**Technical assessment for**

**Ocean Power**

Sector: Electricity generation

Agency Level: Utilities

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# Acronyms and Symbols

* AMPERE – Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
* H2S - hydrogen sulphide
* CH4 - methane
* CO2 – Carbon Dioxide
* CSP – Concentrated Solar Power
* DFI - Development Finance Institutions
* DS – Degree Scenario
* EEC – Exclusive Economic Zone
* EIA - Environmental Impact Assessment
* EIA – Energy Information Administration
* EJ – Exajoule
* ETP – Energy Technology Perspectives
* EU – European Union
* GHG – Greenhouse Gases
* Gt – Gigatons
* GW - Gigawatts
* IEA – International Energy Agency
* IPCC – Intergovernmental Panel for Climate Change
* JRC – Joint Research Centre
* LCA – Life Cycle Assessment
* LCOE – Levelized costs of electricity
* MESSAGE-MACRO – Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback
* MR – Marine Renewables
* MW – Megawatt
* OECD – Organization for Economic Co-operation and Development
* O&M - Operations and maintenance costs
* OTEC – Ocean thermal energy conversion
* OWC – Oscillating water column
* PD – Project Drawdown
* PDS – Project Drawdown Solution
* Ppm - parts per million
* PRO – Pressure retarded osmosis
* PV – Photovoltaic
* R&D – Research and Development
* RED – Reversed electrodialysis
* REF – Reference
* RES – Renewable Energy Sources
* RRS – Reduction and Replacement Solution
* RTS – Rance Tidal Station
* TAM - Total Addressable Market
* TRL – Technological Readiness Level
* TWh – Terawatt hour
* UK – United Kingdom
* UKERC – UK Energy Research Centre
* US – United States
* USD – United States Dollar
* WEC – Wave energy converters
* WEO – World Energy Outlook
* WTE – Waves and Tidal Energy

# Executive Summary

Project Drawdown defines ocean power as: wave energy converters and tidal systems for electricity generation. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants. This assessment focuses on three types of marine renewables: wave energy converters, tidal stream, and tidal barrage, together called wave and tidal. Wave energy converters are devices which convert the kinetic motion of ocean waves into electricity. Tidal stream energy can be tapped by using devices which act as underwater wind turbines, converting the flow of tidal currents into electricity. Tidal plants are large, utility-scale systems which direct the flow of tides through turbines to generate electricity, akin to hydropower electricity generation. Of the many types of renewable energy, wave and tidal energy is arguably the most predictable. While the resource is spread out globally, there are only a few locations where wave and tidal energy can be harnessed commercially. The technologies used to convert marine energy to electricity are quite different. Tidal plants, which are more akin to large hydro plants, have replacement timeframes on the order of 40 years or more. On the other hand, wave energy converters only last a couple of decades.

The total addressable market for ocean power is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption being almost negligible: 1.06 terawatt-hours, representing only 0.004 percent of global electricity. Impacts of increased adoption of wave and tidal from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a Reference Scenario where the solution’s market share was fixed at the current levels. Future adoption of the Plausible and Drawdown Scenarios reflects an adoption pathway derived from recent long-term projection estimates from IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Energy [R]evolution Scenario from Greenpeace (2015); being distinct on the medium and high growth trajectories used, respectively. Optimum scenario for ocean power systems is based on the yearly average values of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram *et al.* (2019) scenario and Ecofys (2018) 1.5ºC scenario.

The *Plausible* Scenario results in the avoidance of 1.4 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050, with US$201.6 billion in marginal first costs and negative US$381 billions of net operating cost savings projected over the same period. In the *Drawdown* Scenario, after integration with other solutions, ocean power adoption depict an impact of 1.4 gigatons of greenhouse gas emissions reductions over 2020-2050 with near US$5261.4 billions of marginal first costs and -488 billions of net operating saving. The *Optimum* scenario presents 8.9 gigatons of carbon dioxide-equivalent, with results on higher capital difference, with US$327.3 billions of marginal first costs and negative net operating saving of 2.48 trillion.

Given the relative immaturity of the wave and tidal industry, it is difficult to predict how it will develop over the next three decades. The uncertainty increases considering the small percentage of wave and tidal systems currently in the global electricity mix and the range of technologies under testing. Once operational, the low carbon footprint of wave and tidal systems makes them increasingly more attractive. Nevertheless, there are many technical, financial, and policy-related challenges which need to be overcome before these systems can be deployed at a large scale in the world. The fact that there are only a couple of utility-scale tidal barrage stations indicates that the deployment may need a big push from governments. Conversely, wave energy’s relative immaturity, coupled with the much shorter timescale on which it operates, is more akin to the early wind energy industry. Once engineers and scientists settle on a design, the market will foloow, prompting true competition and further adoption. The current situation with a smattering of ocean power technology designs means that widespread development and installation is still in a very early stage.

# Literature Review

## State of Wave and Tidal Energy Technologies

Marine (or Ocean) energy refers to the renewable energy types that could be recovered from the ocean in the forms of mechanical (driven by earth’s rotation, moon’s and sun’s gravitational pull – e.g. wave and tidal energy respectively); thermal (driven by temperature gradient caused by differential solar heating of ocean’s surface relative to the lower part – e.g. Ocean thermal energy); and chemical (driven by salinity gradient caused by differential salt concentration of mixing flows from sea and river water). The ocean energy resources recovered in these three forms could be converted into electricity using ocean energy converters designed to operate in consistence with these three underpinning principles.

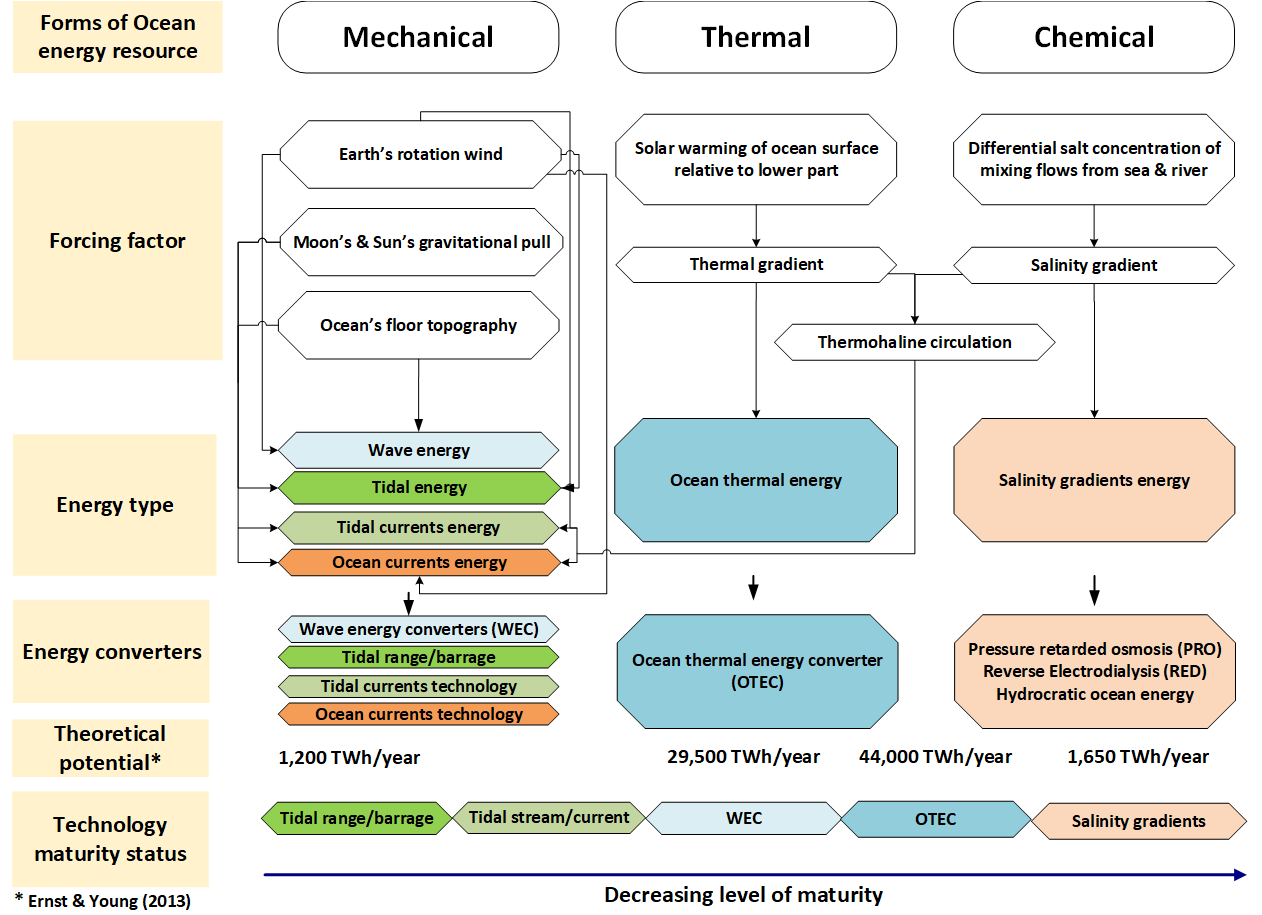


Figure 1.1 Ocean energy resource types, technology, and readiness (Source: Project Drawdown, 2019)

Generally, the energy that can be recovered from the ocean are in six categories, including tidal, tidal currents, wave, thermal gradients, salinity gradients, and deep ocean currents. The energy can be intercepted from the ocean and converted to electricity using various converters or technologies outlined in Figure 1.1 and discussed in the subsequent sections.

### 1.1.1 Tidal range/barrage

Tidal power harnesses the height difference between low and high tide to generate electricity, akin to established hydroelectricity generation techniques. As shown in Figure 1.1, Ocean tides are a phenomenon resulting from the gravitation interaction between the Earth, Moon and Sun, with the tidal effect of the moon more pronounced due to the moon’s relative proximity to earth. Because the tidal force due to the moon is predictable over long-term into the future, the resulting Ocean tides also follow predictable patterns and at most locations there are nearly equal low and high tides in a day. During new and full moons, which happen roughly twice per month, the Sun, Earth and Moon are in line, and therefore the tidal force of the Moon is reinforced by that of the Sun to create “spring tides” where the tidal forces and consequently the range of tide are at their maximum. During half and three-quarter moons, again roughly twice per month, the Moon is 90° from the Earth-Sun plane leading to “neap tides” where tidal forces are at their minimum, as the Moon’s tidal effect partially cancels out that of the Sun’s.

Tides cause seawater to flow from the ocean side to the tidal basin side, which is an enclosed area separated by a barrage, by operation of sluice gates (Figure 1.2). Water flows through the sluice-gated tunnel from the ocean side during high tide to the basin side. The gates are closed when the water levels on both sides match. After some hours, the water level on the ocean side falls due to low tide and the sluice gates are opened when the height difference between the basin side and the ocean side is a maximum. The turbines installed in the tunnels are driven by the water rushing out from a higher level to a lower level, thereby generating electricity in the process. The operation behaves in a way similar to a hydro power station. The tidal height varies from 0-12m depending on the location and a differential of around 7m between the level of high tide and low tide is required for operation of a tidal barrage plant (Tidal Energy - Ocean Energy Council, 2017). In order to provide a longer duration of electricity generation, multi basins and dual flow turbines (electricity is generated by the turbine which runs when water flows in either direction) are also feasible.

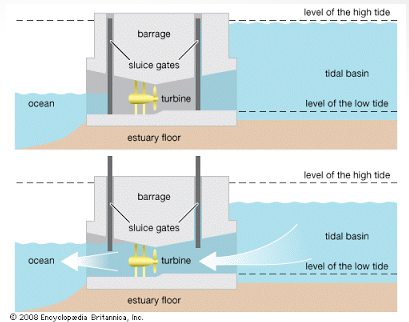


Figure 1.2 Operation of a tidal barrage system (Source: Tidal Power Barrage, 2017)

The world’s first tidal power plant is the 240MW Rance Tidal Station installed in 1966 in Brittany, France. The plant has 24 turbines with a combination of both ebb, and ebb and flood generation capabilities, with annual generation of about 500 GWh, and a capacity factor of 28% (EDF, 2016). At 3.7 ¢/kWh[[1]](#footnote-1), RTS generated electricity at a rate lower than the country’s nuclear power stations (3.8 ¢/kWh)but was more expensive than hydroelectricity (3.2 ¢/kWh) (Energybc: Tidal Power, 2017). It was the largest tidal barrage system in the world before the 254 MW Sihwa Lake Tidal Power Station commenced operation in South Korea in 2011. Other operational tidal power plants include the 20MW Annapolis Royal generating station in Canada – the only in North America, the 3.2MW Jiangxia tidal power station in China, the 1.7MW Kislaya Guba tidal power station in Russia and the 1.25MW Eastern Scheldt barrier tidal power plant. However, this technology has not found much favor due to the large area of land which it submerges, and the increasing concerns on the environmental impacts of the project.

### Tidal currents or tidal streams

These systems are turbines (similar to wind turbines) placed at appropriate locations (often inside a constrained channel) to tap incoming and outgoing flow of seawater during tidal flooding and ebbing. Different modes of deployment such as a twin turbine horizontal axis turbine, vertical axis device and cross flow devices as shown in Figure 1.3 have been tested. These can also be installed to extract energy from deep ocean currents. Examples are the 1.5MW Uldolmok tidal power station in South Korea and the 1.2MW Strangford Lough SeaGen in the UK decommissioned in 2016.

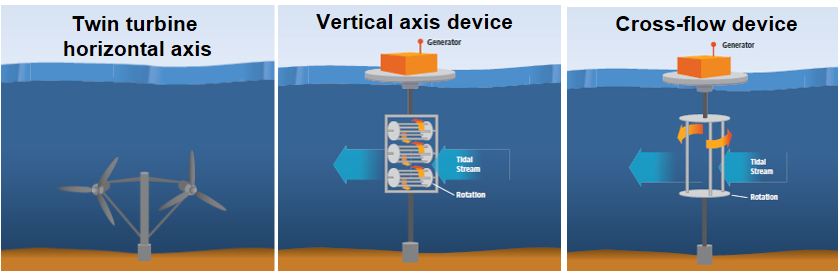


Figure 1.3 Types of tidal stream turbines (Source: Lewis et. al, 2011)

### Wave energy

Wave energy arises from the interaction between the ocean’s surface and the wind circulation caused by earth’s rotation. To capture wave energy propagated through the ocean body, Wave Energy Converters (WECs) with different characteristics and designs have been tested.

1. Wave energy converters (WECs):

These are devices which convert the kinetic motion of waves into electricity. These can be fixed structures above the breaking waves and can be cliff-mounted/breakwater mounted or bottom mounted near shore. Floating systems with mooring in deeper waters have also been tested. Still very much in the developmental stages, WECs use five different types of designs:

1. Point absorber buoys (Figure 1.4): PABs are floating WECs that oscillate with the ocean waves with at least one degree of freedom, and moored to the sea bed. An important attribute of the PABs is their ability to intercept and absorb wave energy from wave fronts that are many times larger than their dimensions. The important design parameters useful for the design of WECs are wave characteristics defined by the wave period, wave height, wavelength, and the depth of water in the vicinity of the wave propagation.

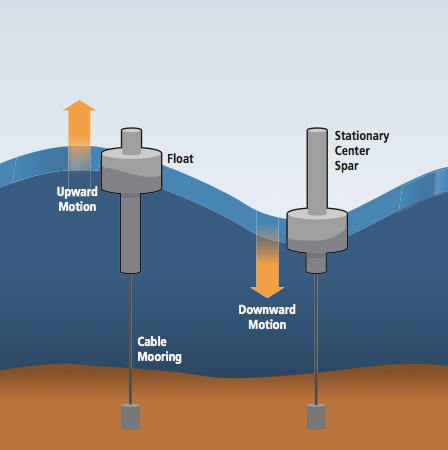


Figure 1.4 Point absorber buoy (Source: Lewis et. al, 2011)

1. *Surface attenuators:* These are multi-armed devices with joint pivot connections and are oriented perpendicular to incoming waves (Figure 1.5). This causes one end to rise before the other and the swelling motion is converted into electricity. A surface attenuator is a line absorber, parallel to the direction of wave propagation.

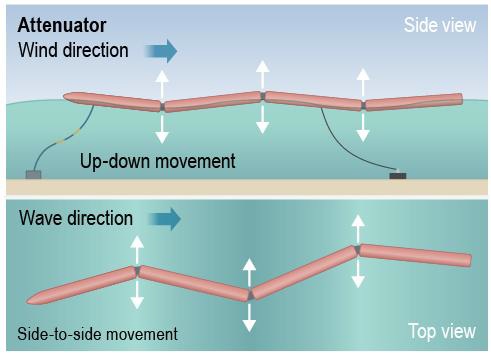
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Figure 1.5 Surface attenuator (Source: Marine and Hydrokinetic Technology Glossary, 2017)

1. *Oscillating water column (OWC)*: Incoming waves enter a chamber where the rising and falling water level compresses air which is forced to flow through a turbine, generating electricity (Figure 1.6). The chamber has two openings – one to the atmosphere, while another is in contact with the ocean water. In principle, OWC uses a column of water caused to oscillate by the impinging wave, to alternately compress and/or expand the air trapped within the device. This process leads to a steady air flow that could be used to drive air turbines.

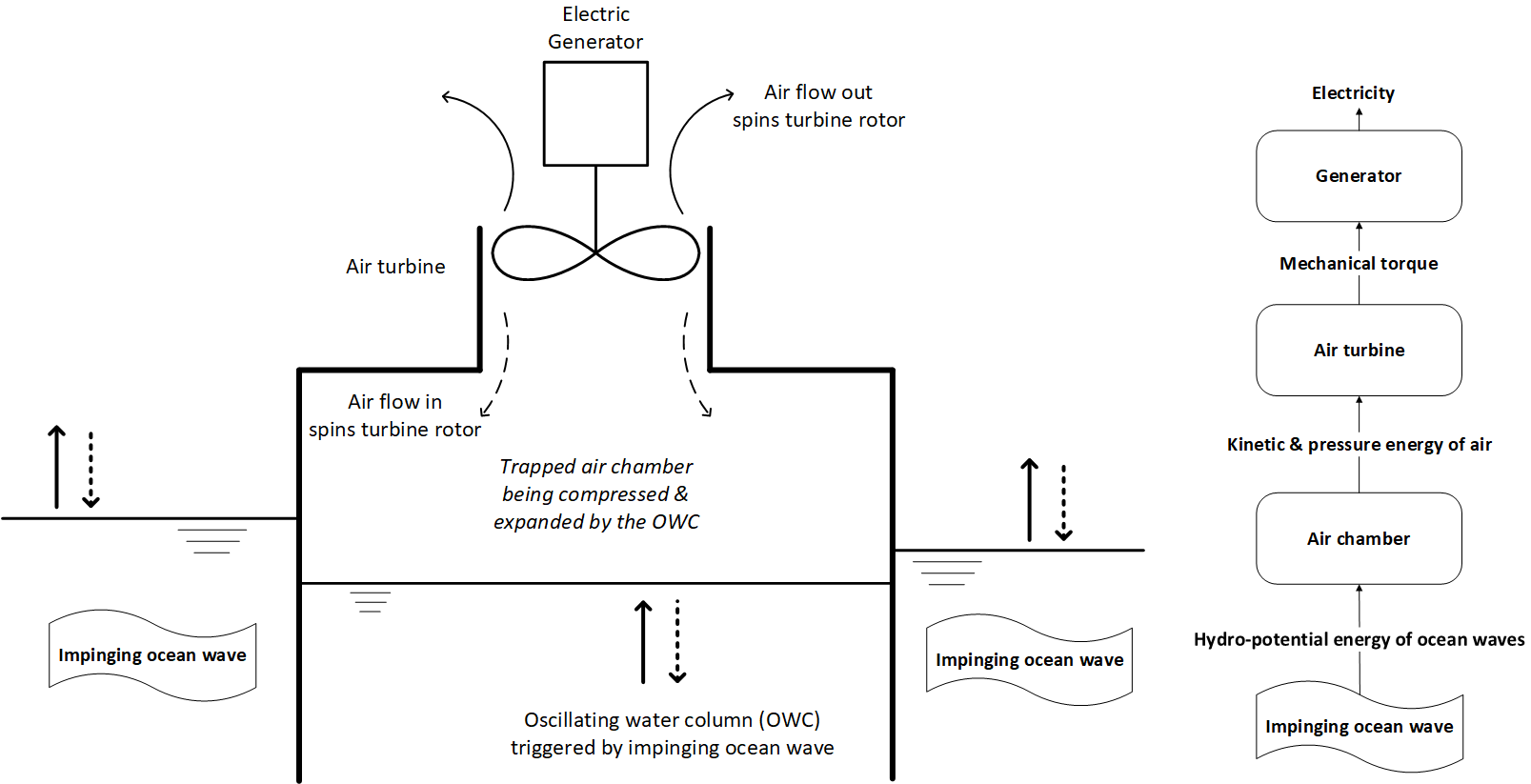


Figure 1.6 Schema of Oscillating Wave Column and energy conversion (Source: Drawdown, 2019)

1. *Overtopping device*: Waves crash atop a device (either onshore or deep offshore) and water flows downward, driving a low head hydraulic turbine to generate electricity (Figure 1.7).

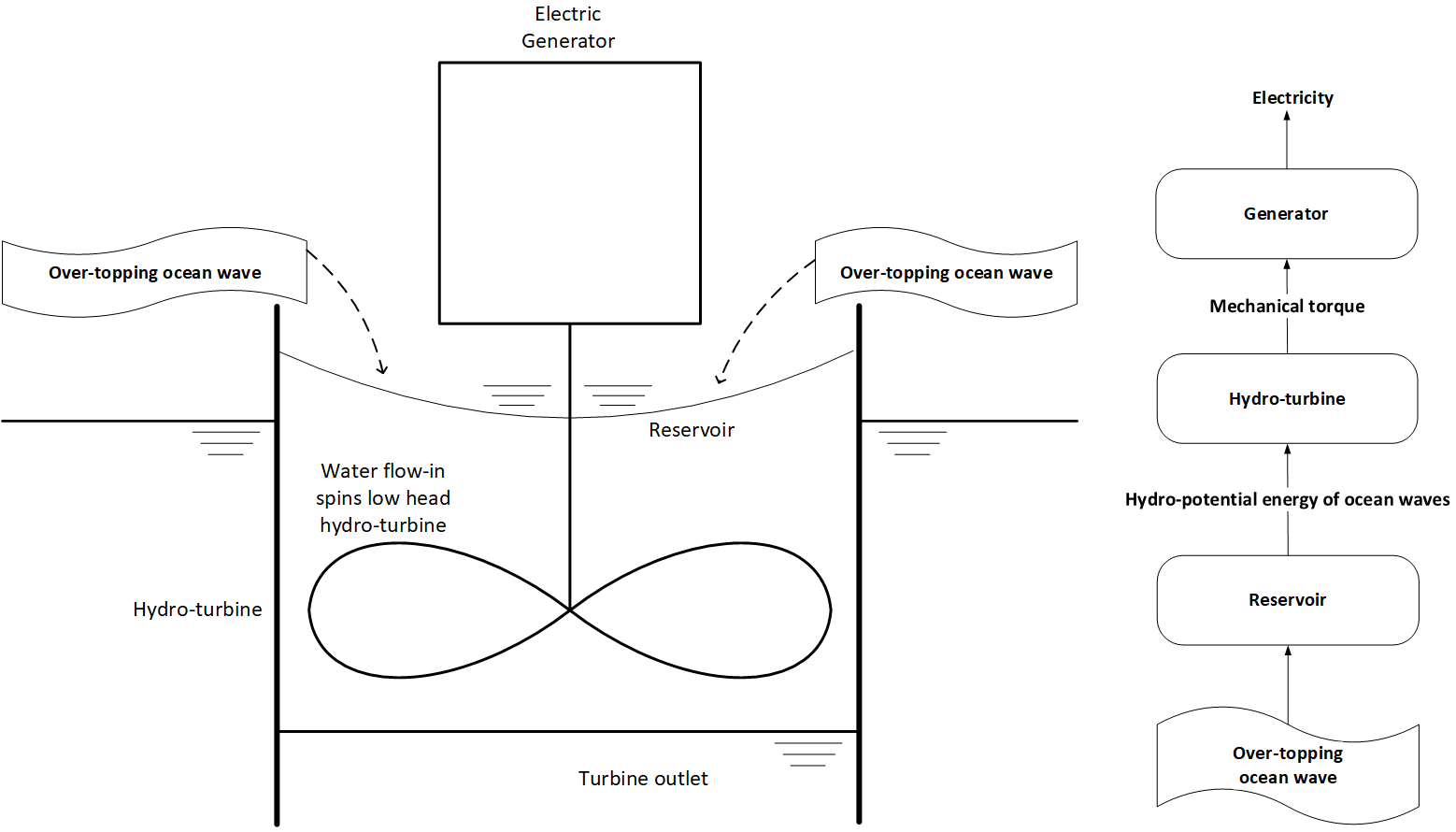


Figure 1.7 Schema of wave overtopping device and energy conversion (Source: Drawdown, 2019)

1. *Oscillating wave surge converter*: Individual mechanical arms tethered to the seabed oscillate with ocean currents and waves. This motion is converted into electricity in a hydraulic and generator system (Figure 1.8).

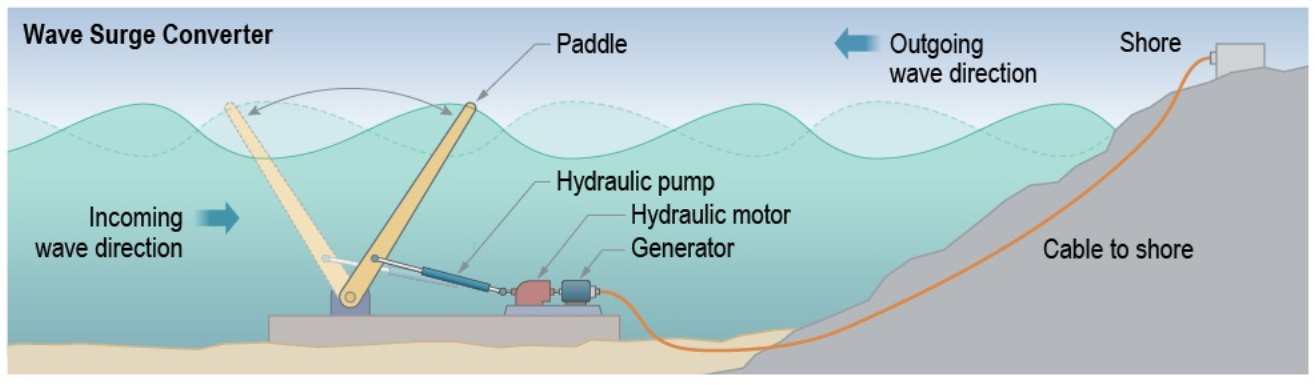


Figure 1.8 Wave surge converter (Source: Marine and Hydrokinetic Technology Glossary, 2017)

1. *WaveStar*: An upcoming WEC innovation by a Danish company to harvest the kinetic energy of the ocean wave, and convert it into electricity in a hydraulic system coupled with a generator.

### Temperature Differential

Similar to geothermal power; ocean thermal energy conversion (OTEC) systems exploit the temperature differences in seawater to run a heat engine. For example, warmer seawater vaporizes a liquid (like ammonia with a low boiling point of −33.34 °C), and the expanding gas can be used to drive a turbine to generate electricity. OTEC plants additionally provide fresh water as a by-product along with electricity which is most useful for islands having human habitation.

### Salinity gradients

At places where sources of freshwater meet saltwater (i.e. at the mouth of a river), the differences in salt concentrations of mixing flows (Gibb’s free energy of mixing) leads to a chemical potential energy which drives the transport of ions through a membrane. This chemical potential energy can be harnessed to generate electricity using technologies such as pressure retarded osmosis (PRO), reversed electrodialysis (RED), and hydrocratic system. Salinity gradient energy or Blue Energy has a good potential in heavily populated Delta regions (Post, 2009).

1. Pressure retarded osmosis (PRO):

The underlying principle of this technology is essentially an interaction between the chemical potential difference (due to salinity gradient between low salt river water, and high salt sea water separated by a semi-permeable membrane), and the applied hydrostatic pressure to the high salt sea water. In PRO device, dilute river water is brought into a membrane contact with concentrated sea water, leading to a chemical potential difference which drives the dilute water through the membrane into the concentrated water. This driving force is then retarded by applying an external or osmotic pressure to the concentrated sea solution. The retardation causes the flow from low-pressure dilute solution side to lock horns with the counter-flow from high pressure concentrated solution side, and the resulting effect is a pressurized volume of transported water which can be used to drive an electrical turbine for power generation.

1. Reversed electrodialysis (RED):

Reverse electrodialysis is another membrane-based technology for renewable energy generation from mixing two flows of water with different salt concentrations. The underlying principle involves the exchange of ions (anions and cations) in alternately stacked membranes between electrodes (anode and cathode), and the electrochemical reactions at the electrodes to release electric current. The spaces between the membranes are filled with two solutions in alternate successions – one with low salinity, and another with high salinity (Tamburini et al,. 2016; Tufa et al., 2018). This difference in salinity causes a potential difference across each stacked membrane, and this is known as a membrane potential. The summation of the membrane potentials is the overall electric potential difference across the outer electrodes, which drives electrons from the anode to the cathode via external circuit.

1. Hydrocratic energy:

Hydrocratic energy system is a non-membrane technology capable of generating electricity from the direct mixing of seawater and fresh water. The direct mixing produces a high volume and upward flow of brackish water, which is less saline than the seawater, but more saline than the fresh water. This flow drives a turbine to generate electricity.

## Adoption Path

### Current Adoption

The fact that MR technologies (except tidal barrage) are so early in development, coupled with the specific geographic locations where resource availability is high, it is no surprise that quite a small portion of global electricity generation comes WTE. Indeed, development of these technologies is limited to a handful of countries, which are also home to the large number of WTE companies, as shown in Figure 1.9. MRs are at various stages of development and testing and most of the deployment is likely to be in OECD countries.

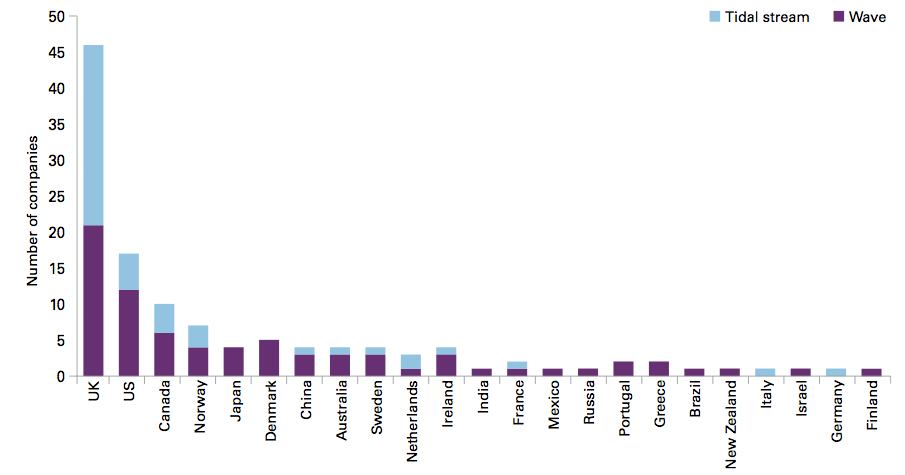


Figure 1.9 Wave and tidal companies by country (Source: The Carbon Trust, 2011)

The wave and tidal energy (WTE) technologies have a current adoption (2018) almost negligible of 1.06 terawatt-hours, representing about 0.004 percent of global electricity generated worldwide. The installed capacity of WTE in 2017 was around 529 MW (REN21, 2018) mainly from tidal power plants including Rance tidal power station (240MW) in France operated by EDF and Sihwa tidal power station (254 MW) in Korea operated by Korea water resources corporation (Tidal Giants - The World’s Five Biggest Tidal Power Plants, 2017). Wave converters (12 MW) and tidal stream (14 MW) contributed to the remaining installed capacity in the world (Mofor et. al, 2014). Figure 1.10 depicts the current WTE facilities and test centers. There are only four projects using WEC which are generating power for commercial use and these are listed in Table 1.1.

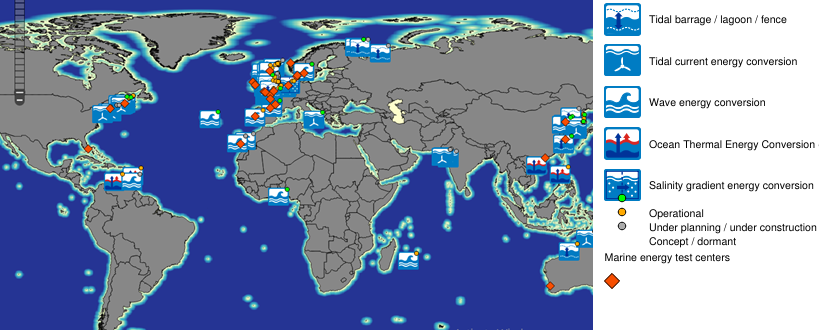


Figure 1.10 WTE project sites (Source: OES, 2017)

Table 1.1 Fully commercial WEC projects

|  |  |  |
| --- | --- | --- |
| **Name** | **Location** | **Capacity (MW)** |
| Pico Wave Power Plant | Azores, Portugal (Atlantic Ocean) | 0.4 |
| Mutriku Wave Energy Plant | Spain | 0.3 |
| Perth Wave Energy Project | Australia | 0.72 |
| Wave Pendulum | China | 0.03 |
| SINN Power's wave power plant | Greece | 0.02 |
| Fred. Olsen’s BOLT Lifesaver wave power plant (Demonstration) | USA | 0.03 |

WECs are still very much in their developmental stages. Akin to where the utility scale wind energy industry was in the 1980s before the three-blade horizontal axis design came to dominate the market, no single WEC design has yet taken hold. As such, most WEC projects are still in experimental stages and offer many opportunities for scientists and engineers to optimize WEC designs (IEA, 2013).

### Trends to Accelerate Adoption

While tidal barrage is commercially in operation since the last 50 years, tidal stream and wave energy converters have been deployed in actual working environment and are most likely to be scaled up for commercial deployment in the near future as these are at the later stages of technological readiness level. The technology readiness level for MRs is shown in Fig. 1.11.

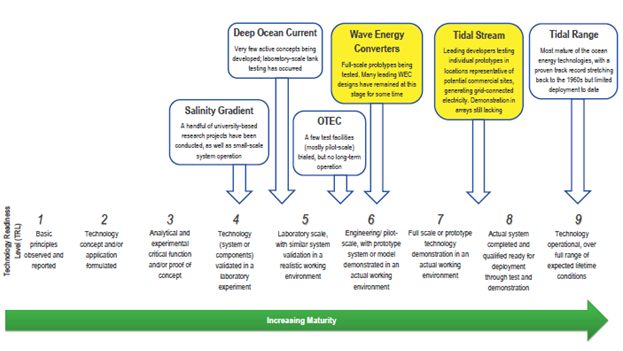


Figure 1.11 Technological Readiness Level (TRL) of ocean technologies (Source: Mofor et. al, 2014)

At the moment, there is no agreement on a universal design which is essential for scaling up the system and for large scale production. There is also a need for big commercial electricity companies to invest in the technology and to support the industry financially and technically. A carbon price on fossil fuels would also accelerate adoption of the technology and would fasten cost parity with conventional energy sources leading to faster realization ambitious adoption targets. Wave and tidal energy (WTE), arguably the most reliable and predictable form of renewable energy, is also currently the most expensive among other forms of renewable energy. Tides can be easily forecasted due to their regularity and the energy produced from waves is also predictable. Though critics like to espouse the infeasibility of WTE, industry experts forecast the growth in the deployment as comparable to the offshore wind sector (Ernst & Young, 2013). Improved learning rates, in combination with continual research, has the potential to drive down costs to a much lower level than the existing costs. In an optimistic and aggressive scenario, the trends may be similar to the adoption of onshore wind, though admittedly it will be harder, as doing things on land is much easier than in water. Co-benefits such as increased jobs, enhancing the coastal economy and protection of the marine environment need to be also emphasized in order to accelerate the global adoption of this solution.

### Barriers to Adoption

There are many challenges in the adoption of the WTE solution which can be divided into technical, financial and policy challenges. Technical challenges include installation of plants, scaling up of plants, maintenance of equipment at sea, transmission of electricity from sea to shore, power conditioning or electronics, capacity factor improvement, etc. High cost of the WTE technologies as compared to conventional as well as other renewable energy technologies is a major financial challenge. These challenges can be overcome provided there is consistent support from the government in setting up and meeting targets for installation of WTE. Since WTE is specific to just a few locations, incentivizing regional supply chains will help drive down overall cost. The role of ‘Energy Policy’ as an enabler for accelerating the adoption of the solution is vital. Policies for encouraging R&D and deployment of WTE such as Feed-in- tariffs, subsidies, tax breaks etc. can help to catalyze private investment in the sector. Stringent implementation of plans for deployment of set targets for renewable energy generation and strict adoption of GHG emission reduction targets would help accelerate the deployment of WTE. Environmental concerns also need to be overcome by undertaking detailed Environmental Impact Assessment (EIA) and by disseminating the findings of the results. Permissions for changing the use of coastal areas and related approvals may also be challenging, and lengthy.

Wave and Tidal energy industry suffers from some of the same hurdles of wind offshore technologies. Improved installation of offshore transmission lines and new developments with floating barges are just two of the areas that would benefit both industries. Given the propensity for funding wind energy projects, the challenges for WTE may be overcome indirectly through the offshore wind industry. Relatedly, the chicken-and-the egg problem of transmission line installations bedeviling wind energy also applies to WTE: specifically, transmission lines are needed to justify a wave or tidal energy project, but transmission operators aren’t inclined to build transmission lines to a site with no method of generating electricity. Wave and tidal energy resources are mostly located far from the shore where grid is located, and the implication is that undersea cables are needed to wheel the electricity to the grid. Once more established WTE technologies take hold and designs are finalized, specific economic incentives and related policies can be implemented. On the other hand, for tidal barrage plants the challenges are analogous to hydroelectricity projects.

Grid integration of tidal power plant presents less variability issues compared to solar and wind power plants because ocean tides are far more predictable than wind and solar. In other words, a combined output of well-planned tidal and wave power plants could meet baseload requirements and contribute to efficient grid operation.

### Adoption Potential

The resource potential[[2]](#footnote-2) of marine renewable energy (MRE) is estimated to be over 1,000,000 EJ/yr and is the largest after the potential of solar energy. However, the technical potential[[3]](#footnote-3) is much smaller and is estimated to be in the range of 3,240-10,500 EJ/yr. Compared to this, the world energy consumption of around 590 EJ in 2014, is a small fraction (IEA, 2016). MRE are also spread more uniformly across the globe and hence can be tapped into by various countries which are poor in hydrocarbon or wind/solar resources. Though, the potential for both wave and tidal resources are distinct. Figure 1.12 illustrates global tide resources to demonstrate the fairly uniform distribution of resources around the world. The optimal locations for tidal barrage are however dependent on the shape of the ocean bed or bathymetry, geography of the coastline as well as the geometry of the tidal basin. Tidal projects are currently concentrated in areas including the north coast of the United States, the western coast of the United Kingdom and the shoreline of South Korea.

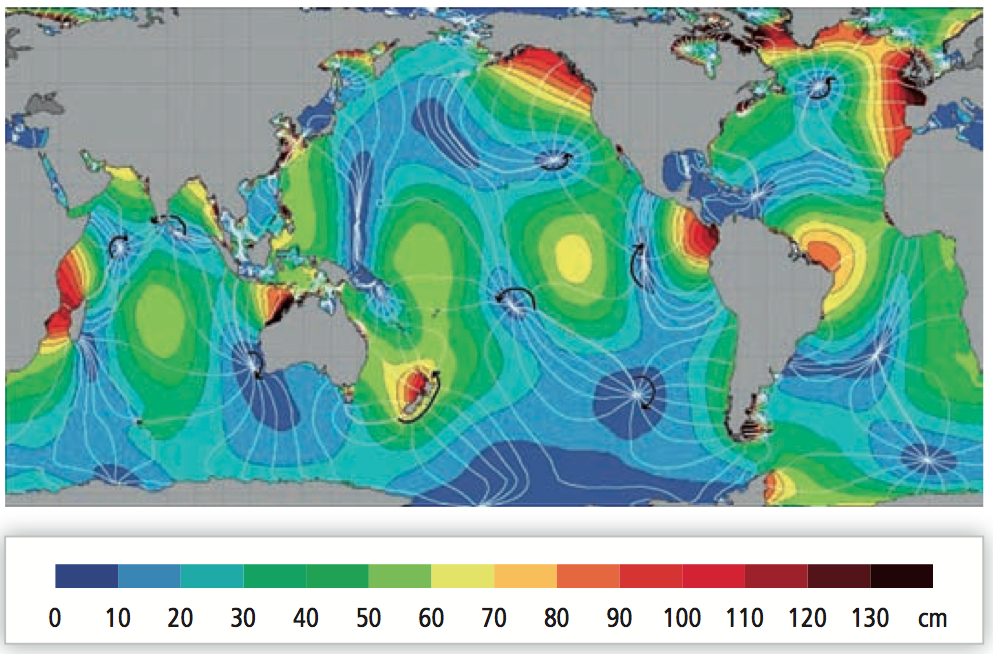


Figure 1.12 Global tidal resource (Source: Lewis et. al, 2011)

The electricity generated from WECs is proportional to the wave period and the square of the wave height. Hence, higher waves correlate to higher wave power. The resource map for wave energy is shown in Figure 1.13 and the darker shades of orange and red indicate high potential of MRs. As seen from the figure, wave energy potential is highest on the west coasts of the United Kingdom, France, Denmark, Spain and Portugal, the northwestern US, southwestern coasts of Chile and Australia apart from the Southern Ocean. Surface waves are generated from water wind interaction and higher wave heights are observed where there are strong winds variations. This corresponds to the band between 30 and 60 degrees’ latitude and near the southern latitudes where there are circumpolar storms (Spots of Potential for Wave Energy Harvest, 2017).

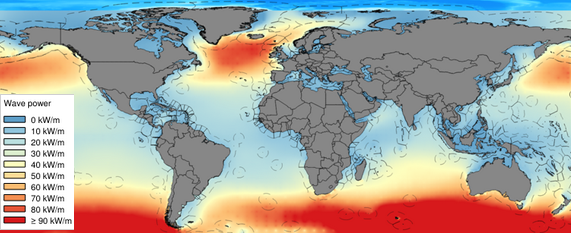


Figure 1.13 Wave energy resources (Source: OES, 2017)

Due to a lack of large-scale utility WTE projects, it is difficult to predict how the deployment would roll out beyond this decade. Forecasts for 2045 range between 15 and 188 GW of installed WTE, the latter being quite optimistic. The IEA ETP (2017) shows 2050 forecast of 31, 153, and 182 GW of installed capacity for reference, 2DS, and B2DS scenarios respectively corresponding to a generation of 97, 478, 566 TWh as shown in Figures 1.14 and 1.15.

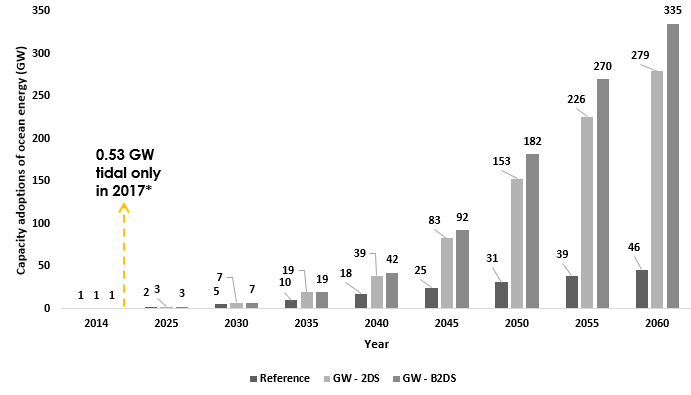


Figure 1.14 Ocean power capacity adoption in various scenarios (Adapted from IEA ETP, 2017, REN21, 2018\*)

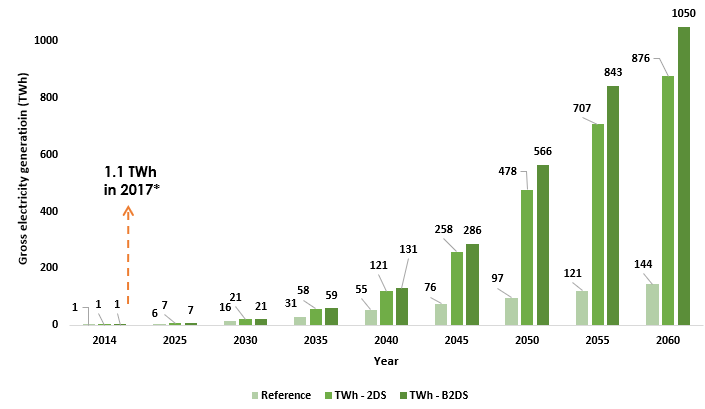


Figure 1.15 Ocean electricity generation in Ref., 2DS and B2DS scenarios (Adapted from IEA ETP, 2017; IEA, 2018\*)

## Advantages and disadvantages of Wave and Tidal Energy Technologies

### Similar Solutions

There are several solutions in the electricity generation sector that replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants, and that could be considered similar solutions. Herein, it is considered similar solutions to wave and tidal technologies the ones that use the same resource: i.e. ocean energy. Similar solutions for generating electricity from renewable ocean energy are OTEC, salinity gradients, tidal currents, and deep ocean currents but they are at relatively early stages of testing and are unlikely to be deployed commercially on a large scale in the near term. Some of the skepticism about the feasibility of wave/tidal energy emerges from the slow progress and the delay in commercialization of technologies. However, it is widely believed that ocean energy technologies are currently at its early stages of development. When seen in this perspective, the developments and the success of various pilot plants using different technologies gives confidence in the emergence of renewable ocean energy as a source of electricity by 2050. Other ocean energy technologies that are potentially similar solutions to wave and tidal power technologies have been discussed in sub-sections 1.1.2, 1.1.4, and 1.1.5.

### Arguments for Adoption

There are some common advantages of WTE systems. First and foremost, the largest (and most obvious) advantage of WTE is its low of GHG emissions in the range of 2 to 50 g CO2-eq/kWh depending on the technology, and whether tidal barrage with or without flood pumping. Generally, tidal barrage without flood pumping has the least carbon footprint, while the GHG emissions of tidal barrage with flood pumping is the higher than that of wave power plant. Second, these energy resources are renewable and do not face the risk of running out unlike fossilized energy resources like oil, gas and coal. The third main advantage is that these resources are widely spread out across the world. Compared to other forms of renewable energy, WTE (especially tidal barrage) is arguably the most predictable. This means that, assuming large enough adoption, WTE could be used together in combination with other renewable energy sources such as wind and solar to overcome intermittency constraints. WEC and tidal currents are also an ideal energy source for Small Island Developing States which have smaller land area but a large Exclusive Economic Zone (EEZ) which can be used to harness ocean energy. A major aesthetic advantage to WTE is that the devices are either partially or completely submerged, out of sight of the general public. Additionally, offshore and underwater installation means that operational noise associated with WTE is dissipated by the ocean. WTE require no additional water to generate electricity. Unlike thermal power plants which require large amount of water for cooling purposes, the only water required is in the manufacturing process. Deployment of MRs enhances coastal economy, provides opportunities for job creation and also contributes to the sustainability of oceans (EOEA, 2010).

### Additional Benefits and Burdens

Some of the common disadvantages of the WTE systems are that considering the present stage of technology readiness, there are only specific sites where WTE systems can be installed. These sites are restricted due to resource availability, geography of the shoreline, technical constraints and economic viability. Systems based on tidal currents and WEC include a high upfront cost due to additional requirement such as laying of underwater cables for transmission of electricity, construction of an offshore platform, additional cost of trained personnel for maintenance and operation etc. The equipment is inherently more difficult to maintain due to the harsh and corrosive nature of the sea and its environment. On the other hand, the main disadvantage for tidal barges is that a large land area is flooded leading to loss of land. Areas where WTE systems are employed have to be cordoned off for shipping, fishing and other uses. Specifically, in the case of tidal barrages, movement of large marine animals and ships through the channels on which the barrage is built is disrupted apart from the risk of destruction of an ecosystem that relies on the ebb and flow of tide, especially during the construction phase (Meisen and Loiseau, 2009).

Due to the limited number of WTE installations, ecological impacts of these systems are still not well understood. The best assessment is based on the RTS where it has been observed that certain species of eels and fish have disappeared from the area, but other species that seemed to have vanished, namely sea bass and cuttlefish, have returned (de Laleu, 2009). Other studies have shown that turbines associated with tidal barrage systems pose little threat to dolphins, whales and sharks (Lewis et.al., 2011). However, planners must be especially vigilant when siting the plant and in monitoring the ecological impacts of WTE systems. Relatedly, care must be taken to avoid heavily trafficked shipping and boating routes and other ecologically sensitive areas for deployment of WTE systems.

It is also noted that the installation for WEC and tidal stream are subject to a corrosive marine environment and physical stresses which makes them susceptible to frequent breakdown. On the other hand, equipment used in tidal barrages are relatively less exposed to the harsh element of the sea. As compared to wind (including offshore) and solar (both PV and CSP) the cost of WTE is relatively high which is one of the reasons of poor adoption of these technologies. Scaling up of WTE technologies is also difficult and some more R&D is required for overcoming technical challenges. The fall in cost of fossil fuels has also resulted in a lack of interest in deployment of WTE. Lastly it has been observed that the targets for adoption have not been met by governments due to various reasons over the past few years and forecasts for the deployment have been revised downwards over the years by the International Energy Agency. Table 1.2. presents a comparison of selected pros and cons of the solution with others in the same sector and with the same energy source.

Table 1.2 WTE and other RES solutions comparison to conventional electricity generation technologies

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Parameter | Conventional  electricity generation technologies | Ocean thermal energy converters | Salinity gradient  energy converters | Tidal currents technologies | Ocean currents technologies | Wind (Offshore) technologies |
| *Land Area Requirement* | Very high | High | High | High | High | High |
| *Water Requirement* | Very high | Nil | Low | Nil | Nil | Nil |
| *Visual Disamenity* | Very high | Low | Low | Low | Low | Low |
| *GHG*  *Emissions* | Very high | Very low | Very low | Very low | Very low | Low |
| *Electricity Generation Flexibility* | Very high | High | High | High | High | Low |
| *Grid Balancing Requirement* | Nil | Unknown | Unknown | Unknown | Unknown | High |
| *Operation and Maintenance* | Very high | Very high | Very high | Very high | Very high | High |
| *System integration cost* | Medium | Very high | Very high | Very high | Very high | Very high |
| *Deployment Costs* | Medium | Very high | Very high | Very high | Very high | High |

# Methodology

## Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for replacement of conventional electricity generation technologies (i.e. coal, oil, natural gas) and related emissions for an alternative solution (see the Drawdown RRS Model Framework and Guide for more details). These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units (TWh), and for investment costing, adoptions are also converted to implementation units (TW). The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2050 and the comparison of these scenarios (for the 2020-2050 segment) is what constitutes the results.

For this solution, the approach was to analyze the impacts of increased adoption of wave and tidal power systems. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for WTE. Following project Drawdown methodological assumption (further description available on the Drawdown RRS Model Framework and Guide), in order to grasp the total impact of an increased adoption of the solution during the assessed time frame; the REF scenario assumes future adoption of WTE remains fixed at the current adoption (i.e. 2018) percentage of Total Addressable Market (TAM), estimated at 0.04 percent (1.06 terawatt-hours) of electricity generation. The TAM for this solution is based on the common project Drawdown projected global electricity generation in terawatt-hours till 2050 (Section 2.3.).

The developed alternative PDS scenarios, draw on existing adoption scenarios for WTE to model several alternative adoptions. The RRS model contains both financial and climate analyses in order to model the global and regional impacts of adoption in the PDS scenarios compared to the REF scenario. What the model thus prognosticates is the total financial costs and benefits of adoption cases for wave and tidal power, as well as the contribution this adoption can make to annual and cumulative emissions reduction.

## Data Sources

This section presents key data sources utilized in the mode to evaluate the adoption of Wave and Tidal power technologies. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, it was done a variable meta-analysis of existing literature to create low, high, and mean estimates. For each solution variable, it is conducted a sensitivity analysis of, on average, 14 data points reported in the literature and in some cases as many as 21. This allows to calculate robust and reliable inputs for the financial, technological and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

The previously used scenarios for 2017 book results considered two sources of data with a total of six (6) scenarios, namely: IEA ETP 2016 (3 scenarios); and Greenpeace 2015 (3 scenarios). The newly collected sources of data were three with a total of seven (7) scenarios including IEA (2017) Energy Technology Perspective (Reference Technology, 2 Degrees, and Beyond 2 Degrees scenarios); IEA (2018) World Energy Outlook (Current Policy, New Policy, and Sustainable Development scenarios); and Ecofys. (2018) 100% Renewable Energy scenario. These sources present data for ocean energy without specific reference to the type of technologies considered. However, it is expected that the generation data are mainly for tidal power plants which is the dominant ocean technologies in operations globally, and some wave power plants.

Recent capital cost estimates from several data sources, presenting data for all of the regions contained in this analysis were examined to determine the average capital cost of wave and tidal power installations (e.g. WEC, 2013; JRC, 2013; JRC 2014; Astariz *et al*., 2015; MacGillivray *et al*, 2014; Greaves & Iglesias, 2018; Zeyringer et al, 2018; Dincer *et al*, 2018; PMSS, 2010; de Andres et al, 2017; Tsiropoulos et al, 2018; Quitoras et al, 2018; Segura *et a*l, 2018; etc.). Investment costs for wave or tidal systems can vary significantly by region and by technology type as shown by the cost data available for the world, the UK, France, etc.

Learning rates for both waves and tidal technologies are expected to continue to reduce costs, making the technologies more competitive and ultimately cheaper than conventional sources. Information for learning rates of these technologies was retrieved from Lewis et al. (2011); Hayward and Graham (2013); JRC (2014); Tsiropoulos et al (2018); Zeyringer et al (2018); MacGillivray (2016); Vazquez & Iglesias (2016); and Radfar et al (2017).

Cost estimates for fixed and variable operation and maintenance (O&M) of wave and tidal were collected from e.g. IPCC, 2011; Bloomberg, 2013; UKERC, 2014; Greaves & Iglesias, 2018; Radfar *et al*, 2017; Tsiropoulos et al, 2018; Zeyringer et al, 2018; Vazquez & Iglesias, 2016; Quitoras *et al*, 2018; and Segura *et al*, 2018). These estimates were used to calculate total operating costs of ocean energy adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PD scenarios. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for both coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

The lifetime of wave and tidal technologies remains uncertain due to the relatively few projects in the market. Data was collected from *e.g.* IPCC (2011), IEA (2014), JRC (2014); Thomson (2014); MacGillivray *et al* (2014); Chang et al (2018); Zeyringer *et al* (2018); Dincer *et al* (2018); PMSS (2010); de Andres *et al* (2017); Tsiropoulos et al (2018); and Radfar *et al* (2017) ranging from 18 to 50 years.

In order to compare capital and O&M costs of WTE systems adoption in the PD scenarios to that of conventional generation technologies, it was obtained cost data for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which conducted its own sensitivity analysis of a number of sources from the literature[[4]](#footnote-4), and other sources such as OECD (2015), Lazard (2016). In all variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average. The weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

To calculate the total impacts and benefits of increased solution adoption (on PDS scenarios), technical data was also integrated, including average annual use, plants lifetime, and average efficiencies. All three of these are key to determining the variable OM costs and the total fuel costs for conventional generation sources, as these costs are determined by the average number of hours the power plant is generating electricity, as well as the average price of fuel inputs and the average efficiency rate. Average plants efficiency is calculated from several global sources (IPCC, 2014; IEA, 2010), as well as from the U.S. EIA (2015).

Average annual use of conventional generating technologies is higher than that of wave and tidal energy, the range of capacity factors for different conventional generating sources can still vary based on type of technology and location. For this reason, data was collected from a range of different sources (EIA, 2016; IEA, 2016b; Lazard, 2016) that represent most of the regions contained in this analysis.

The model’s analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with WTE plants. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines. In order to account for indirect emissions from conventional technologies and WTE systems—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities—it were analyzed a range of peer-reviewed lifecycle analysis (LCA) studies for the different types of technologies available in the market (e.g. Masanet et *al*., 2013; POST, 2011; Walker and Howell, 2011; and Uihlein; 2016; JRC, 2014; Thomson, 2014; and Dincer *et al*, 2018) ranging from 2–56 gCO2/kWh.

## Total Addressable Market

Solutions assessed in the Electricity Generation Sector share a common market for future adoption defined by the total terawatt-hours (TWh) of generation demanded from 2015-2060. This shared total addressable market (TAM) is used to bound this sector technologies rollout over time. The TAM is determined based on the assessment of estimations of current and future electricity generation from a combination of models and scenarios from different sources, including Greenpeace (2015); International Energy Agency (IEA) - Energy Technology Perspectives (IEA, 2017); IEA World Energy Outlook (WEO) (IEA, 2018); Equinor (2018); Ecofys (2018); The Institute of Energy Economics Japan (IEEJ) Outlook 2019 (2018) and Ram *et al.* (2019). See Project Drawdown report - Assessing the Total Addressable Market and Major Assumptions for more details on the methodology used to develop the electricity TAM. The updated 2019 study follows the same methodological approach with the inclusion of newer sources.

Four prognostications of the TAM for this assessment were derived by using comparable scenarios from each of the above-mentioned sources which were categorized by expected climate mitigation scenarios (i.e. Ambitious, Conservative, and Baseline) and the scale of deployment of renewable energy sources (RES) (i.e. 100% RES scenarios). The sources used mostly provide results at a decadal level, which were interpolated to provide annual values for Project Drawdown calculations.

The Ambitious Project Drawdown TAM Scenario is constructed from the average of yearly values of four scenarios: the IEA (2017) 2D Scenario, the IEA (2017) B2D scenario, Renewal Scenario from Equinor (2018), and IEA (2018) WEO SD scenario. The Conservative Project Drawdown TAM Scenario follows the average yearly values of the IEA (2018) WEO New Policy scenario (NPS); Reform Scenario from Equinor. (2018), IEEJ Outlook (2018) Advanced Tech scenario, and IRENA (2019b) Roadmap 2050 REmap case. The Baseline Project Drawdown TAM Scenario is built by the average of the Equinor (2018) Rivalry Scenario, IEEJ Outlook (2018) Reference Scenario, IEA (2017) Reference Case and IEA (2018) WEO Current polices Scenario (CPS). These three Project Drawdown TAM scenarios show an estimated range of electricity generation from 45,286TWh to 49,706TWh by 2050. Baseline TAM is used for PD Plausible scenario assessment.

An ambitious TAM scenario for a 100% RES by 2050, which is aligned to project Drawdown Optimum and Drawdown scenarios, utilizes the Greenpeace (2015) Advanced [R]evolution Scenario, Ram et al (2019) analysis and Ecofys (2018) 1.5ºC degree scenario were considered. The estimated electricity generation for this TAM reaches 70,942 TWh by 2050.

## Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

### Reference Case / Current Adoption

For the Reference (REF), adoption is fixed at the current adoption[[5]](#footnote-5) (in percent) of the market. That is, the current percentage of total electricity generation (TWh) provided by Wave and Tidal systems constant throughout the study period to 2050. As the market grows, the total number of WTE plants adopted grows equally to maintain the percent adoption at its starting value in 2014. It is acknowledged that this, in reality, may not be a “business as usual” considering changes taking place worldwide, but it allows measurement of the impact of recent and even more aggressive policies on greenhouse gas emissions.

### Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

#### Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For wave and tidal technologies, this scenario is based on the evaluation of yearly averages of four optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Energy [R]evolution Scenario from Greenpeace (2015); using a medium growth trajectory.

#### Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). For wave and tidal systems, this scenario uses the same sources as the Plausible, being based on the yearly average values of IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Energy [R]evolution Scenario from Greenpeace (2015); though using a high growth trajectory.

#### Optimum Scenario

This scenario represents the most optimistic case, in which clean, renewable energy solutions such as wind, solar, and other renewable energy sources capture 100% of electricity generation by 2050, with both fossil fuels and transitional solutions fully phasing out by 2050. This scenario for wave and tidal systems is based on the yearly average values of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram *et al.* (2019) scenario and Ecofys (2018) 1.5ºC scenario.

## Inputs

### Climate Inputs

In order to calculate the climate impacts of the project Drawdown scenarios, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, it was estimated WTE electricity generation globally and regionally from 2020-2050 and then calculated the emissions reductions due to the replacement of conventional electricity generation sources with the solution. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

While being a renewable energy technology, wave and tidal energy plants do not have direct emissions related to combustion of fuels. Project Drawdown modeling considers the analysis of indirect emissions related to the different factors that contribute to a LCA for WTE systems. In modeling the lifecycle emissions of Wave and Tidal adoption in the scenarios, it is used a fixed value (t CO2-eq per TWh) considering information from several WTE technologies rather than a decreasing one due to the difficulty of projecting future grid-tied emissions on a regional basis. The climate results will thus be more conservative than would be the case if it was assumed a decreasing average lifecycle emissions value for WTE systems.

The values collected in the RRS model show lifecycle GHG emissions for a range of different WTE technologies across different regions, technologies and system sizes. The analysis draws from recent published GHG emission estimates for WTE that have ranged from 1.8 to 53 g CO2eq/kWh over their lifetime. The wide span in results for WTE reflects different assumptions around capacity factor, conversion efficiency, operating lifetime and technology. Table 2.1 presents the boundaries of the data boundaries on the model and the selected model input.

Table 2.1 Climate Inputs

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Indirect CO2 Emissions (Solution) | *t CO2-eq/TWh* | 5,148 – 34,830 | 19,989 | 28 | 9 |

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[6]](#footnote-6).

### Financial Inputs

RRS model constructs PDS adoption scenarios for wave and tidal electricity generation globally and regionally for each year until 2050. It is modelled both the capital costs and the fixed and variable OM costs associated with the alternative scenarios compared to those of the REF scenario. A detailed description of the methodology used is available in the Drawdown RRS Model Framework and Guide.

The financial calculations examine the first cost in US$ per kW and the operating cost in US$ per kW (fixed costs) and US$ per kWh (variable costs). For this, many inputs estimating annual output and lifetime output per WTE electricity generation, along with first costs (per functional unit), were calculated. A lifetime capacity of 68,901hours (around 23 years) was calculated depending on the average powerplant annual use. Estimates in the literature presented for the learning rate of WTE systems vary, ranging from 6% (Vazquez & Iglesias, 2016) to 20% (Zeyringer et al., 2018). Another example from Lewis et al. (2011) that assumes that as a first-order estimate, ocean energy industries (except tidal range, which is already comparatively mature) could follow an 11% learning curve.

For the solution (i.e. WTE), the conventional current mix of fossil fuel electricity generation technologies (coal, gas, and oil) replaced were identified. Costs and operation for both generation technologies (solution and conventional) were considered to obtain the differential result.

A mean value of the data set range collected is assumed for installation costs of WTE systems which results in a total first cost of US$11,631 per kilowatt[[7]](#footnote-7). A first cost learning rate of 11.8 percent was considered; and this has the effect of reducing the installation cost to US$4,181per kilowatt in 2030 and to US$3,006 in 2050, compared to US$1,786 per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants). Additionally, a net present value discount rate is fixed at 9.68 percent appropriate for utility-scale projects and use across all Drawdown electricity generation solutions with this level of agency.

Fuel prices for conventional technologies are derived from IEA (2019) data, averaging 2007-2018 historical registries for oil, coal and natural gas used for electricity generation and calculated through a weighted average by fuel from the current electricity generation mix. Tables 2.2. and 2.3 depict the dataset ranges and the model inputs for the conventional and solution technologies.

Table 2.2 Financial Inputs for Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Conventional) | *US$2014/kW* | 470.5 – 3,101 | 1,786 | 24 | 8 |
| Fixed Operation and Maintenance Costs (Conventional) | *US$2014/kW* | 3.44 – 65.86 | 32.95 | 18 | 4 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/kWh* | 0.0014 – 0.0079 | 0.0048 | 22 | 7 |
| Fuel Price (Conventional) | *US$2014/kWh* |  | 0.0492 |  | 1 |
| Learning Rate Factor (Conventional) | % |  | 2.00% |  |  |

Table 2.3 Financial Inputs for Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Solution) | *US$2014/kW* | 2,112 – 21,150 | 11,631 | 71 | 18 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 93.49 – 562.73 | 328.11 | 18 | 9 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* | 0.038 – 0.102 | 0.07 | 23 | 7 |
| Learning Rate Factor (Solution) | % | 7.4 – 16.2% | 11.80% | 30 | 9 |

### Technical Inputs

Table 2.4 Technical Inputs Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Conventional) | *hours* | 121,807 – 222,351 | 172,079 | 12 | 6 |
| Average Annual Use (Conventional) | *hours* | 3,337– 6,587 | 4,962 | 23 | 4 |

Table 2.5 Technical Inputs Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Solution) | *hours* | 53,068 – 84,736 | 68,901 | 24 | 15 |
| Average Annual Use (Solution) | *hours* | 1,469 – 4,511 | 2,990 | 37 | 14 |

## Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology are available on the Project Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide report. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. No distinction was applied to wave or tidal technologies adoption, neither to different type of more specific technologies due to the very mature nature of these technologies and the high uncertainty of the future market development.
2. The adoption data from the different sources are usually given on interval of 5 to 10 years. To achieve data completeness for the years within the gap, data interpolation was performed using the best fit model amongst 1st, 2nd, and 3rd polynomials. In cases where there are spikes, stepwise interpolation with one or more of the outlier datapoint(s) removed are performed to smooth out the trend, and complete the data for the missing years.
3. First costs, O&M costs, and other variables in the VMA sheet for all the six ocean energy technologies are averaged together even though they show some differences. In future, this assumption could be tested by using the data points for a technology, say OTEC or Tidal only, and compared with others. Splitting may be potentially feasible for WEC, and Tidal barrages while other ocean energy technologies remains in R&D, and demonstration stage.

## Integration

The complete Project Drawdown integration documentation with details on how all solution models in each sector are integrated, and how sectors are integrated to form a complete system will be available at [www.drawdown.org](http://www.drawdown.org). Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Therefore, the data derived from individual solutions models was then inputted into sector-level integration models to generate final results for all solutions within a global system. The links between this sector and all the others is important, but major interactions occur with energy demand-side sectors like Transport and Buildings and Cities.

Through the process of integrating wave and tidal power with other solutions, the total addressable market for electricity generation technologies was adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies (for example LED lighting and heat pumps) as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

## Limitations / Further Developments

The RRS model assumes equal weighting to all three considered technologies, wave, tidal barrage and tidal stream. From a cost perspective and a scaling perspective, this may not be accurate as it a non-homogeneous mix of technologies and hence may be subject to questioning. Technologies that are modular (e.g. wave) show one mechanism to scaling similar to wind, where the resource is defined by zones. But tidal barrage (and to some degree tidal streams) are very dependent on localized bathymetry and would follow a scalability pathway that is limited by these resources and the environmental impacts (more similar to hydro power plants). Additionally, modular technologies enjoy deeper cost reductions due to scale of production than site-specific installations, where the cost of installation is driven by engineering and installation costs, not equipment costs. Hence clubbing the three technologies which have different dynamics may not be accurate and use of equal weighting and simple averaging may introduce some errors in the overall results.

The estimate of global adoption of the solution is strictly limited by the availability of data on the forecasts of deployment of WTE over the next few decades. While estimates till 2020 predict a likely deployment of around 2 TWh of electricity generated from the adopted solution, this is subject to actual deployment of plants at sea. Further developments such as reduction in cost, beyond the learning rate of 11.8% is likely, provided the commercial scale deployment of WTE increases significantly.

# Results

In the following section are depicted selected results for a thirty year time period (2020-2050) derived from the RRS model evaluating the impact of increased adoption of Wave and Tidal Power technologies for electricity generation when compared to the use of conventional technologies.

## Adoption

Comparing the results from the three modeled scenarios to the Reference Scenario allow to estimate the climate and financial impacts of increased adoption of WTE systems. The Plausible Scenario (PDS1) projects 0.79 percent of total electricity generation worldwide coming from wave and tidal systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share reaches 0.74 percent and 2.49 percent, respectively. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of WTE plants.

Table 3.1 World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| Wave and Tidal Energy (WTE) | *Electricity Generation (TWh)* | 0.954 | 398 | 522 | 1,769 |
| *(% market)* | 0.0042% | 0.87% | 0.74% | 2.5% |

Figure 3.1 World Annual Adoption 2015-2060

## Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6). The Plausible Scenario results in the avoidance of 1.6 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of WTE technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 2.05 and 10.58 gigatons of carbon dioxide-equivalent, respectively. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table 3.2 Climate Impacts

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.19 | 1.61 | 0.19 |
| ***Drawdown*** | 0.25 | 2.05 | 0.25 |
| ***Optimum*** | 0.86 | 10.66 | 0.86 |

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on emission reduction for this solution is 1.41 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 1.38 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 8.88 gigatons of carbon dioxide-equivalent for the *Optimum* Scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq

|  |  |  |
| --- | --- | --- |
| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 0.15 | 0.02 |
| **Drawdown** | 0.19 | 0.02 |
| **Optimum** | 0.93 | 0.07 |

Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction 2015-2060

## Financial Impacts

The financial impacts incurred by replacing conventional grid electricity sources with WTE systems are significant. Plausible scenario presents US$407 billion in marginal first costs and negative US$381 billions of net operating cost savings are projected over the same period. PDS2 (i.e. Drawdown) depicts near US$528 billions of marginal first costs and -488 billions of net operating saving; while PDS3 considers higher capital difference, with US$880 billions of marginal first costs and -488 billions of net operating saving of 2.48 trillion.

The capital costs for PDS adoption of WTE systems will require significant investments, as the cumulative capital costs are just over US$560 billion under the Plausible Scenario, near US$735 billion for PDS2 and over US$1533 under PDS3. The learning rate used in this analysis lead to a continued decrease in the capital costs of WTE systems till 2050. These projected decreases in the capital costs of WTE systems are in line with most projections for future costs. Below in Table 3.4 are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

Table 3.4 Financial Impacts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 351 | 201.6 | -381 | -60 |
| **Drawdown** | 460 | 261.4 | -488 | -76 |
| **Optimum** | 970 | 327.3 | -2,483 | -337 |

# Discussion

Given the relative immaturity of the WTE industry, it is difficult to predict how it will develop over the next three decades. The uncertainty increases considering the small percentage of WTE currently in the global electricity mix and the range of technologies under testing. The assumptions made in this analysis, corroborated by other studies, provide an optimistic, albeit conservative, forecast for global adoption of WTE. Because WTE is localized to just a few places, region wise forecasts were omitted from this analysis.

The fact that there are only a couple of utility scale tidal barrage stations indicates that the deployment may need a big push from governments. While, the Rance Tidal Station has proven the viability of utility-scale tidal barrage stations and has been in operation since the 1960’s the next tidal station was installed off the coast of South Korea only in 2011. This is due to the massive upfront capital costs, requirement of large area of land and environmental concerns of building such a system. The RTS was built in 1966 and only a few years ago, did it finally finish “paying for itself” and now provides electricity at a cost on par with France’s fleet of nuclear power stations. However, developments indicate that many tidal power stations have been stuck on the drawing board for decades and there is unlikely to be a revival in their fortunes.

Conversely, wave energy’s relative immaturity, coupled with the much shorter timescale on which it operates, is more akin to the early wind energy industry. Once engineers and scientists settle on a design, the market will converge, prompting true competition and further adoption. The current situation with a smattering of WEC designs (not to mention the lack of any widespread utility-scale WEC system in place anywhere) means that development and installation has not yet actually begun.

While WTE is, and will continue to be a small percentage of the total world’s electricity generation, it may not be a significant solution for Drawdown. Considering the large potential which MRs provide, it can be a major contributor to electricity generation, provided the limitations are overcome. The GHG reduction can however become significant provided there is a fall in the prices due to an ambitious learning rate, which may lead to a reasonably optimistic adoption percentage of the solution.

It is obvious from the resource characteristics that ocean energy is a remote type of resource, and therefore future plans to integrate electricity generation from ocean into the grid will face transmissions challenges, as well as identification of effective power purchase agreement to de-risk investment in ocean energy. Although, literature on power purchase agreement related to ocean energy off-take are sparse, it is generally expected to follow the PPA attributes for geothermal or offshore wind power. Therefore, a financial or virtual power purchase agreement which does not require both the independent power producer and the buyer to be located in the same grid region is most likely a suitable option (EPA, 2016).

## Limitations

As seen, the accelerated installation of new wave and tidal capacity will not be without challenges and the competition with other RES technologies will be high. There will be economic, policy, and social hurdles to overcome on the pathway set out in the Drawdown scenarios, and some of these will require significant changes to the way electricity is bought, sold and used. But given the potentially high climate impacts of global wave and tidal adoption, it is paramount that these challenges are taken, in order to realize the benefits.

This research does not look at the aspects of impacts on marine life, and environmental and social safeguards of tidal and wave power plant which is one of the major sustainability standard requirements for most lenders like the development finance institutions (DFIs). Consideration of ESS may affect variables such as the level of investment, and in-turn the adoption of tidal and wave energy.

## Benchmarks

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to other five publicly available scenarios from IEA (2016, 2017, 2018), Greenpeace (2015) and Ecofys (2018) . The benchmarked results account for ocean energy electricity generation. PDS1 and PDS2 compare similarly to IEA (2017) 2DS and B2DS, while PDS3 is closer to higher adoption scenarios of 100% RES generation, where a more diversified technological portfolio is needed, with waves and tidal having a more important role.

Table 4.1 Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation in 2050 (TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **398** | **0.9%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **522** | **0.7%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **1,769** | **2.5%** |
| IEA Energy Technologies Perspectives (2016) – 6DS | 104 | 0.2% |
| IEA Energy Technologies Perspectives (2016) – 4DS | 162 | 0.4% |
| IEA Energy Technologies Perspectives (2016) – 2DS | 594 | 1.4% |
| Greenpeace Energy [R]evolution (2015) – Reference Scenario | 76 | 0.2% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario | 1,482 | 3.0% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario | 2,010 | 3.0% |
| IEA World Energy Outlook (2018) – Current Policy Scenario | 73 | 0.1% |
| IEA World Energy Outlook (2018) – New Policy Scenario | 143 | 0.3% |
| IEA World Energy Outlook (2018) – Sustainable Development Scenario | 226 | 0.5% |
| IEA Energy Technologies Perspectives (2017) – Reference Technology Scenario | 97 | 0.2% |
| IEA Energy Technologies Perspectives (2017) – 2DS | 447 | 1.1% |
| IEA Energy Technologies Perspectives (2017) – B2DS | 519 | 1.2% |
| Ecofys (2018) – 100% RE | 1528 | 2.2% |

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# Glossary

**Adoption Scenario** – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in the use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate the high growth of the solution.

**Approximate PPM Equivalent** – the reduction in the atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

**Average Abatement Cost** – the ratio of the present value of the solution (**Net** **Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario** and is used to build the characteristic “*Marginal Abatement Cost*” curves when Average Abatement Cost values for each solution are ordered and graphed.

**Average Annual Use** – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, the total number of passenger-km driven by a hybrid vehicle in a year depends on the country and the typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

**Cumulative First Cost** – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Direct Emissions** – emissions caused by the operation of the solution, which are typically caused by the lifetime use of the solution. They should be entered into the model normalized per functional unit.

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account, not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

**First Cost**- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

**Functional Unit** – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high-speed rail provides billions of passenger-km of mobility.

**Grid Emissions** – emissions caused by the use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

**Implementation Unit** – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV’s in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

**Indirect Emissions** – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service is provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a good drops by 2% every time total production doubles.

**Lifetime Capacity** – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

**Lifetime Operating Savings**–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

**Lifetime Cashflow NPV**-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

**Marginal First Cost** – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

**Net Annual Functional Units (NAFU)** – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

**Net Annual Implementation Units (NAIU)** – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

**Net Operating Savings** – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

**Operating Costs** – the average cost to ensure the operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

**Payback Period** – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

**PDS/ Project Drawdown Scenario** – this is the high growth scenario for the adoption of the solution.

**PPB/ Parts per Billion** – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

**PPM/ Parts per Million** – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

**REF/ Reference Scenario** – this is the low growth scenario for the adoption of the solution against which all **PDS scenarios** are compared.

**Replacement Time**- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

**TAM/ Total Addressable Market** – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents the world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of the grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

**Transition solutions** - are considered till better technologies and less impactful are more cost-effective and mature.

**TWh/ Terawatt-hour** – A unit of energy equal to 1 billion kilowatt-hours.

1. This is the fully depreciated, debt-free cost [↑](#footnote-ref-1)
2. Resource potential is the theoretical physical potential of the energy content of the resource. [↑](#footnote-ref-2)
3. Technical potential is smaller than resource potential as it takes into account topographic, land use and system performance constraints. [↑](#footnote-ref-3)
4. The IPCC’s 5th Assessment Report analyzes the following sources: Coal: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013). Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011), IEA (2013a), IEA-RETD (2013), Schmidt *et al.* (2012), US EIA (2013). [↑](#footnote-ref-4)
5. Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated [↑](#footnote-ref-5)
6. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-6)
7. All monetary values are presented in US$2014 [↑](#footnote-ref-7)