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Ocean Energy

350PPM

Capitalist Solutions to Climate Change

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Written July 2020.

Introduction

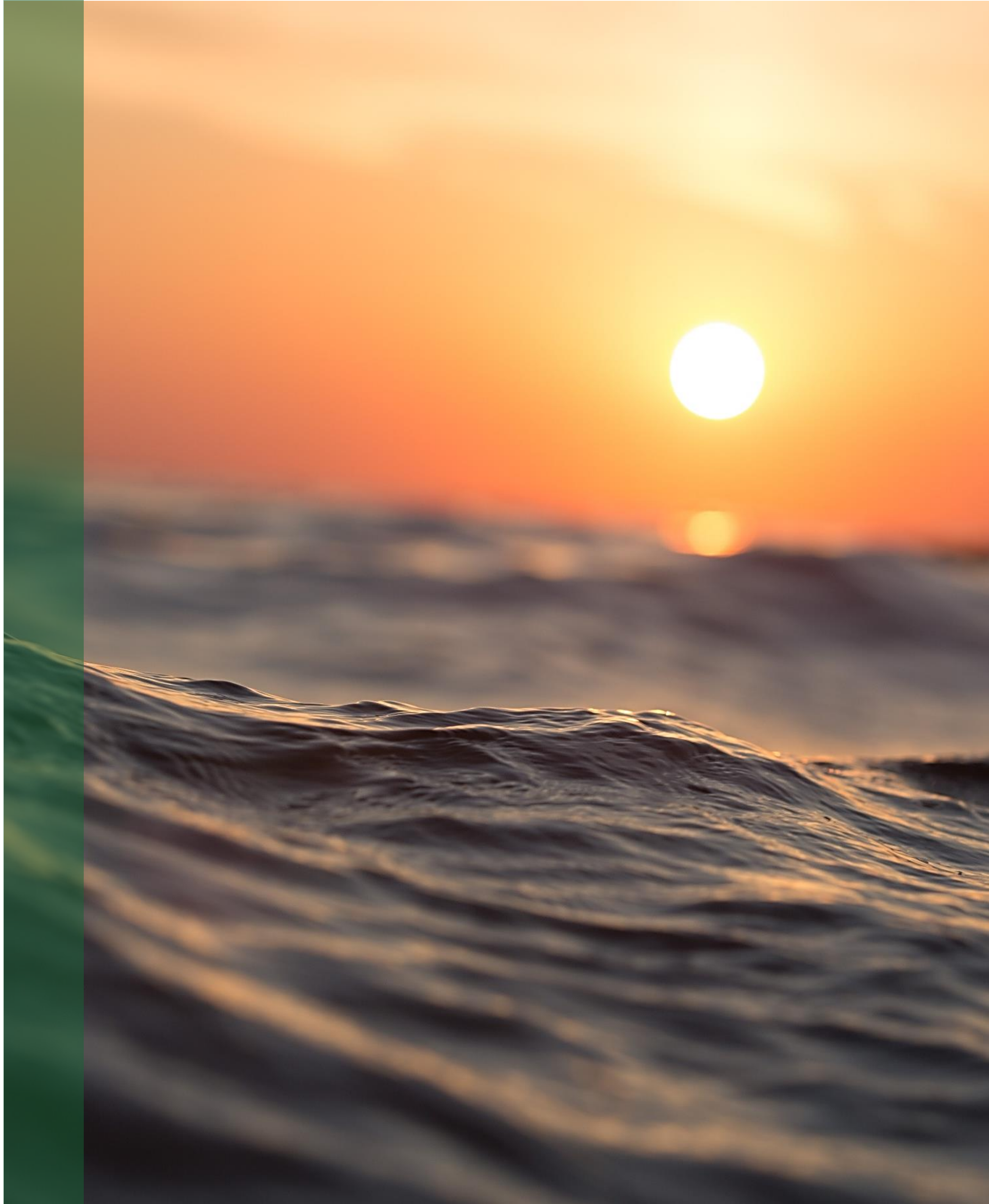
Oceans cover 70% of the earth's surface. Driven by earth's rotation and interaction with the sun and moon, this immense mass of water is constantly on the move. This motion, together with the thermal and chemical properties of seawater, provide a vast and almost entirely untapped source of renewable energy.

This report provides a brief introduction to the entertaining topic of capturing energy from the oceans. Estimates suggest this could cover the entire global electricity demand.

We begin by looking at the types of ocean resource that exist, and the technologies that seek to exploit them. Our focus in on wave and tidal as these are the closest to commercialisation, though still largely in their demonstration phase and uncompetitive with wind and solar.

We then zoom out and consider what role ocean energy (OE) might find in the global energy system, both today and in the future, as costs come down. We find that OE could be useful both as a complement to, and in hybridised form with, other on-grid renewables, though is likely to start out mainly off-grid.

Finally, we look at market forecasts which suggest that 10 GW of OE capacity by 2030, and 100s of GW by 2050, are possible. Where wind and solar have gone, there is no reason why ocean cannot, to a notable degree, follow.



Contents

Ocean Energy Types

For our purposes, OE is a term encompassing renewable energy technologies that employ the kinetic, gravitational, chemical or thermal properties of seawater. This definition excludes things like offshore wind, offshore solar and marine biomass as these do not use seawater directly.

These technologies are classified most broadly by the specific ocean resource they seek to capture and convert into a more useful form, typically electricity. These resources, ordered by descending maturity of the associated technologies, are:

- **Tidal range** – oscillating change in the height of coastal seawater due to the tides.
- **Tidal currents** – oscillating horizontal flow of coastal seawater due to the tides. Also known as tidal stream (we use both terms).
- **Ocean waves** – oscillating 3D motion of the ocean surface caused mainly by the wind.
- **Thermal gradients** – difference in temperature between the surface and deep ocean caused by solar heating.
- **Ocean currents** – unidirectional flow of water in the open ocean caused by global wind, heat and salinity (saltiness) distributions.
- **Salinity gradients** – difference in salinity that occurs at the boundary between sea and fresh water.

These resources vary in their predictability and variability. We explore the properties of each resource, and the associated technologies, in detail later. Our focus is on tidal and wave technologies as these are the only ones on the cusp of commercialisation (or already there for tidal range).

Resource Potential

Whilst wave and thermal resources are theoretically available across large areas of the oceans, others are more limited in the areas from which they can be harvested. Taking this, and the energy inherent in each resource into account, it is possible to estimate the worldwide energy potential for each resource. **Figure 1**, below, is one attempt at this.

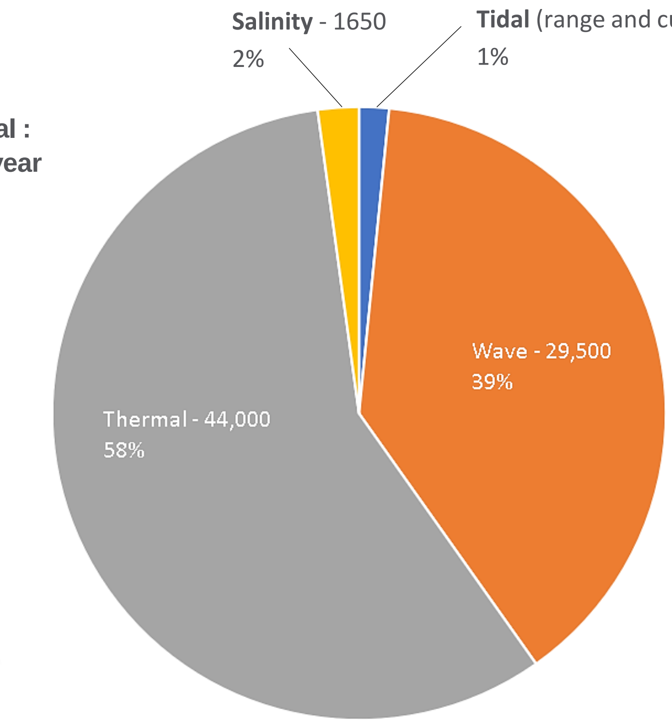


Figure 1 – OE worldwide energy potential (TWh/year). Source: Ocean Energy Systems (OES), 'An International Vision For Ocean Energy 2017'. Ocean currents not well known.

The total resource potential shown in **Figure 1** - 82,900 TWh/year - is a huge amount of energy, over 3 times the global electricity demand in 2019. This is one of the reasons people get excited about OE.

Note that much lower estimates exist; **Figure 1** is a theoretical maximum potential and says nothing about the practicalities of resource exploitation on this scale. For example, the technology is not yet there to consider the immediate, large-scale exploitation of many of the ocean resources. Another caveat is that - assuming the technology exists - the available resource is simply *one* factor to consider in establishing a location's viability. **Figure 2**, below, suggests some other important factors.

Figure 2 - factors that go into site selection for an OE project (example uses wave energy specifically). Bathymetry is the study of underwater depth. Geology is important for some devices fixed or moored to the ocean bed.

Figure 3, below, ranks countries by the opportunity present in their local wave and tidal resources. The UK has great tidal and wave resources, as does France.

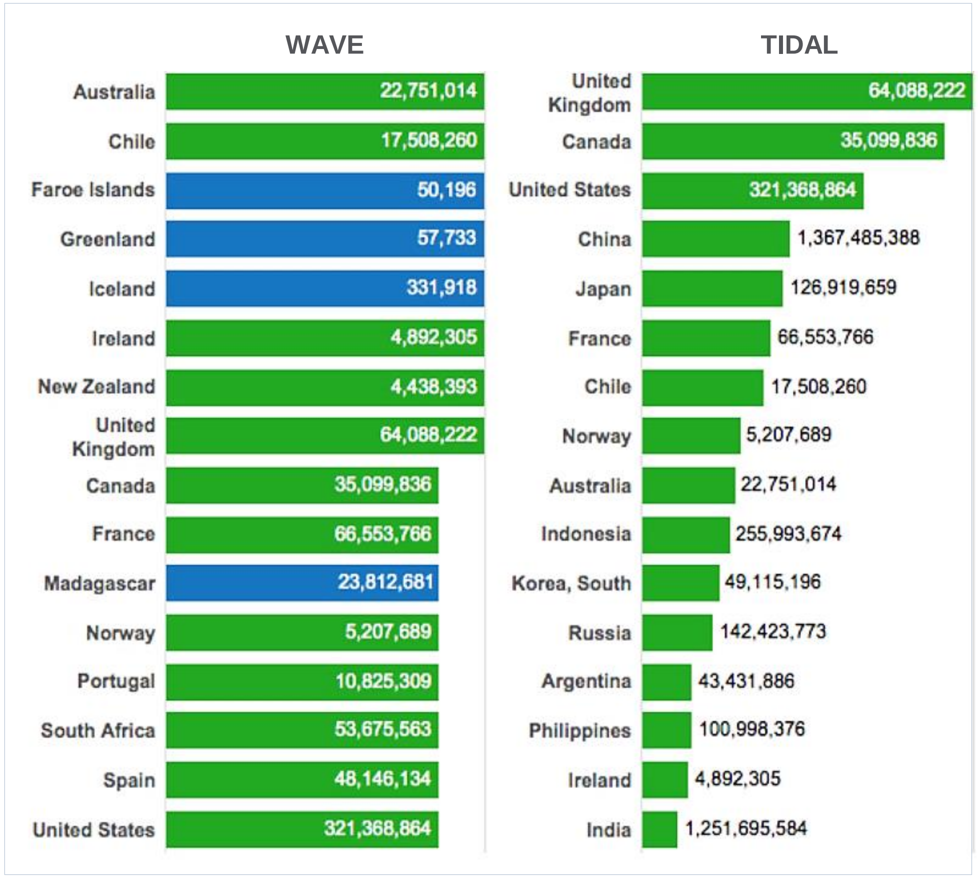


Figure 3 - ranking of countries by marine energy opportunity. Source: Highlands and Islands Enterprise – 'Marine Energy – Key Steps to Maintain a Great British Success Story'. Ranking is based on quality and accessibility of resource (figures show population, green indicates higher quantity and quality of available data).

Current Deployment

Compared to mainstream renewables such as wind and solar, current deployment of OE is very limited, with only ~0.5 GW deployed in total, an insignificant fraction of all renewable energy capacity. See **Figure 4**. Most of this capacity comes from two large tidal range projects in France (240 MW) and South Korea (254 MW). Beyond these projects, most deployments are for test purposes, rather than final commercial use. Wave and tidal current devices are often first deployed at one of the ~50 open sea test sites available around the world. To oversimplify, the cutting edge of OE consists of: (a) demonstration tidal current arrays, composed of a handful of devices; (b) single demonstration wave energy devices, at either reduced or full size; (c) a few pilot projects for the other technologies.

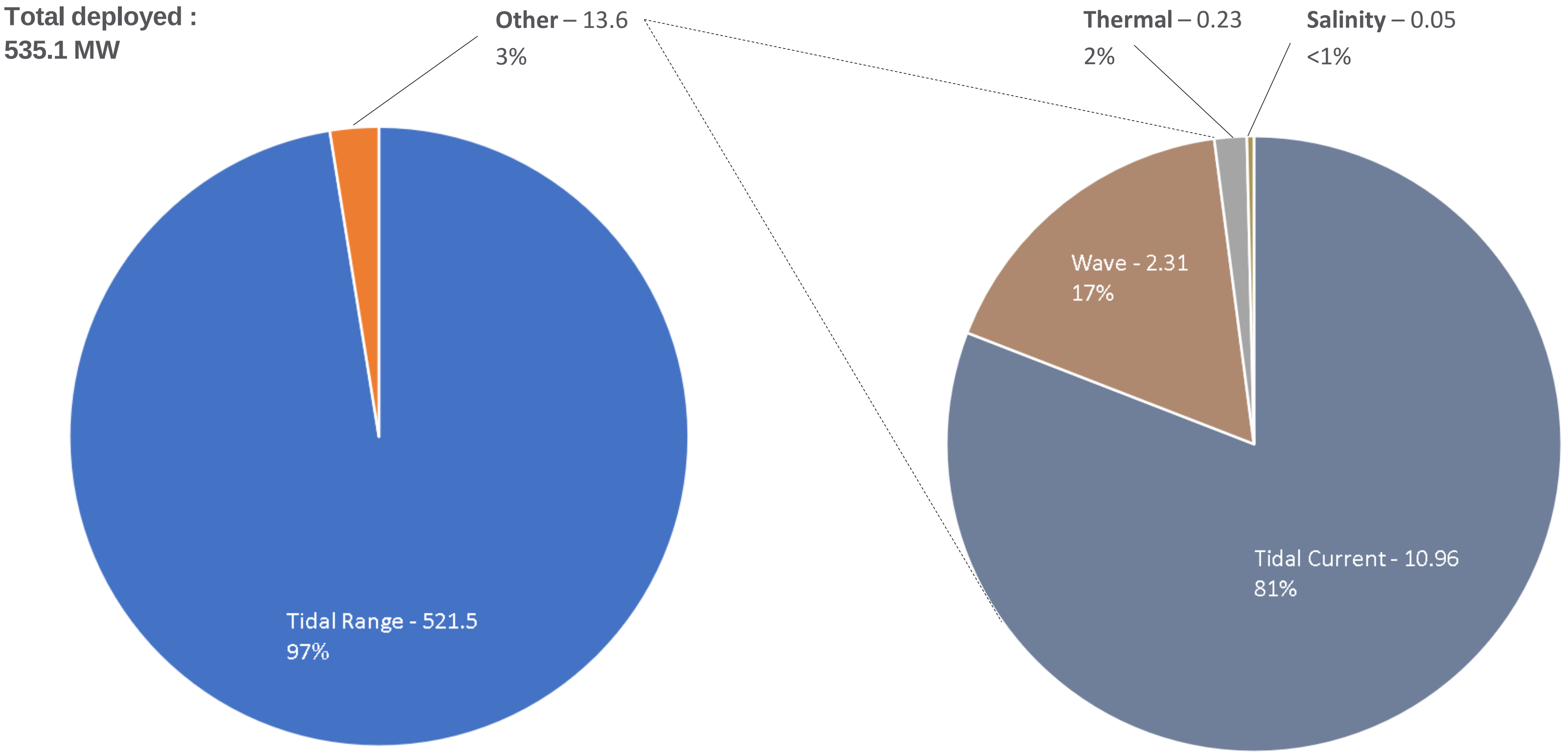


Figure 4 – 'current' worldwide OE deployment (MW). Source: [IRENA (International Renewable Energy Agency) presentation].

Useful Links

Resource, facilities and deployment:

[UK Marine Energy Database]

[Ocean Energy Systems' ocean resources and facilities map]

Concepts and developers:

[Wave]

[Tidal Current]

Wave Energy

Waves are generated primarily by wind blowing across the ocean surface. Their power is determined by the speed of the wind, its duration and the fetch - the distance of open water over which the wind blows. In coastal waters, the depth and shape of the ocean floor (and coastline) also play a role. The most energetic wave conditions are found at latitudes greater than 40 degrees from the equator, and off the west coast of continents, see **Figure 5**, below.

In comparison with wind and solar, wave energy has a much higher spatial energy concentration, with less potential for sudden changes in the resource. Although there is daily and seasonal variation, waves arrive day and night, 24 hours a day. What variation there is – commonly higher waves in the evening and winter - ties in neatly with patterns of electricity consumption.

Wave Motion

A single wave is conceptually easy to understand, with its passing causing water molecules to move in a circular motion as viewed from the side, with the size and energy of these circles falling off exponentially with depth. See **Figure 6**.

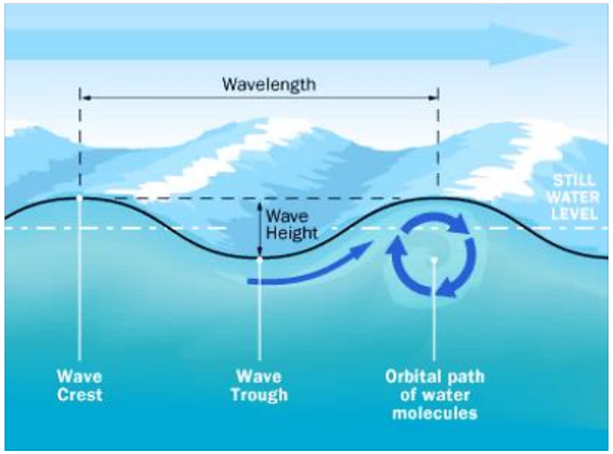


Figure 6 – diagram of an ocean surface wave.

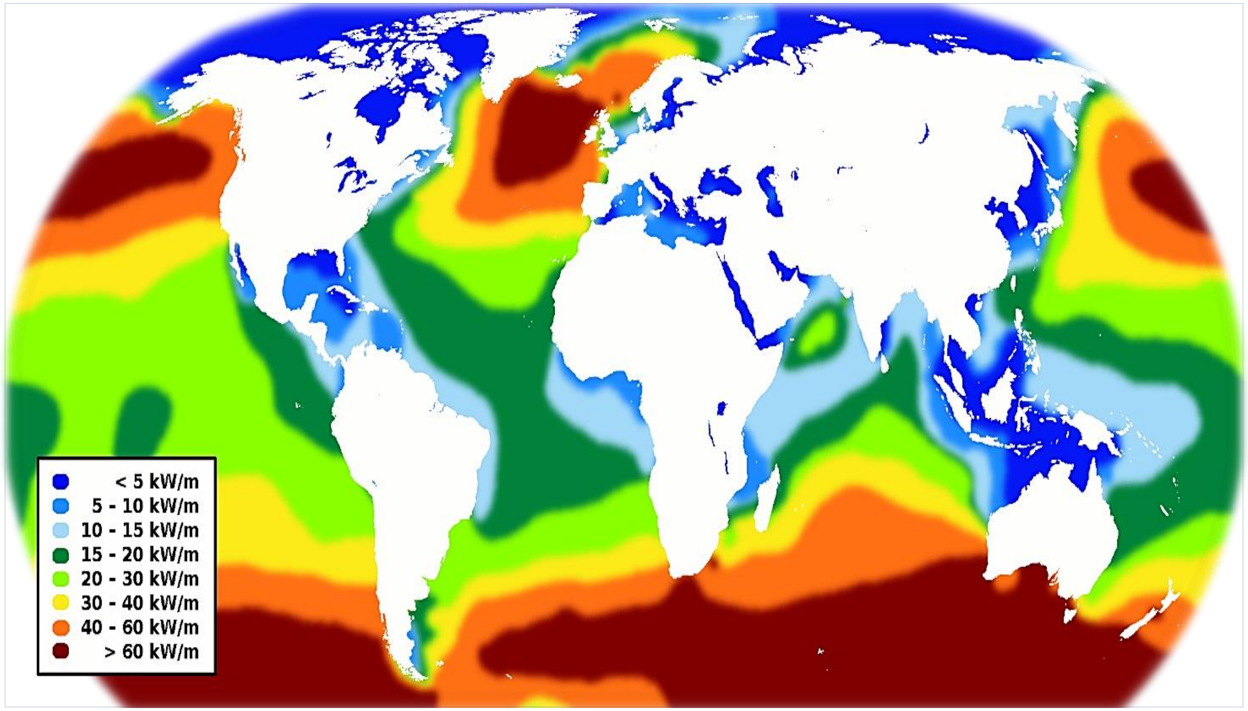
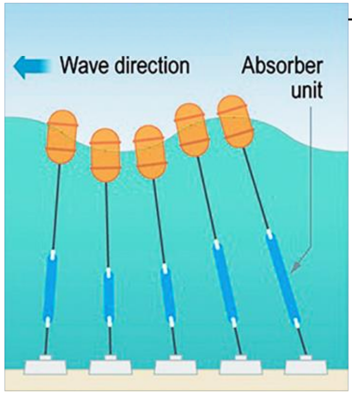


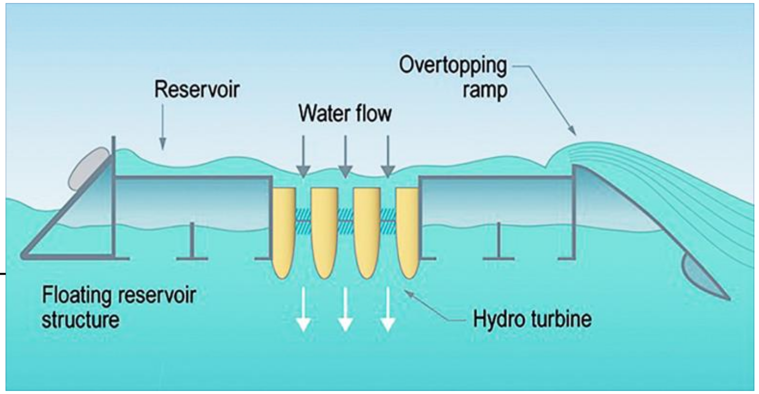
Figure 5 – global annual mean wave power distribution. Source: [by Ingvald Straume - own work, CC0.]

Less easy to understand and predict is the motion of water molecules at any given point in the ocean. This is determined by the combined effect of all the waves passing through. Waves can be of varying amplitudes (up to 30 metres high on occasion), wavelengths (up to 100s of metres for ocean swells) and directions, and have randomness to their arrival pattern. This yields a complicated 3D motion. There are many ways for Wave Energy Convertors (WECs) to translate this motion into the desired output, typically grid-compliant electricity. At the highest conceptual level, there are three types of WEC – (a) water moves a body whose motion generates electricity; (b) water moves air whose motion generates electricity; (c) water directly generates electricity (via hydro turbine). Devices can be further classified by factors such as: how the initial ocean interaction is converted into electricity (known as the power take-off arrangement); whether they are fixed to the seabed or floating; whether they are fully submerged or surface-piercing; how they are held in place (see methods), which is a more complex process than, for example, mooring a ship; and where they can be deployed (onshore, nearshore or offshore), amongst others. **Figure 7** shows some common types of WEC:

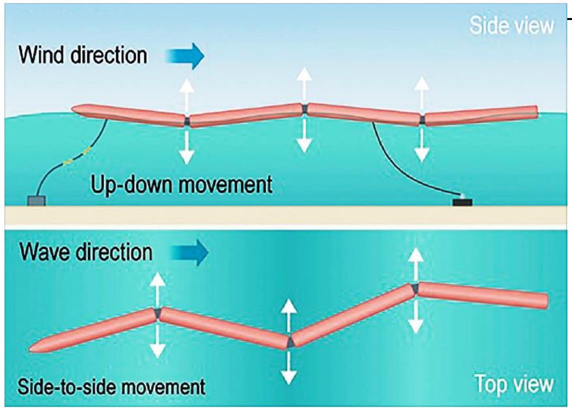


Point absorber - a structure consisting of a steady base and floating top. The relative motion of the top to the base is converted to electricity.

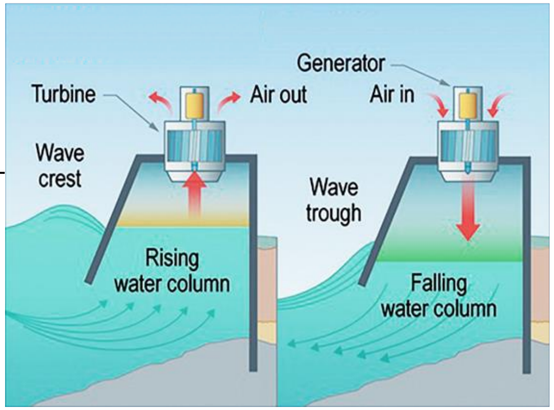
Figure 7 – the common types of Wave Energy Convertor (WEC). Image source: IRENA and EMEC.



Overtopping/terminator device - these capture water as waves break into a storage reservoir. Electricity is generated by dropping the captured water through a conventional low-head hydro turbine.



Attenuator - a segmented floating device which operates parallel to the wave direction, effectively riding the waves. Electricity is generated from the relative motion of the linked segments.



Oscillating water column - an air chamber (or several chambers) with its lower end open to the ocean and its top connected to the surrounding atmosphere via an air turbine. As the waves oscillate within the chamber, air is forced through the turbine, generating electricity. The picture shows this arrangement fixed to the shore, but these can also be floating devices.

See animations

Continuing from the last page, the remaining common types of WEC are:

Oscillating wave surge convertor - an oscillating pendulum that captures the 'surge' of passing waves, the component in the direction of wave travel. One end of the pendulum is usually fixed to the ocean floor. These tend to operate close to shore where wave surge is stronger.

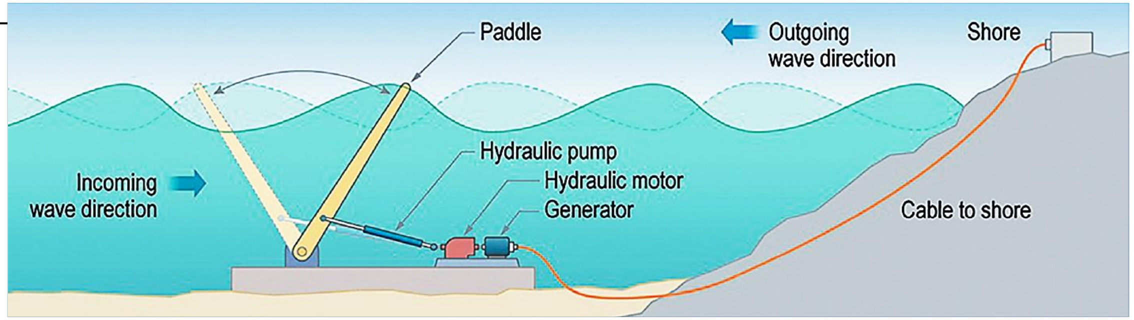
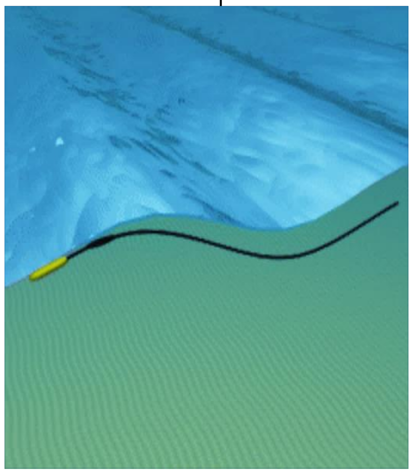
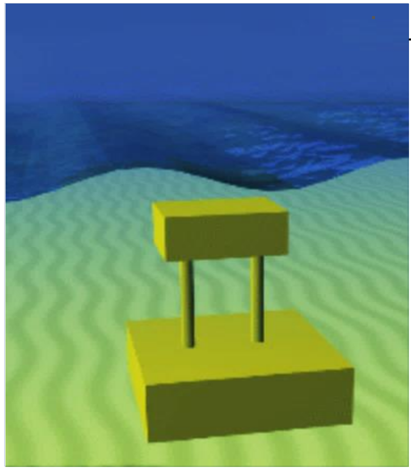


Figure 7 – the common types of Wave Energy Convertor (WEC). Image source: IRENA and EMEC.

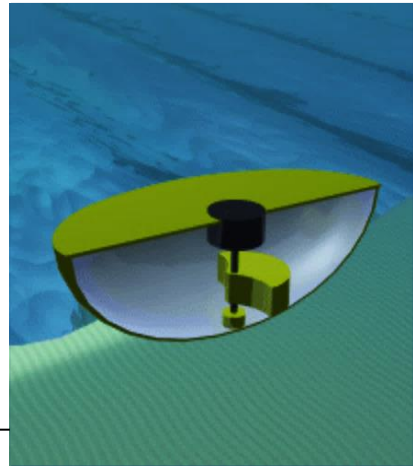
Bulge wave - a floating rubber tube filled with water, moored and oriented in the direction of wave travel. Water enters the tube at the stern. The passing wave causes pressure variations along the length of the tube, creating a bulge. As the bulge travels through the tube it gathers energy, which is used to drive a low-head turbine located at the bow. The bulge then returns to the sea.





Submerged pressure differential - these use the pressure differential caused by passing overhead waves to pump a fluid through the system to generate electricity. These are typically attached to the seabed near to the shore.

Rotating mass - these floating devices use the heaving and swaying motion of waves to drive either an eccentric weight or a gyroscope causes precession. In both cases the movement is attached to a electric generator inside the device.



See animations

As can be seen from the variety of designs in **Figure 7**, the wave sector is still in its experimental phase. **Figure 8** shows what type of WEC are popular with the ~250 global wave developers. Point absorbers are the most popular but

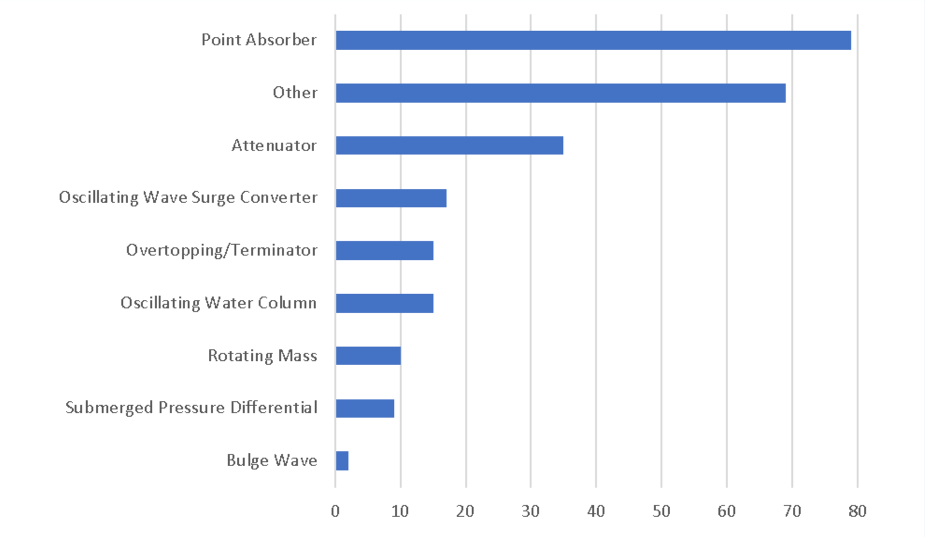


Figure 8 – count of wave device type used by wave developers, as tabulated by the European Marine Energy Centre (EMEC).

there is a wide spread. Due to the range of different wave climates found around the world, and interest in applications offshore, nearshore and onshore - offshore offers the greatest potential in terms of resource, but is usually associated with the largest installation and maintenance costs - there may *never* be convergence on a single device type. We highlight the specific factors that impact the commercial viability of different WEC designs in the case study that follows. In general, the levelised cost of electricity (LCOE) of WECs – the unit lifetime electricity cost - is higher than tidal devices and deeply uncompetitive with solar and wind. We explore LCOE later.

Figure 9 shows how the installed global wave energy capacity has developed over the past decade (see **Figure 4** for current active capacity). **Figure 9** highlights the dominance that Europe – largely the UK – have had in the wave sector to date. The UK has 29 known wave developers (not all of whom may still be active), second only to the US. The UK benefits from excellent wave resources, world-leading test facilities - such as the European Marine Energy Centre (EMEC) - and industrial excellence in linked sectors such as offshore oil and wind.

At this stage, most deployments are single demonstration devices, outputting 100s of kW to a few MW at peak, rather than the farms of multiple devices, able to provide 10-100s of MW, envisaged in the future. As commercial entities are, in general, not yet prepared to shoulder all the risk, device development has been heavily dependent on grant funding.

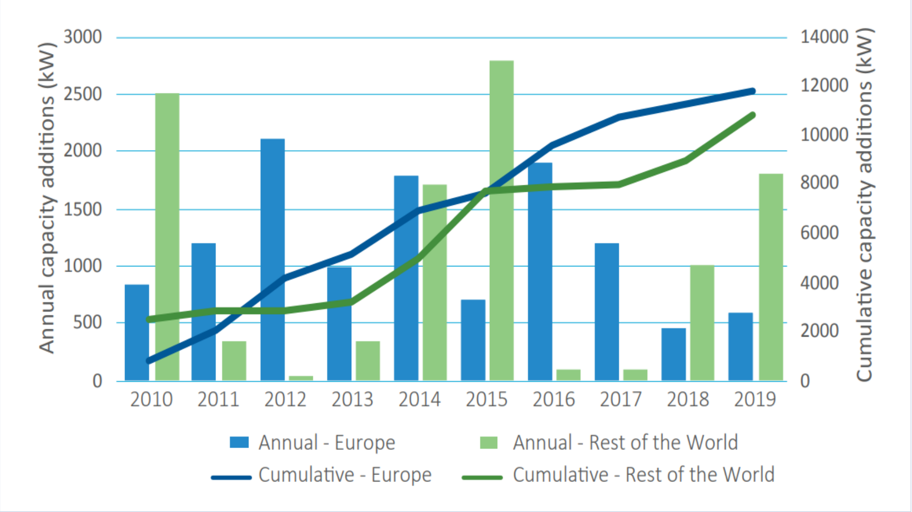


Figure 9 – installed and cumulative wave energy capacity. Source: Ocean Energy Europe, 'Ocean Energy - Key Trends and Statistics 2019'.

Case Study: HACE

As a way of illustrating some general points about competitiveness, in this section we look at [HACE] (Hydro Air Concept Energy), a French company developing a floating WEC of the 'oscillating water column' type. [See a video of how it works]; diagrams on the next page. HACE has already developed and validated a 50-kW-peak prototype. The next stage is the industrialisation of a 100-kW-peak module. Each module uses multiple water columns to capture wave energy efficiently. The generation of non-intermittent electricity is enabled by multiple columns feeding a single air turbine. Modules can be combined like Lego into arms to form standalone, commercial scale devices or, alternatively, modules can be integrated with other structures (examples shortly). **Figure 10** shows the prototype and future plans.

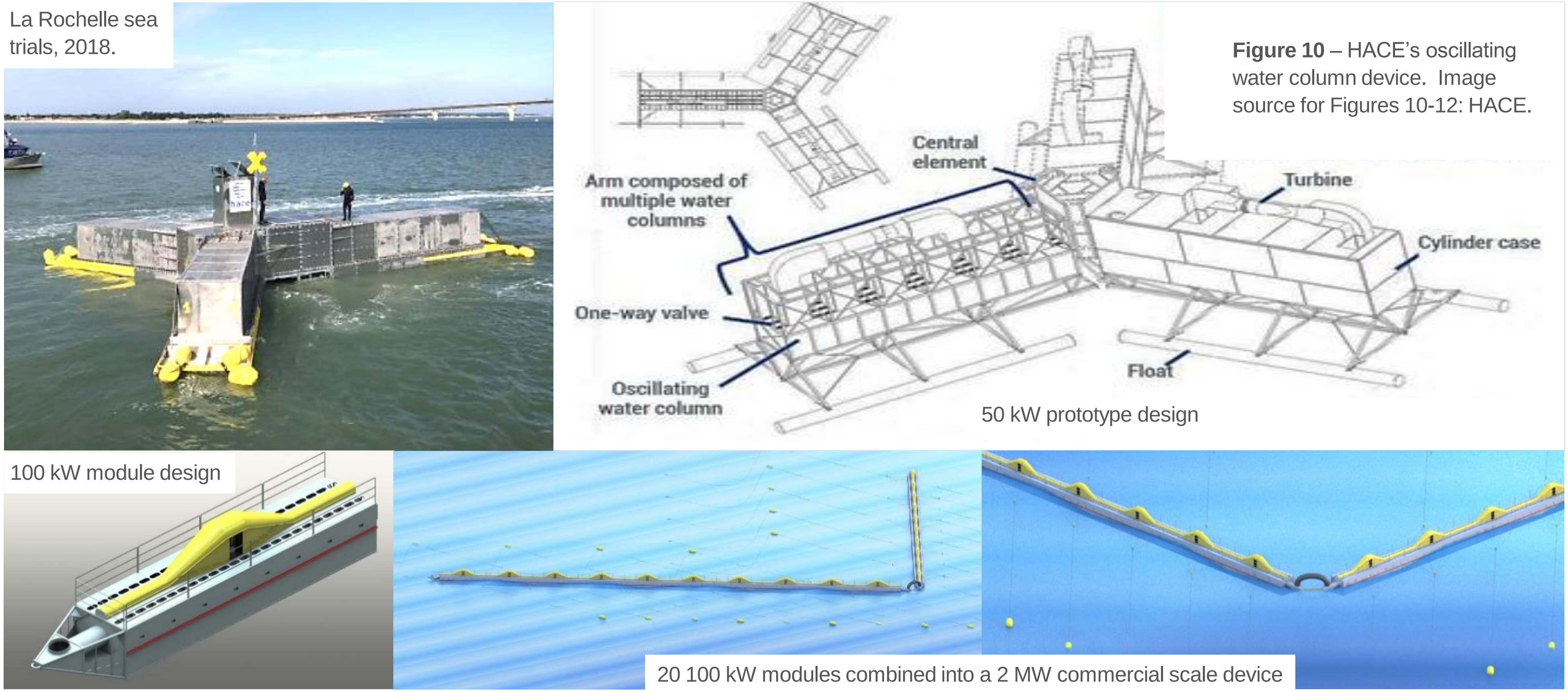
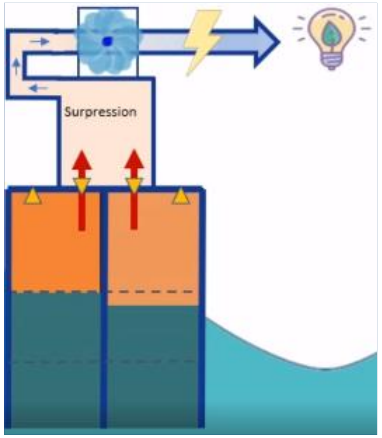
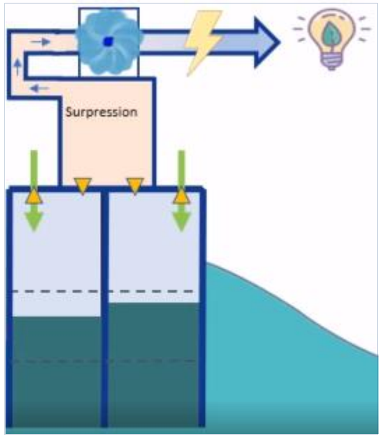


Figure 10 – HACE's oscillating water column device. Image source for Figures 10-12: HACE.



A rising wave compresses the air; this is let out to drive a turbine.



A falling wave sucks in external air, allowing process repetition.

Figure 11 – HACE operation.

Competitive Attributes

Below we list some of the qualities that OE devices need to be useful and commercially competitive, and look at how these apply to HACE. We focus on WECs, but the broader points apply more generally. We also assume the only output is electricity - some devices have different or additional outputs. There is often a trade-off between these qualities.

Low Visual and Environmental Impact

To get permission to build in the first place, especially close to shore, a device needs a low visual and environmental impact. In general it is believed that OE – with the possible exception of tidal range - poses limited risk to sea life and habitats, though the evidence is limited, given limited deployment. See the 2020 State of the Science Report for more. Addressing issues more easily quantified, HACE's device is less than 2.5 metres high – so has minimal visual impact - with a claimed lifetime carbon footprint of < 1 gCO_2e/kWh, less than any other form of generation.

Durable and Reliable

A device must be able to survive and continue operating in the harsh ocean environment for decades. This applies to the overall structure, as well as the individual parts of the station-keeping and generation mechanisms. According to simulation, HACE's structure is capable of withstanding, without damage, a perpetual storm lasting more than 50 years. For station-keeping, HACE can employ a dynamic mooring system, if appropriate. This ensures that each arm maintains a constant distance to the seabed, as long as the wave height is below a threshold level; above this level, the arm is allowed to move to prevent damage. Other relevant HACE design features are included in the section on cost.

High, Consistent Electrical Output

A device must maximize the energy it transfers from the ocean into electricity, taking into account the variability of sea conditions. This electrical output must be in the form required by the offtake grid (or other offtake). An output that is steady, rather than constantly varying, is more useful and valuable. Achieving all these things can be challenging for WECs. The HACE design segments the swell into "pixels" (i.e. water columns) to maximise capture across the wave spectrum, including small and chaotic waves, which have traditionally been more challenging. HACE claim to be able to harvest energy from 91% of the total wave spectrum, and from all directions. Conversion to electricity is optimised by using a specially designed air turbine. As multiple water columns, with the wave at a slightly different stage in its cycle in each, all feed air into a single air turbine, the electricity generated is described as non-intermittent. A capacity factor - average power generated divided by the rated peak power - of approximately 70% is expected, though this will vary by location. This figure is far higher than usually quoted for WECs - 30-40% is more typical. 70% implies generation of ~12 GWh/year for a 2 MW-peak device.

Widest Available Market

A device's market potential is maximised if it is suitable for a wide range of deployment scenarios and applications. Whilst some devices are limited to and optimised for one deployment scenario, HACE's solution is described as a 'hub', aimed at supporting a wide range of activities across deployment scenarios (meaning from onshore to far offshore).

This activity support primarily involves providing energy, initially in the form of electricity, but also possibly in a secondary form, such as hydrogen or ammonia. See our sector research on hydrogen for an explanation of why this might be useful.

In addition to energy provision, HACE modules can also protect marine assets from the sea. Marine assets include things like oil and gas platforms, offshore wind turbines and harbours (more detail and examples later). Protection is provided because the orbital movement of water molecules is disorganised by the modules.

Figure 12 shows two examples of HACE modules being used for simultaneous energy provision and asset protection. Both involve the integration of modules with other structures.

For floating wind, HACE's modular design enables fast and efficient technology integration without constraining the type of turbine that can be used. Such integration has a number of advantages - energy extraction is maximised and intermittency potentially minimised from a given patch of ocean, whilst certain costs - incurred with separate deployments - are eliminated (no need for two separate links to the electrical offtake, or for separate installation and maintenance). The stability of the turbine is also improved, with reduced forces applied to the anchors, drastically increasing the lifespan of the mooring lines.

Please note, we discuss the role of OE more broadly in a later section.

Figure 12 - two examples of HACE module integration with marine infrastructure for asset protection and energy provision. Above, a marina with modules integrated into the boundary. Below, floating wind turbines with modules integrated into their bases. The combined wind-wave device can use a single cable for electricity export.

Low Cost

Finally, a device must provide the above qualities as cheaply as possible over its lifetime. Cost is minimised if materials and components are cheap, and if a device is easily manufacturable, transportable, deployable and maintainable. Cost-reducing aspects of HACE's design and operation include:

- The framework is made from a common, weldable, marine metal. Its assembly is sequenced to allow the transition from human welders to robots with the same manufacturing process.
- The framework has a lightweight honeycomb structure. This lowers: (a) material costs; (b) transport costs; (c) mooring requirements and costs; (d) wear and tear.
- The design has few components and therefore reduced failure modes.
- The turbine is specially designed for this application, reducing costs and increasing reliability.
- There is physical separation of seawater and moving parts (the turbine) to prevent damage.
- The water columns are self-cleaning to avoid interference from marine life.
- Modules are container-sized and therefore easily transportable on land and at sea.
- At sea, every stage of operation can be performed by small vessels (30 metres long, rather than >90 typically), which are more readily available (and have lower emissions) than larger vessels. Small vessels enable deployment to be carried out 10 times more cheaply than conventional offshore nautical means. Deployment is also rapid and uses limited personnel, reducing risk as well as cost.
- For surveying coastal sites, autonomous (unmanned) vehicles can be used. These have no impact on the site or risk for personnel. Deployment vessels could potentially be autonomous as well.
- For maintenance purposes, all components are accessible from above, on a dry and safe gangway. A high level of redundancy ensures high availability, though, if necessary, key components are easily swapped out without tools, by one person, without stopping or reducing energy production.

To recap, the levelised cost of electricity (LCOE) is the unit cost of a device's electricity over its lifetime. Utility scale solar has a LCOE of ~30, onshore wind ~35, and offshore wind ~75 €/MWh, according to Lazard (2019, midpoints converted from dollars). At 2 MW scale, HACE estimates a LCOE competitive with solar, which, if validated in practice, would be truly revolutionary. We say more about LCOE later.

Tidal Energy

The periodic changes in sea level known as the tides are caused by the gravitational interaction between the spinning earth, moon and sun. Though there are exceptions, high and low tides occur twice a day at most coastal sites worldwide. Tides are entirely predictable, other than a weather overlay, meaning they provide an equally predictable, if variable, source of renewable energy for us to exploit. There are two approaches to this - capture energy from the **tidal range** or **tidal stream**.

Tidal range is the difference in sea level height between high and low tides at a given location. This can vary each day depending on the location of the sun and moon, and globally depending on the coastal location. Tidal range is amplified at certain geographic locations by the shape of the coastline, and the shape of the ocean floor.

Figure 13 shows how the tidal range varies worldwide. Large tidal ranges, such as in the UK, hold the greatest potential for energy capture.

Tides are accompanied by an incoming (flood) or outgoing (ebb) horizontal flow of water at the coast. This flow is called a **tidal stream** or tidal current. Tidal streams can be exceptionally strong in areas where large tidal ranges are further constrained by local topography. However, when the tides switch direction, there are periods of time when there is little or no tidal stream.

Figure 13 also suggests the general regions where high potential tidal streams may be located. Major tidal streams have been identified along the coastlines of every continent, making it a global, albeit site specific, resource (as is tidal range).

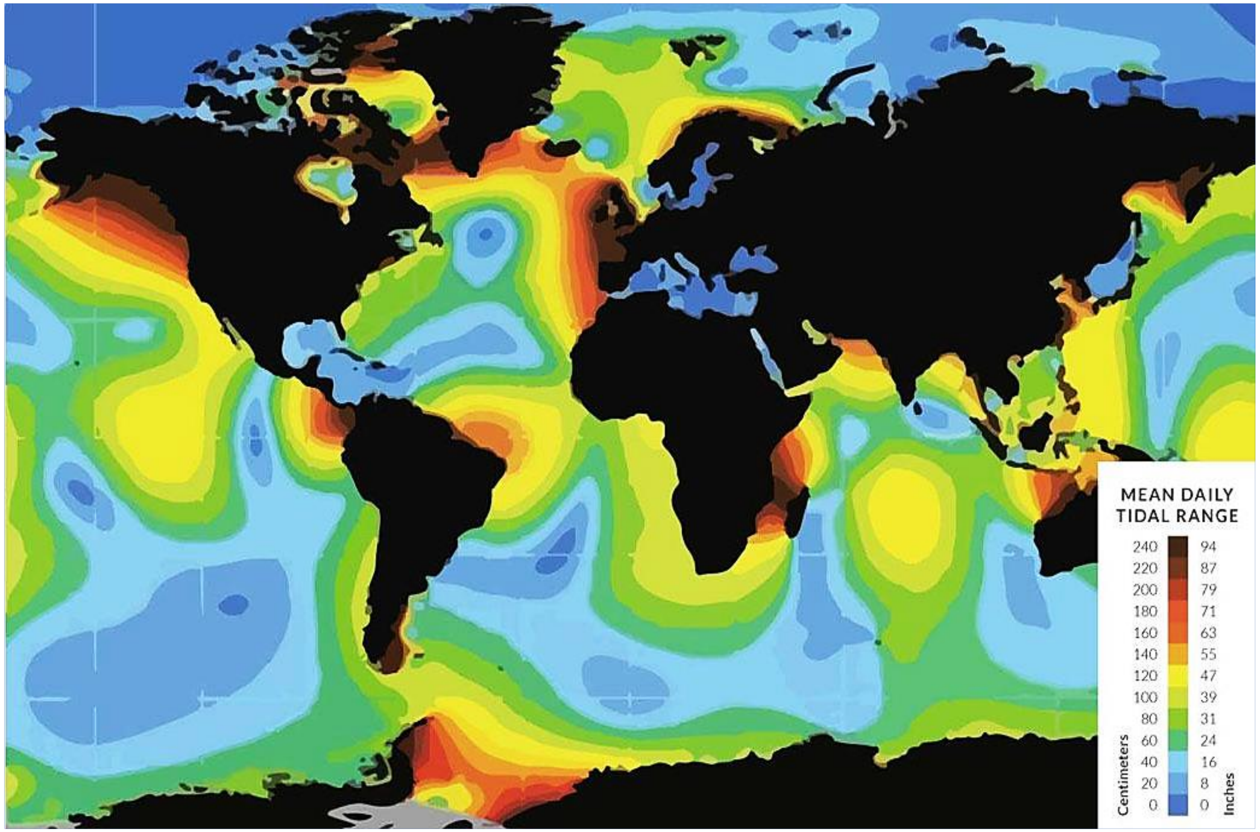


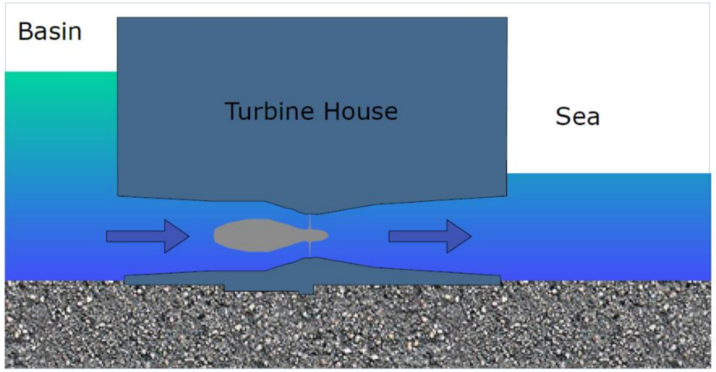
Figure 13 – map of mean daily tidal range. Source: Minesto.

Tidal Range

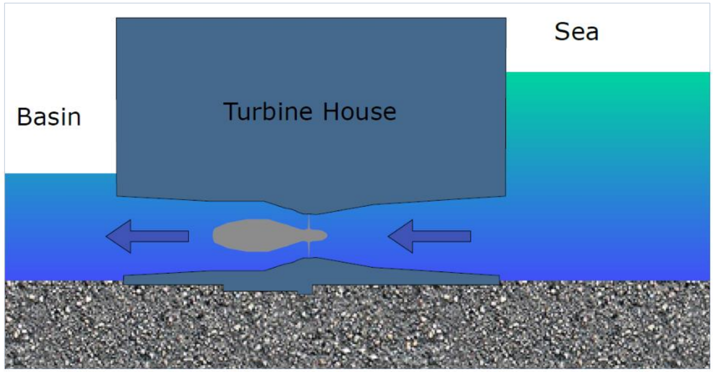
Unlike other OE technologies, certain forms of tidal range are mature, with decades of proven reliability in existing commercial projects. As shown in **Figure 4**, tidal range accounts for most of the installed OE capacity worldwide.

Tidal range technology is based on conventional hydropower principles. It works by impounding a large body of tidal water; as the tidal height varies outside the impounded area, water is discharged either into or out of the area through hydro turbines, thereby generating electricity. See **Figure 14**. Assuming generation on both ebb and flow tides - not always the case - there are four opportunities for electricity generation per day.

Figure 14 – generating electricity using tidal range. Image source: Tidal Lagoon Power.



Generating on the ebb tide



Generating on the flood tide

The two existing tidal range plants impound the water using a **tidal barrage**, sited across the mouth of an estuary. For example, the French tidal power station in the estuary of the Rance river has a 750 metre long barrage containing 24 bidirectional turbines. These provide a combined average output of 57 MW, with a peak output of 240 MW, meaning a capacity factor of ~24%. In addition to energy generation, tidal barrages offer other uses such as flood control and a route for transport across the estuary. Although suitable estuaries are a limited resource, an emerging alternative is to use enclosed basins that do not dam an estuary; these are called **tidal lagoons**. These can be enclosed by coast on one side, or be surrounded by the sea on all sides. Multiple lagoons are also being considered as a way of generating baseload (constant, always on) renewable electricity.

Although electricity generation can be cheap once constructed, and tidal range plants are expected to last over a century, getting them built is clearly a struggle. This is mainly due to the high capital costs, though limited suitable locations and planning constraints - in part due to visual and environmental impacts (particularly of tidal barrage) - do not help. In addition, most governments have incentivised the development of cheaper renewable energy sources over tidal range. The net benefits may justify future tidal range development, particularly in combined applications (e.g. with flood control in mind). At this moment in time, however, most commercial activity is focused on other ocean technologies.

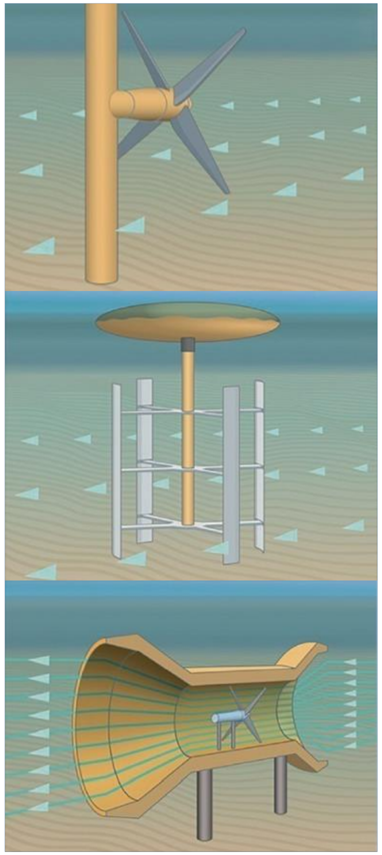
Tidal Stream

In contrast to tidal barrage, tidal stream is an emerging technology which remains largely at the demonstration phase of its development. The tidal stream sector is often compared with an earlier version of today's wind sector, in part because the basic principles are similar, just using free flowing water to turn turbines (or otherwise create electricity), not air. Due to the much higher density of water, the turbine blades can be smaller and turn more slowly, whilst still delivering an equivalent amount of power. Unlike the wind sector, which has largely converged onto one design, the tidal stream sector is still experimenting with designs, many of which were wind designs originally. Single devices typically have a peak output of 100s of kW to a few MW. The main types are:

Horizontal axis turbine - the tidal stream causes a rotor to rotate around a horizontal axis and generate power. These typically have 2-4 blades per rotor. With 3 blades, this is the classic wind turbine design.

Vertical axis turbine - the tidal stream causes a rotor to rotate about the vertical axis and generate power. These typically have 2-4 blades per rotor.

Enclosed tips (venturi) - these use a funnel-like collecting device to concentrate the tidal flow. The concentrated flow may drive a turbine directly, or the induced pressure differential can drive an air turbine.



Oscillating hydrofoil - these employ a hydrofoil - water equivalent of an aerofoil used by aeroplanes – to create lift. The hydrofoil is attached to an arm. The tidal stream causes the arm to oscillate up and down. This repetitive motion is converted to electricity.

Tidal kite - a tethered underwater kite that looks like a small plane and has a turbine below the wing. To increase the speed of the water flowing through the turbine, the kite automatically traces out a figure-of-eight shape in the tidal stream.

Archimedes screw - a corkscrew-shaped device that draws power from the tidal stream as the water moves up and through the spiral, turning a turbine.

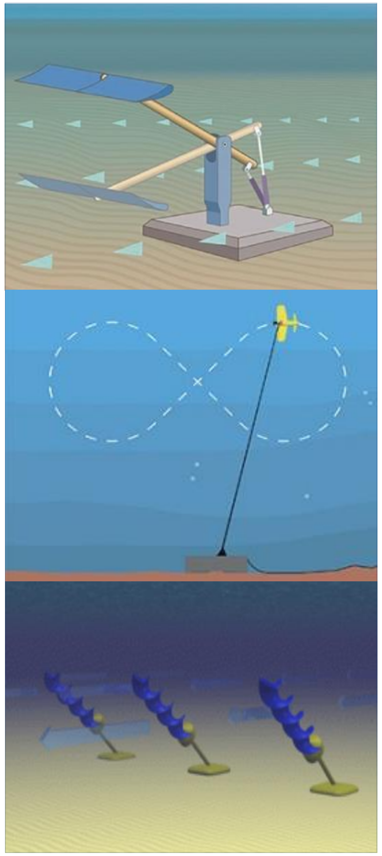


Figure 15 – the main types of tidal stream device. Image source: EMEC.

See animations

Figure 16 shows what type of device are popular with the ~100 global tidal stream developers. **Figure 16** shows that tidal developers have converged more onto one type of device – the horizontal axis turbine – than wave developers (compare **Figure 8**), suggesting greater technological maturity.

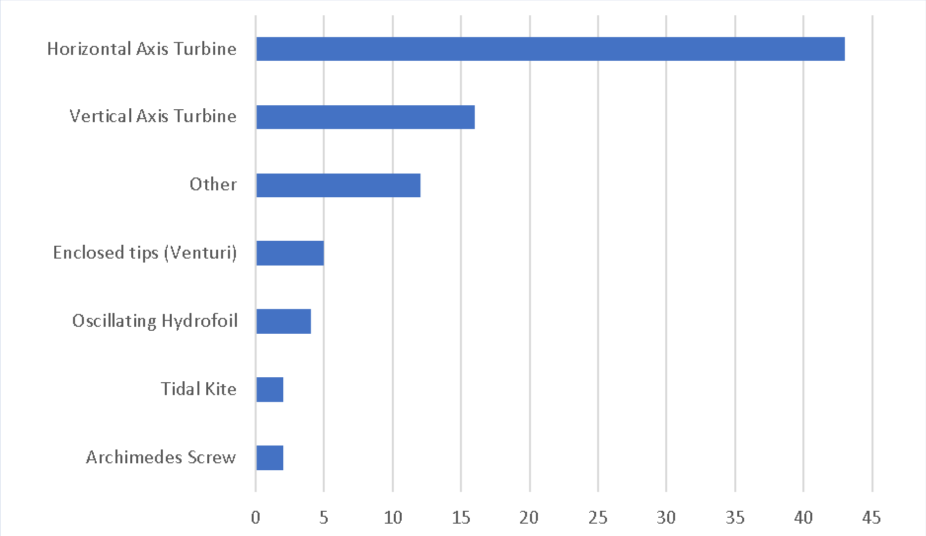


Figure 16 – count of wave device type used by wave developers, [as tabulated by the European Marine Energy Centre](#).

Beyond the basic type, tidal devices can be further classified, similarly to wave, by factors such as: the power take-off arrangement; whether fixed to the seabed or floating; whether fully submerged or surface-piercing; how the device is held in place ([see methods for doing this](#)).

Factors impacting the commercial viability of tidal stream devices are similar to those highlighted earlier in the [wave case study](#). Again, the aim is to maximise energy extraction at minimum cost. In general, the LCOE of tidal energy is lower than wave (with marginally higher capacity factors expected), but is still deeply uncompetitive with solar and wind. [We explore LCOE later](#).

An aspect of competitiveness unique to tidal is the speed and depth of tidal stream in which a system can efficiently operate. Early designs required strong tidal flows (2.5 m/s+) and shallow depths (25-50m). Newer designs are targeting slower streams and deeper depths, which opens up the accessible market by a factor of more than 10, [according to tidal kite developer Minesto](#).

Figure 17 shows how the installed tidal stream capacity has developed over the past decade. **Figure 17** highlights the dominance that Europe – largely the UK – have had in the tidal stream sector to date. [According to the European Marine Energy Centre](#), the UK has 26 tidal stream developers; USA, 22.

Several small arrays of tidal stream devices are already in operation, such as the [four turbine 6 MW MeyGen array](#), developed in the UK by [SIMEC Atlantis](#). Like wave, project development has been heavily dependent on grant funding, but will need - and, subject to the performance of current arrays, may be able to secure - commercial funding to scale up to ~100 MW arrays.

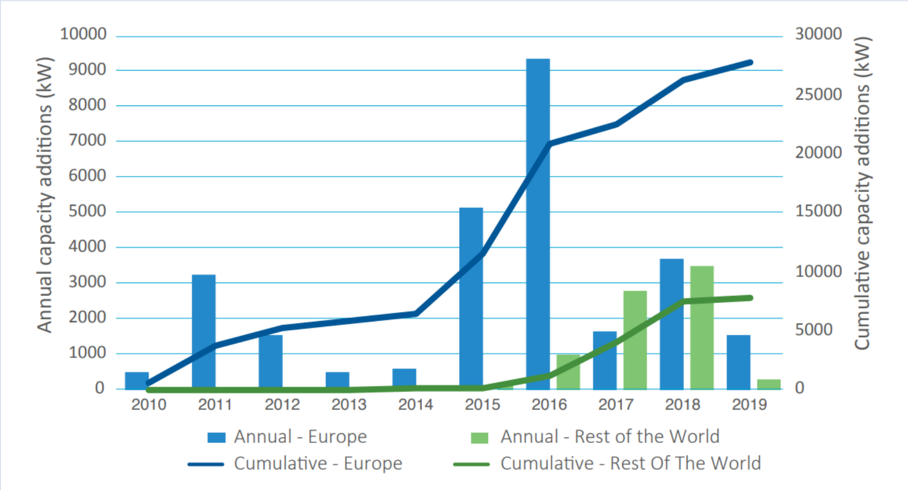


Figure 17 – installed and cumulative tidal stream capacity. Source: Ocean Energy Europe, '[Ocean Energy - Key Trends and Statistics 2019](#)'.

Other Technologies

Compared to wave and tidal, the other ocean resources – ocean currents, salinity gradients and thermal gradients – have less established technologies, with far fewer companies working on solutions. We take a brief look at these in this section.

Ocean Currents

Currents flow in complex patterns around the world's oceans. These are driven by the latitudinal distribution of winds, and by regional differences in ocean temperature and salinity (earth's rotation also plays a role). Although often located at deep ocean sites, ocean currents tend to operate most strongly near the surface, see **Figure 18**.

Open ocean currents are generally slower than tidal currents, but flow continuously (and usually horizontally) in the same direction, with low variability. Ocean currents do move seasonally, however, and are being impacted by climate change.

Ocean current flow can be captured using similar hydrokinetic technologies as employed for tidal stream. On the positive side, the continuous resource potentially enables high capacity factors (~70-95%) – getting on for baseload renewable electricity generation – meaning increased energy output and therefore a lower cost of energy. Another positive - the scale of projects could potentially be much larger than tidal stream.

On the negative side, the location, low speed and seasonal variability of the resource, as well as the lack of resource mapping, all increase the technical and commercial difficulty.

Currently, there do not appear to be any ocean current devices in the water. Of the ~50 global open ocean test facilities, only one is dedicated to ocean currents. It remains unclear how many ocean currents may prove enticing enough to draw interest for project development. We note that a few companies, such as Minesto, are actively targeting ocean currents as a secondary market for low speed tidal stream devices.

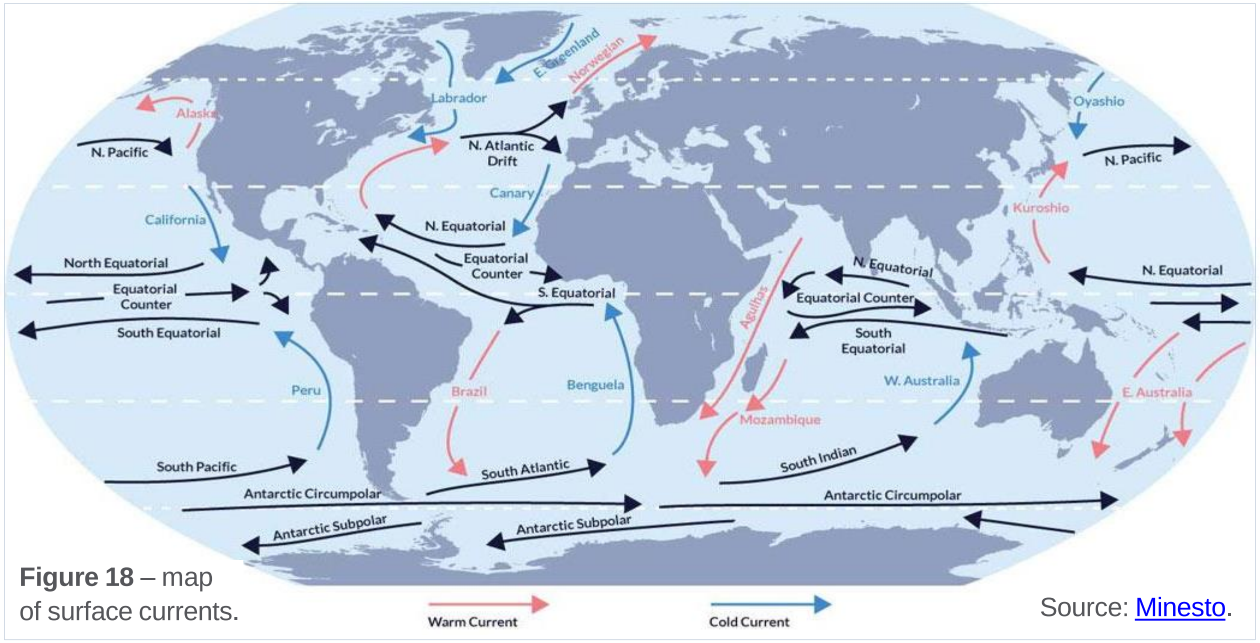


Figure 18 – map of surface currents.

Source: Minesto.

Ocean Thermal Energy Conversion

The sun constantly adds heat to the upper layers of the oceans. This creates a useful temperature difference between the surface and seawater at depths below 1000 metres. This can be exploited for heating, cooling, desalination or conversion to electricity by various Ocean Thermal Energy Conversion (OTEC) processes. OTEC requires practical temperature differences of at least 20 ºC. These are principally found in the tropics, on either side of the equator, see **Figure 19**.

As shown in **Figure 1**, the theoretical global resource potential for ocean thermal energy is the highest among all the OE resources. However, the energy density of OTEC systems is relatively low compared to wave and tidal. On the plus side again, although there is a slight seasonal variation in temperature gradients, the resource can be considered continuously available and therefore with the potential to create baseload electricity. The temperature gradient is turned into electricity using some form of heat engine. **Figure 20** shows how this works for an open cycle OTEC, which produces potable water, as well as electricity.

First used in 1930, OTEC has only seen the development of a few pilot scale (10-100s kW) plants to date, though MW scale projects are in the pipeline. Commercial use is envisaged to be at a scale similar to conventional thermal power generation (~100 MW). Plants could either be located at the coast, for example to provide desalination, refrigeration or seawater air conditioning (SWAC), or exist offshore, perhaps even roaming around to produce, for example, hydrogen on demand.

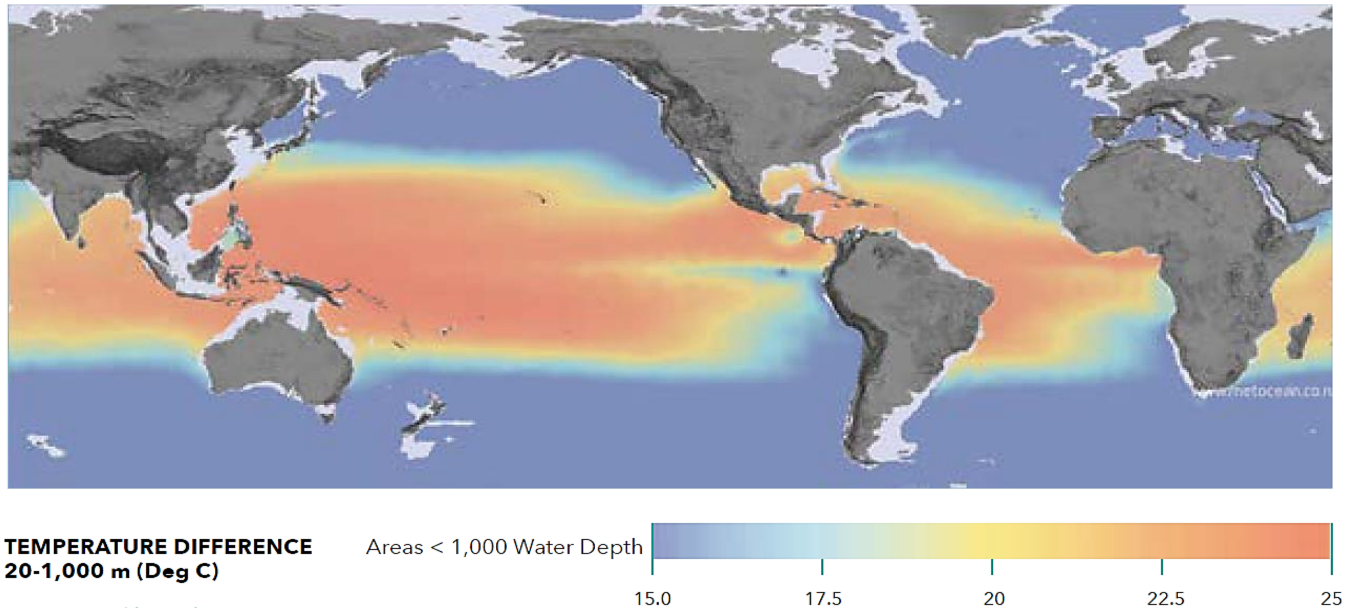


Figure 19 – OTEC world distribution map. Source: OES, '[An International Vision for Ocean Energy, 2017]'.

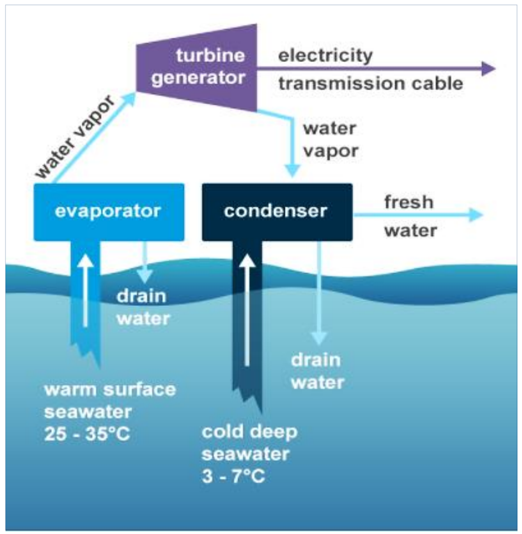
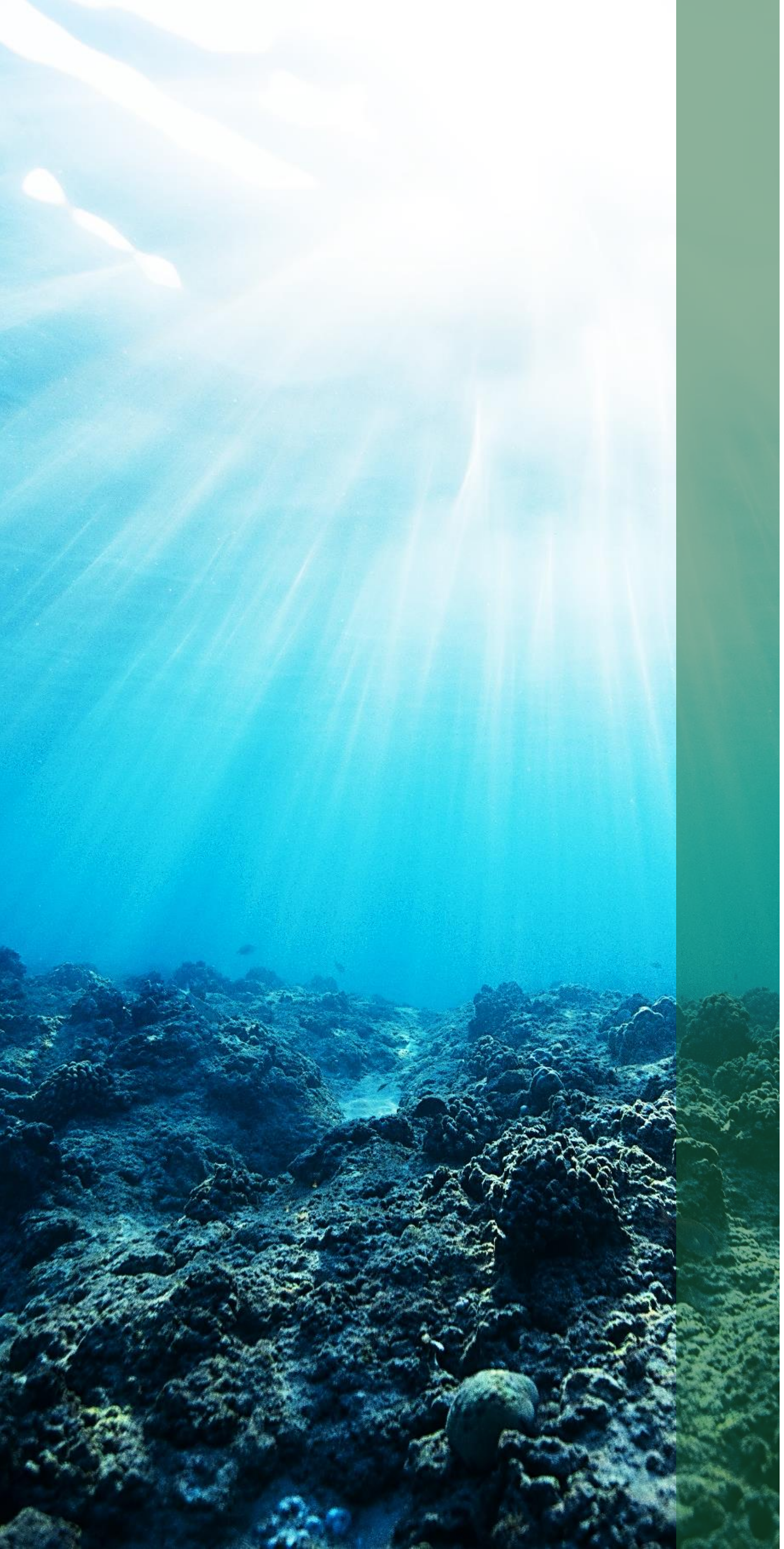


Figure 20 – How OTEC generates electricity. This is the open cycle form of the process.

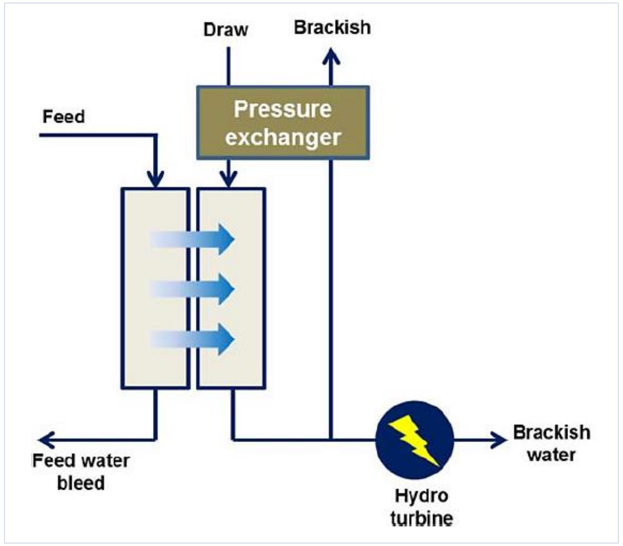


Salinity Gradient Power

At the interface between sea and river water, the salinity changes significantly. This provides a chemical potential which can be converted into electricity. As the salinity gradient is continuous, there is the potential to generate baseload power, if cost-effective technologies can be created. Two concepts being pursued are **reverse electrodialysis** and **pressure retarded osmosis**. Both processes rely on osmosis, the movement of solvent molecules across a semi-permeable membrane into a region of higher solute concentration.

Reverse electrodialysis involves the passage of charged particles across a stack of alternating cation and anion exchange membranes, creating an electrical potential difference across the stack; this is essentially a salt battery. With pressure retarded osmosis, water permeates through a semi-permeable membrane from fresh to seawater sides, with electricity generated by depressurizing the volumetric increase on the seawater side via permeated flow through a hydro turbine. The only waste product is slightly salty water. See **Figure 21**. Neither of these - or other - salinity gradient technologies have proceeded beyond small prototype plants. Expensive membranes are one barrier. Salinity gradient is the least technologically mature of all the ocean technologies.

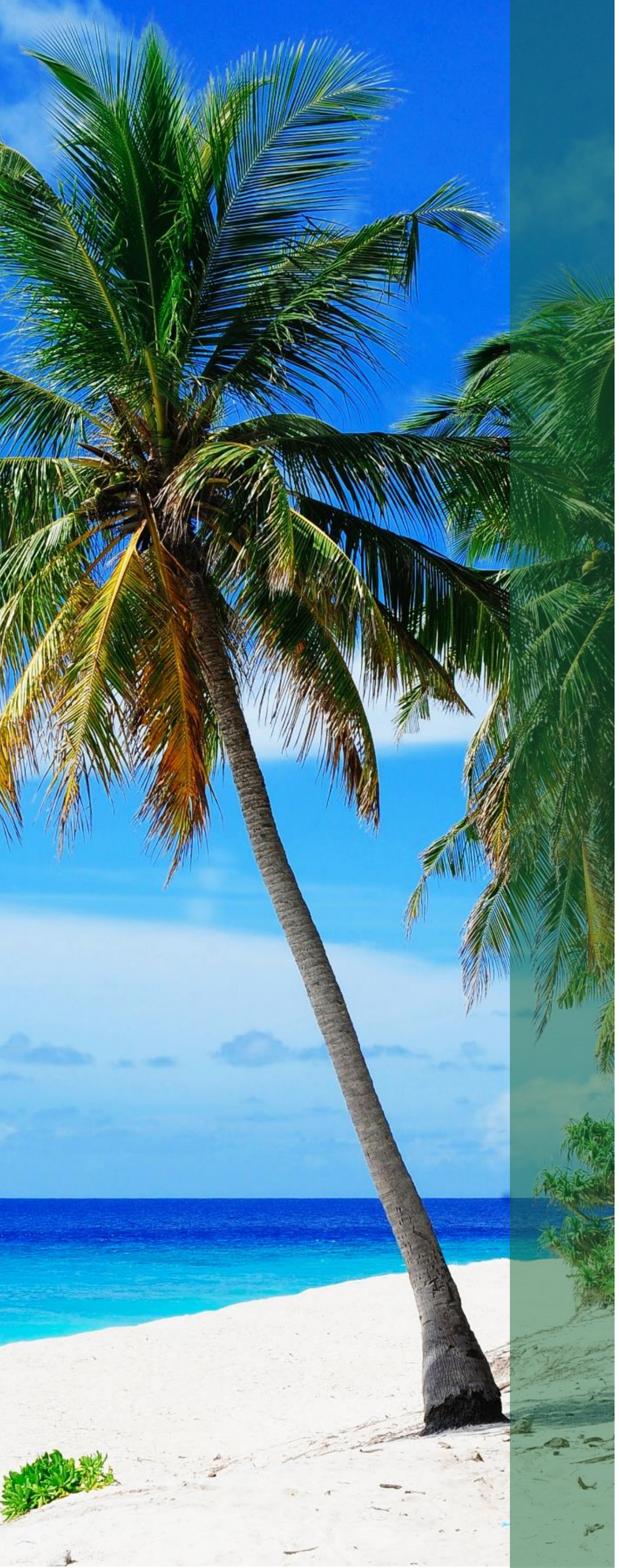
Figure 21 – Schematic of pressure retarded osmosis. Feed = fresh water. Draw = seawater. Image source.



Ocean Energy Role

Having introduced the main types of OE, let's take a step back and ask what future role OE might play in the global energy system. First we recap and expand on the key advantages of OE:

- **Global renewable resource -** some type of ocean resource is available on all continents, offering energy security and independence, emissions-free.
- **Minimal use of land** - land is a scarce resource in densely populated costal regions - 75% of humanity are situated less than 20 km from the coast. Unlike onshore renewables, most types of OE use limited land.
- **Limited risk to marine environment** - though the evidence is limited, most OE types are believed to pose minimal risk to sea life and habitats (tidal range a possible exception).
- **Limited visual impact** - some devices are located under the ocean surface or over the horizon, or otherwise have minimal visual impact from the shore.
- **Energy-rich resource -** those devices that exploit moving seawater benefit from a high energy density resource in comparison with wind and solar.
- **Predictable output** - ocean resources range from partially to highly predictable. The linked electrical output is equally predictable. Whilst there is unpredictable intermittency associated with some ocean resources, there is less potential for sudden changes in the resource compared with wind and solar.
- **Renewable baseload electricity -** some of the more experimental types of OE may one day be able to produce baseload electricity. In combination with energy storage, this could apply to *all* types.



Initial Role

OE is, in general, currently far too expensive to directly compete with conventional grid-connected renewables. It is therefore likely to start out in niche applications - where particular synergies exist – and off-grid applications – where alternative generation options are often more limited, more expensive and more polluting. Some example starter markets, many of which are already being actively pursued, include:

- **Island and remote coastal communities -** providing power in place of fossil fuel powered generators, or instead of or together with other - more unpredictable and intermittent - renewables.
- **Oil and gas platforms -** providing power, including for the electrolytic production of hydrogen.
- **Desalination, refrigeration and seawater air conditioning -** providing electricity to power these services, or providing these services more directly using OTEC.
- **Mining -** powering coastal and subsea mining.
- **Coastal marine infrastructure (port/marina/etc.) -** powering shore operations and docked vessels.
- **Aquaculture -** powering seafood farms, potentially far offshore; we explore this entertaining example later.
- **Data centres -** powering floating data centres; these benefit from free cooling provided by the seawater.
- **Offshore renewables (in hybridised form with) -** see section below.

As we noted earlier, in addition to energy generation, the wave devices of our case study company HACE can also provide protection from the sea for marine assets such as those included above.

Fully Integrated Role

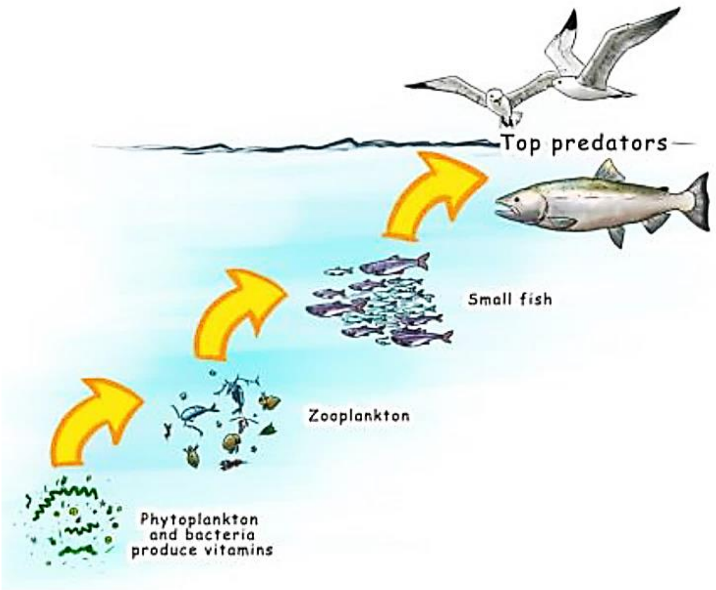
As the technology matures, costs will inevitably come down - as we detail later - meaning the advantages of OE can come to the fore. From an electricity system point of view, OE provides another clean way of balancing supply and demand. Importantly, ocean technologies have different generation profiles to traditional renewables – they generate at different times and with different variability. They can therefore act as a complement to, rather than necessarily competing with, other grid-connected renewables. Simply put, we are more likely to be able to completely decarbonise the energy system with OE than without it. The prospect of baseload renewable electricity is particularly enticing.

Taking integration with other renewables one step further, several companies are currently looking at hybridising wave energy with floating wind on the same site. We explained why this is a neat idea in the earlier case study.

Wave Energy for Food Generation, CO_2 Capture

In this section we outline one of the more intriguing and ambitious applications that low cost wave energy opens up. This early stage concept comes from WHALE, partner of wave energy company HACE (see earlier case study).

Figure 22 – the marine food chain (more accurately food web). Image source: WHALE.



As we stated earlier, the ocean covers 70% of the planet's surface. However, 90% of this is effectively a 'desert' with limited marine life. This is because the organisms on the lowest rung of the marine food chain – phytoplankton - who grow by photosynthesis, cannot get established. See **Figure 22**.

Photosynthesis requires the presence of both light and certain nutrients (e.g. nitrogen, phosphorus and iron). However, in the open ocean these nutrients are not available at the shallower depths that receive sufficient light. This means no photosynthesis, no plankton, and no higher marine life.

Thankfully, these important nutrients *are* available in the open ocean at greater depths. If these can be brought closer to the surface - a process called upwelling which happens naturally near the coast - then the entire web of marine life can be kick-started.

This is where wave energy comes in. It can provide in situ power to transfer the nutrients from deep to shallow water artificially. This can be done using conventional air bubbling equipment (used for decades in water tanks), adapted for very large and deep volume.

The anchored WHALE system consists of: (a) this adapted air bubbling equipment; (b) ropes at the surface, to foster a seaweed culture and serve as a fish attracting device; (c) a connected buoy to monitor performance. The phytoplankton from the bubbling process, together with the seaweed at the surface, provide a direct feed source for higher marine organisms. These are farmed and harvested for profit.

Starting in shallower water (300-500m deep), the ambition is to install 100,000 systems, in groups of 100 system farms, over the coming decades. At this scale, approximately 100 Mtons of seafood, with a value of $100B, could be sustainably produced a year. This is approximately half the size of the current seafood market, approximately half of which comes from wild capture, an increasingly unsustainable practice.

In addition, at this scale approximately 10 Btons of CO_2 could be stored in plankton (more accurate figures would include other factors in the carbon accounting). This is carbon capture on a scale which could make a significant difference to climate change, and at essentially no cost, as it is a happy side effect of the process. Most other forms of carbon capture are likely to be unfeasibly expensive on this scale.

Clearly this idea will be very challenging to pull off, and, on further investigation, may not turn out to be feasible. However, without cheap in situ power, of the type HACE can provide, this will never get off the ground.

Market Forecast

Having laid out qualitatively the future role that OE might play in the preceding section, in this section our speculation turns more quantitative. How far and fast can OE grow from its near zero base (**Figure 4**) towards its lofty potential (**Figure 2**), and what are the barriers? The 2019 starting point is summarised in detail in Ocean Energy System's (OES) annual report *.

Current Pipeline

Our first clue is projects currently in the pipeline, which according to a recent reckoning by IRENA (International Renewable Energy Agency), amounts to almost 3 GW, with half of this in Europe (includes UK). See **Figure 23**, below.

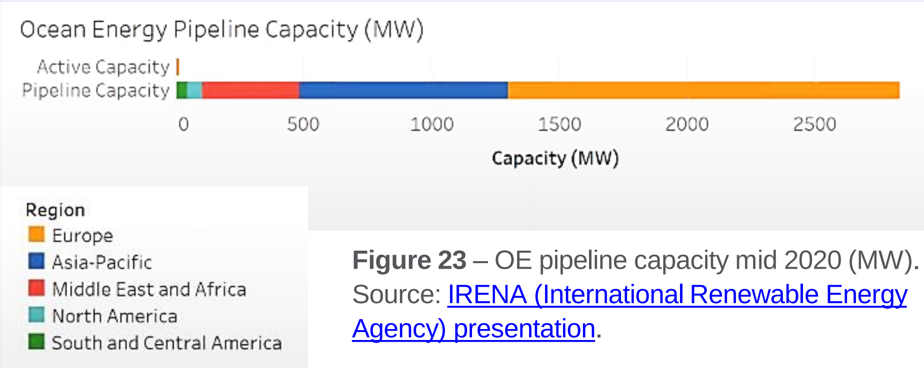


Figure 23 – OE pipeline capacity mid 2020 (MW). Source: IRENA (International Renewable Energy Agency) presentation.

IRENA do not distinguish by resource type, but we assume this is majority tidal with wave making up most of the remainder. As illustrated somewhat comically in **Figure 23**, 3 GW of new capacity would dwarf the current active capacity, suggesting explosive near-term growth.

Challenges

There are a host of technical, economic, environmental, social and infrastructural factors that can present barriers for any given OE project, and therefore the sector as a whole. We highlighted some previously in Figure 2, and in the Case Study, and explore the role of costs and government further below. A more detailed exploration of barriers to development and deployment can be found in this IRENA report.

Reducing Cost

Of the things of which it can control, the sector needs to prove and improve reliability, performance and costs, all of which are interlinked and reflected in the LCOE. Some designs will fall by the wayside during this process, allowing money to be funnelled into the surviving designs.

To recap, utility scale solar has a LCOE of ~30, onshore wind ~35, and offshore wind ~75 €/MWh. In general – and putting aside HACE - the LCOE of current pre-commercial wave and tidal devices are 1 to 2 orders of magnitude above this, with wave more expensive than tidal.

According to OES, based on responses from developers in 2015, the LCOE is expected to drop rapidly as devices are deployed in pre-commercial and then first commercial arrays. For the first commercial array, the LCOE is forecast at ~110-240 for tidal, and ~100-400 for wave (€/MWh). The LCOE inputs can be found in the Appendix. Subsequently, OES expects costs to drop further, following a standard learning curve. Wind and solar PV managed a roughly 15% and 20% drop in costs per doubling in capacity, respectively. Ocean learning curve estimates are given in the Appendix.

* OES is a technology collaboration programme which operates under a framework established by the International Energy Agency (IEA). Visit their website.

To recap and expand on earlier points, LCOE can potentially be reduced by the following:

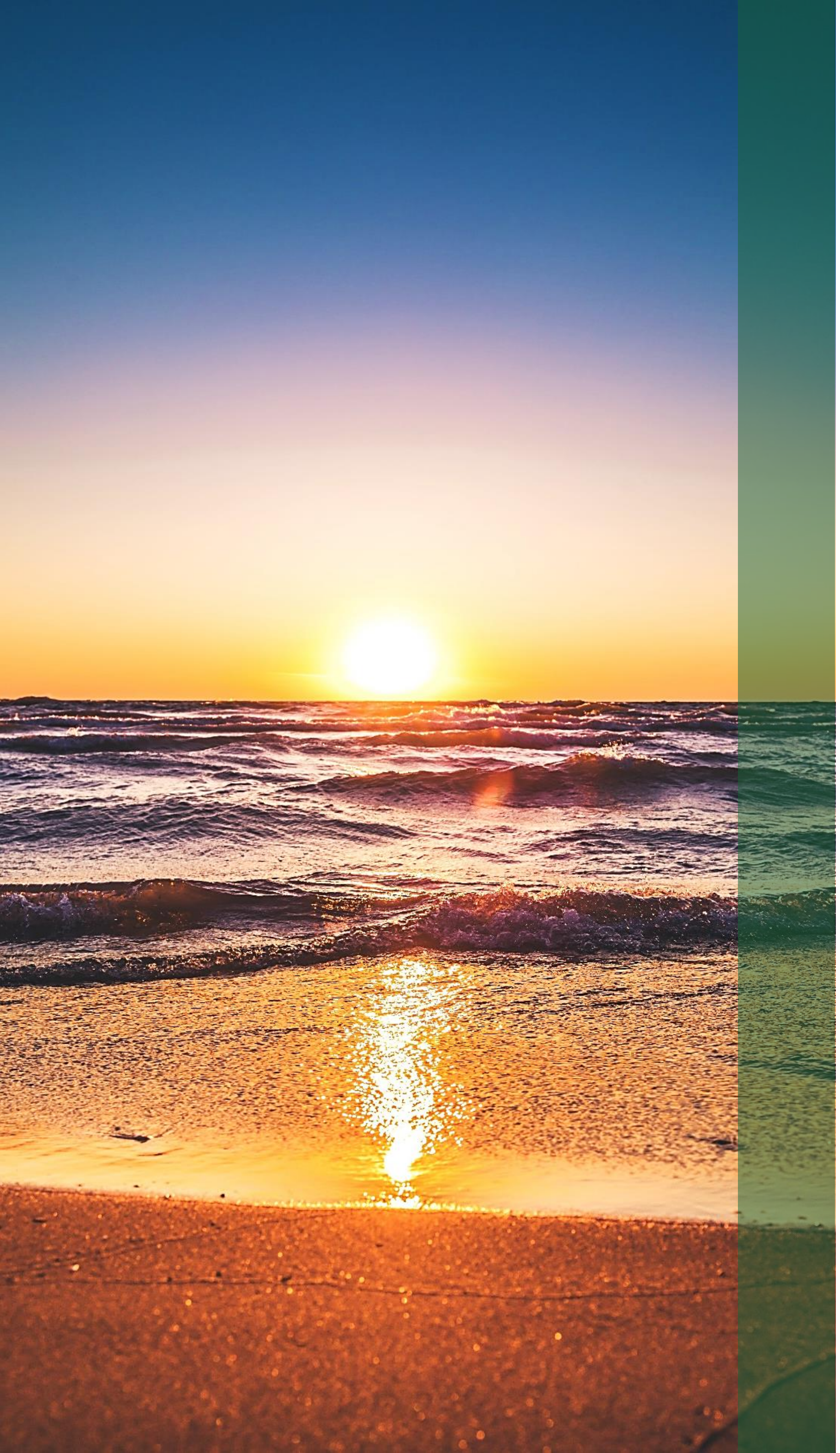
- Better resource analysis and forecasting.
- Optimising site selection.
- Fundamental design modifications.
- Recruiting related supply chains, such as oil and gas, offshore wind, shipping and aquaculture.
- Standardisation of components, e.g. power take-off, foundations and moorings.
- Manufacturing at scale.
- Deployment in arrays.
- Integration with other technologies, such as offshore wind.
- Operational efficiencies: installation, maintenance and recovery.
- Performance data gathering for improved reliability and availability.

Government Policy

Of the things out of its control, government policy is key for the sector. Government policy towards OE ranges from indifferent to actively supportive. A summary of the policy in each country can be found in OES's 2019 annual report (which also looks at deployments). Although the introduction of net-zero emissions legislation in a growing numbers of countries is a positive, policy is often focused on other, cheaper renewables. IRENA would like countries to explicitly include OE in country energy roadmaps – often not the case - and then to establish clear policies to achieve the energy targets established therein. They see a need for a mix of innovative funding schemes and revenue support. The relevant legal and regulatory framework is another key area for governments to address.

In the UK, grant funding, excellent test facilities and other factors have helped push the sector close to commercialisation. However, without revenue support, it may still struggle. OE can - in theory at least - compete for CfD (Contracts for Difference), a government guaranteed price for future electricity generation. In practice though, it has to compete against offshore wind, so is effectively frozen out of this mechanism (proposed changes may help). Offshore wind also has an explicit government sector deal. OE does not.

Unlike the UK, some countries *are* offering targeted revenue support. For example, the Canadian province of Nova Scotia (~€350/MWh) and China (~€330/MWh) both have a Feed-In Tariff for tidal stream. This works as a top-up amount per unit of electricity generated.



Long-term Forecast

Assuming the challenges mentioned in the previous section can be overcome - and a healthy pipeline suggests the sector *is* making progress - what sort of growth can realistically be expected for OE? Let's look at a few viewpoints…

Some sector advocates simply suggest that OE will supply a certain percentage of the global electricity supply by a certain date. 10-20% by 2050 is commonly floated. For comparison, wind and solar combined provided about 8% of electricity supply in 2019.

Turning to energy organisations, IRENA forecasts 10 GW of worldwide OE capacity by 2030 (source same as **Figure 23**), 30% of which is already in the pipeline. OES sees a potential to develop 300 GW of wave and tidal by 2050, and possibly as much again from OTEC. They suggest this could create 680,000 direct jobs by the same date and require investment of over a trillion dollars. Areas with the best resource, such as the UK, will be the main beneficiaries. National Grid's Future Energy Scenarios 2020 sees up to 10.5 GW of OE for the UK by 2050.

As for OE hardware developers, some like to compare themselves with their wind turbine equivalents. This is not completely unreasonable, especially for offshore wind with tidal stream, though the extra difficulties of generating under rather than above water makes the comparison imperfect. The implication (hope) is for a similar rate of rapid growth going forward that the wind turbine industry has experienced historically. The wind turbine market – onshore and offshore combined – is today worth almost $50 billion annually. Vestas is currently the market leader and is reporting annual revenues of $10+ billion.

Using a 10% of European electricity supply by 2050 expectation, our case study company HACE puts the value of sales to provide this scale of electricity using their wave devices at €600 billion. This gives another idea of the potential scale of money involved.

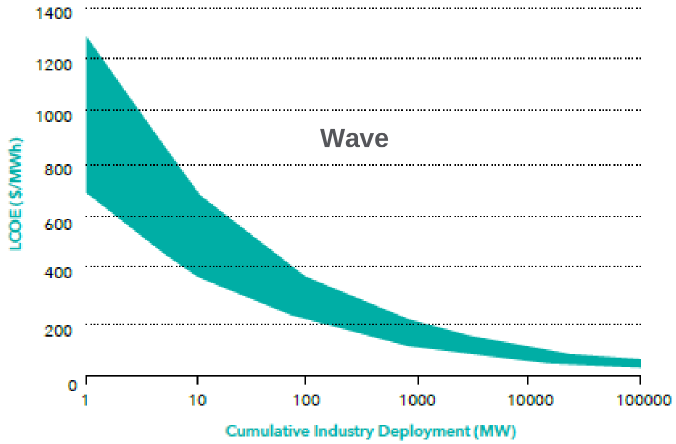
To summarise this report in a sentence…the resource is vast and untapped, progress is being made towards mass commercialisation, and the creation over the coming decades of an industry of significant scale is a distinct possibility. We are certainly enthusiastic about the sector and recommend investors take a closer look.

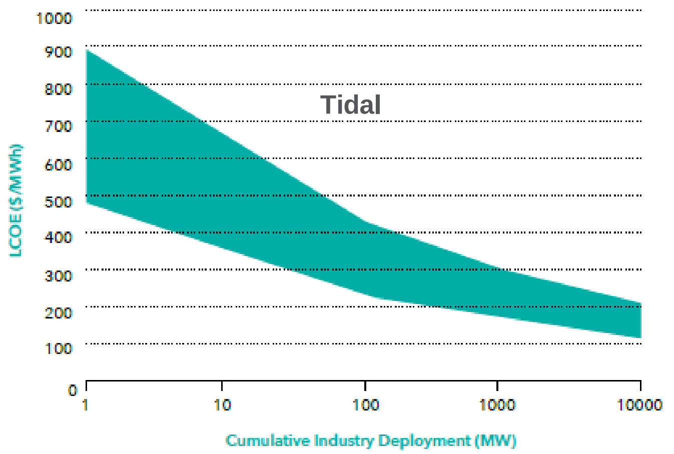
Appendix – LCOE Estimates

Deployment Stage	Variable	Wave		Tidal		OTEC	
		Min	Max[1]	Min	Max	Min	Max
First array / First Project[2]	Project Capacity (MW)	1	3 [3]	0.3	10	0.1	5
	CAPEX ($/kW)	4000	18100	5100	14600	25000	45000
	OPEX ($/kW per year)	140	1500	160	1160	800	1440
Second array/ Second Project	Project Capacity (MW)	1	10	0.5	28	10	20
	CAPEX ($/kW)	3600	15300	4300	8700	15000	30000
	OPEX ($/kW per year)	100	500	150	530	480	950
	Availability (%)	85%	98%	85%	98%	95%	95%
	Capacity Factor (%)	30%	35%	35%	42%	97%	97%
	LCOE ($/MWh)	210	670	210	470	350	650
First Commercial-scale Project	Project Capacity (MW)	2	75	3	90	100	100
	CAPEX ($/kW)	2700	9100	3300	5600	7000	13000
	OPEX ($/kW per year)	70	380	90	400	340	620
	Availability (%)	95%	98%	92%	98%	95%	95%
	Capacity Factor (%)	35%	40%	35%	40%	97%	97%
	LCOE ($/MWh)	120	470	130	280	150	280

The above table is taken from the Executive Summary of OES's 2015 report on the LCOE of ocean technologies. It is slightly dated now, but is an interesting source nonetheless. For the full context behind this table, and what the superscripts mean, see the original source.

The graphs to the right show one attempt at estimating the learning curves of wave and tidal (how the cost varies with deployment). These graphs are from OES's 'An International Vision For Ocean Energy 2017' report, but appear to be using data from the 2015 report mentioned above.





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