

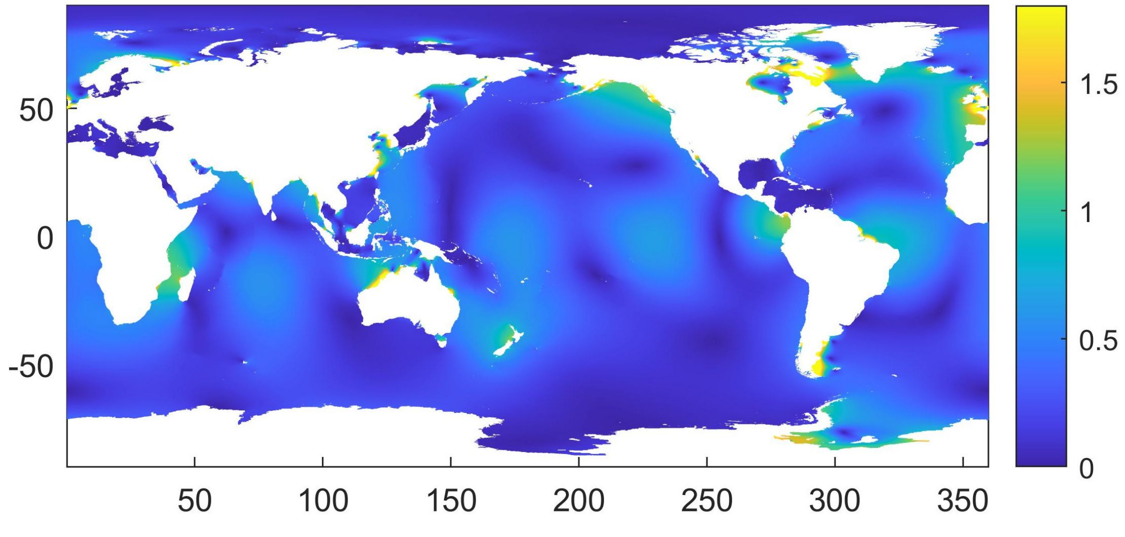

Figure 7: Global distribution of M2 amplitude (m).

6.2. Tidal energy potential and commercial progress

Global tidal dissipation (based on the M2 tidal constituent) is around 2 TW, and so this represents a upper limit of the tidal energy resource [11]. The resource tends to be concentrated in particular areas, and it is only feasible to convert the tidal energy into electricity close to the coast and where there is a grid connection. However, the majority of tidal dissipation occurs in shelf seas, and the tidal range is very large in regions that are in resonance, for example the Bay of Fundy in Canada [12]. Therefore, the exploitable tidal energy resource could be relatively large compared to the theoretical resource, e.g. in contrast to other ocean energy resources such as OTEC. For example, Neill et al. [13] estimated the technical global tidal range resource to be in the region of 1 TW.

Five tidal range power plants have been constructed around the world – the first of which was La Rance in France, which opened in 1966 [14]. All existing tidal range power plants are *barrages*, i.e. they span the full width of an estuary or channel. It is generally considered that the next generation of tidal range power plants will be *tidal lagoons* (which only partially impound an estuary or seaway), since these are associated with lower capital cost and reduced environmental impacts [10].

In contrast to tidal range, although there has been a lot of activity in the tidal stream sector over the last 20 years, as yet there is minimal installed capacity (around 10 MW globally, compared to 500 MW of installed tidal range power). In 2008, the Marine Current Turbine (MCT) dual rotor SeaGen device was connected to the grid in Strangford Lough (Northern Ireland). The device had a rated capacity of 1.2 MW and was decommissioned in the period 2016 – 2018. SeaGen delivered over 11.6 GWh during its life time, and its successful decommissioning demonstrated the feasibility of commercial tidal stream energy developments at all stages of project life cycles. Currently the largest tidal stream array in operation, the 6 MW Phase 1A MeyGen project in the Pentland Firth (Scotland) consists of four 1.5 MW horizontal axis turbines. Up to June 2019, the project has delivered 17 GWh to the grid.

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