Ocean Power Generating Technologies - a Vast Renewable Energy Potential

By Dr. Jutta Lauf, Dr. Reiner Zimmermann, Wsewolod Rusow

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Electric power generation is taking an ever-growing share of the global energy consumption of industry, private households and even the military. Modern societies rely increasingly on stable and secure electric power supplies, with a trend to non-fossil, renewable energy sources.

This article explores the ocean's vastly untapped power production potential, the physical and chemical energy forms as well as the conversion principles and technologies used. Some ocean power generation technologies have already been exploited for decades and, in one case, centuries, with well-established technologies. Others are currently in developing states or exist as prototypes only.

This article explains relevant technical terms followed by a technical discussion of the most intuitive technologies which harness the potential and kinetic energy of the tides and waves. Then the vast thermal energy of tropical oceans for producing electricity will be discussed, as well as the technologies using spatial water salinity gradients.

CHARACTERISTICS OF NON-RENEWABLE AND RENEWABLE ELECTRICITY TECHNOLOGIES

For conventional power plants a constant fuel supply is crucial for their production capabilities. The supply and transport chains for non-renewable sources like fossil fuels and uranium are well established and technically mature. Fluctuations in production, market availability, transport and pricing are mainly due to geostrategic changes and political decisions. For conventional renewable energy sources for electric power production, a comparably reliable and continuous supply is only given for geothermal power plants as the conductive thermal heat is provided by the physical processes in the earth's core.

Power generation from renewable energy sources other than geothermal – like from solar radiation, movement of air masses (i.e. wind) or rivers (gravitational hydropower) - is volatile and not fully controllable. However, for ensuring a demand driven and reliable electric power production by renewable technologies, energy supply forecasts

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for short-term (days to weeks) and long-term (months to years) availability are crucial. Hourly forecasts for wind speed, solar radiation and precipitation are available for a few days only. Battery storage options of large amounts of electricity during periods of oversupply are extremely expensive and are currently not feasible. In contrast, long-term predictions for tides, sea temperatures and salinity concentrations – which drive ocean technologies described in this article - are available and reliable from a local to a global scale.

If the energy supply can only be forecasted in a short-term scenario (solar, wind, hydro) the power generation technology is termed un-predictable. If forecasts are available on a long-term basis, the technology is termed predictable. Long-term predictability of renewable power production is sometimes considered as good as for conventional power plants. This classification directly leads to the more commonly used concept of the controllability of a power plant. Controllability is given when a plant can make use of its full capacity within its respective reaction time. This is only possible, when sufficient energy for power generation is constantly available.

The limited predictability of wind speed and solar radiation in combination with lacking storage capacities render electricity production from wind turbines, photovoltaics (PV) or concentration solar power (CSP) an inflexible power source. In contrast, the power production from CSP plants with thermal energy storage (CSP-TES) or hydropower dams with pumped hydropower is a controllable and flexible energy source due to the inherent energy storage capacity lasting from hours to a few days. This allows the control of electric power production on demand (Table 1).(Lauf et al. 2021; Lauf and Zimmerman 2023)

In industrial regions outside of the global Sunbelt it is currently not possible to cover the high electricity demand with renewable energy sources, while within the global Sunbelt calculations by Benitez et al. 2021 (IRENA 2020) have shown that this task can be achieved by installing CSP-TES plants (Lauf et al. 2021). Outside the global Sunbelt the use of ocean power may contribute to establish fully renewable electricity supply systems. The potentials of electric power production from the oceans will be discussed in the following.

THE ELECTRIC POWER PRODUCTION POTENTIAL OF THE OCEANS

The current electric power production from saltwater resources, often called "ocean power", is very small with respect to the global electric power production. The current globally installed electricity production capacity across all ocean power technologies is relatively small and represents only about 0.5% of the worldwide installed electric capacity (Figure 1).

The energy content of the ocean is sourced by (a) the gravitational influence of the moon causing tidal movements, (b) wind action which injects potential and kinetic energy into the water, (c) radiation from the sun which increases the thermal energy content and (d) the influx of ions (salts) from freshwater systems which increases the chemical energy of the water. All these energy sources are large and predictable over time, though not always on longer timescales e.g. months. Thus, covering high electricity demands from renewable ocean energy sources appears to be possible. Tidal range or stream power is using (a), Wave power is using (b) and to a lesser extent (a), Ocean Thermal Energy Conversion is using (c), Salinity gradient power is using (d).

The global electric power production is still dominated by fossil fuels. Nuclear energy capacity is small, by definition non-renewable and may have limited future expansion potential due to environmental and supply concerns. Global renewable electric power capacity is currently dominated by solar, wind and hydropower technologies. Biomass energy contribution is small and faces limited expansion potential due to the food vs. fuel competition, amongst other reasons. Geothermal power generation

Table 1: Production characteristics of common renewable and carbon-free energy technologies relying on sun, wind, and freshwater resources.

Technology	Predictability of production	Storage capacity	Controlability	Flexibility
Wind	Short-term	No	No	No
Photovoltaic (PV)	Short-term	No	No	No
Concentrating Solar Power (CSP)	Short-term	No	No	No
Concentrating Solar Power with Thermal energy storage (CSP-TES)	Short-term	Thermal energy	Yes	Yes
Geothermal	Long-term	Thermal energy	Yes	Yes
Hydro dams	Long-term	Reservoir	Yes	Yes
Biogas/Biomass	Long-term	Fuel	Yes	Yes

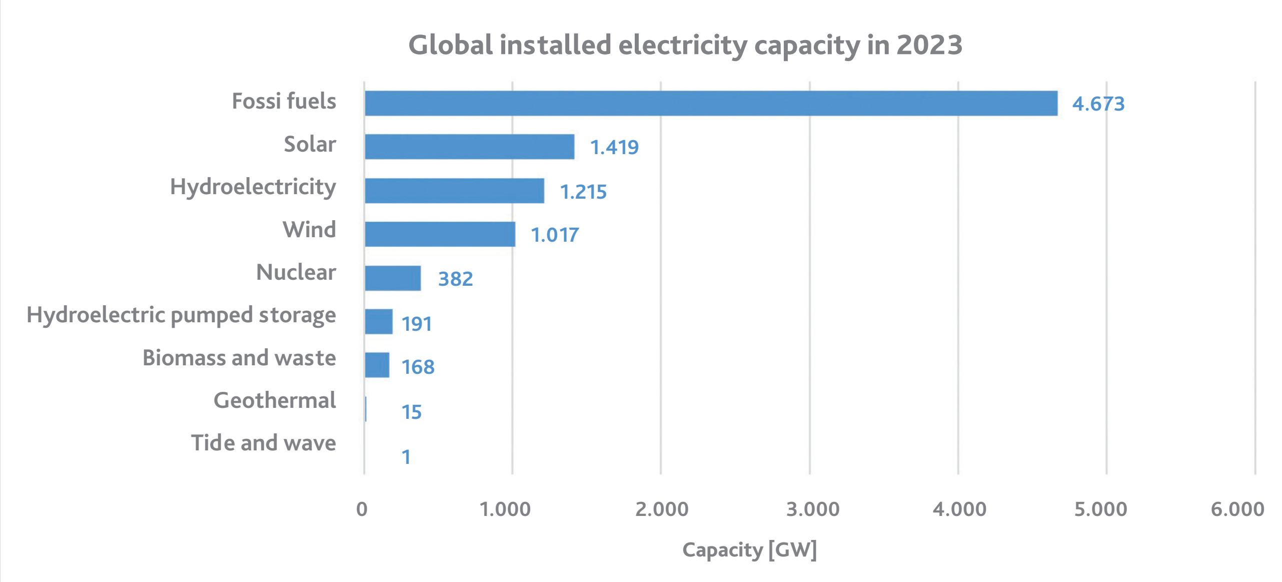

Figure 1: Worldwide installed electricity capacity [GW] in 2023 by energy source. Modified after Statista (2025). (Statista 2025)

capacity is marginal but has a regional untapped future potential (Figure 1).

Compared with all the technologies mentioned above, electric power generation from the oceans is still marginal with a total of 534.7MW (Figure 2 A). From this installed capacity almost all power plants use tidal range technologies (532.1MW).

The discussion of future ocean power production potential is dominated by Wave Energy, Ocean Thermal Energy Conversion (OTEC) and Salinity Gradient technologies (Figure 2 B). While being the oldest and most established technology, tidal range power generation is often neglected in the current discussion due to a lack of investment and technological development in the past decades, thus being deemed an outdated technology by investors.

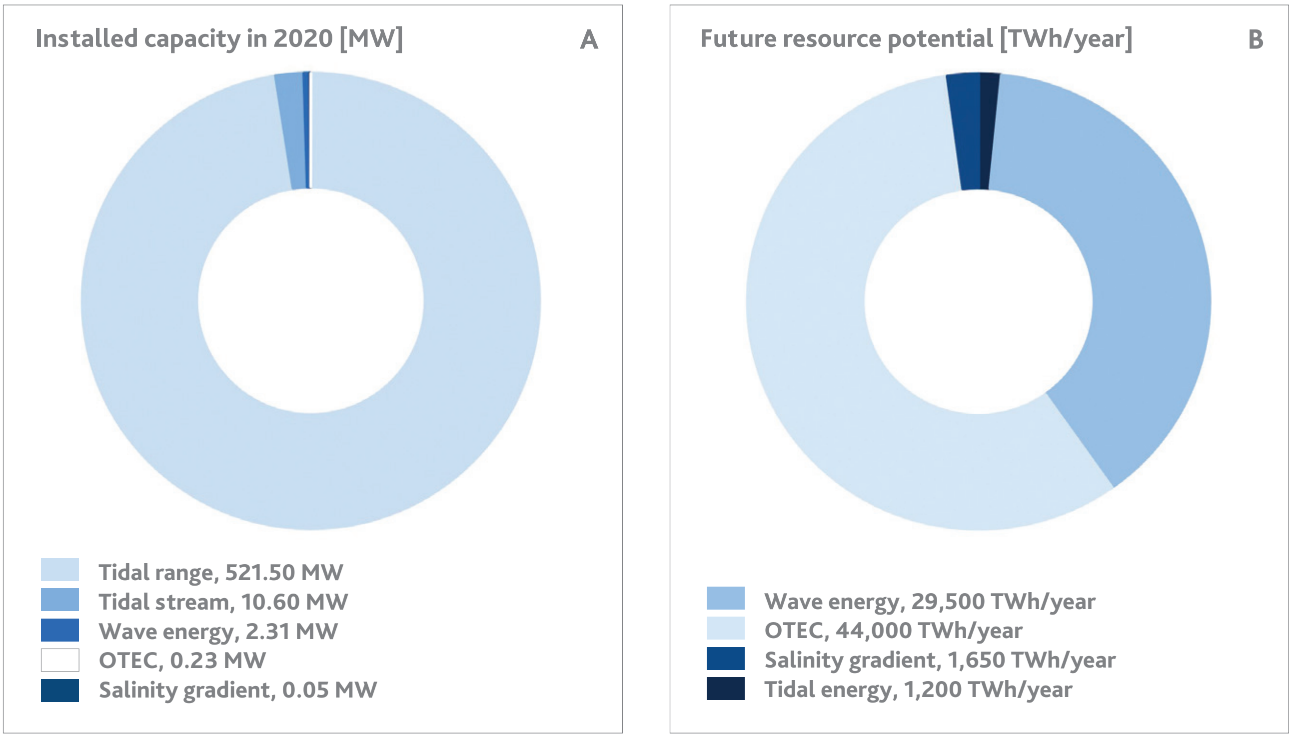

Figure 2: Actual and potential future share of ocean power technologies: (A) Installed capacity of ocean power technologies in 2020 and (B) projected future yearly global production potential. Tidal energy shown in (B) represents the sum of tidal range and tidal stream technologies.
Modified after International Renewable Energy Agency 2020. OTEC = Ocean Thermal Energy Conversion (IRENA 2020).

The technology with the highest future production potential is estimated on a conservative basis to be OTEC (44 000TWh yr^{-1}) followed by wave energy plants (25 500TWh yr^{-1}). The combined annual production potential for all ocean power technologies could also reduce the energy dependence of power technologies and is estimated to be between 45 000 and 130 000TWh of electricity, respectively. This would cover twice the current global demand.(IRENA 2020)

Given the huge energy potential and the fact that ocean power could be generated in most regions of the world where nations have access to coastal areas, NATO countries could reduce their current geostrategic dependence on fossil fuels as well as on future Sunbelt-generated renewable energy and increase independence of remote military bases. Ocean power partially eliminates regular and timely fossil fuels transportation needs, increases the energy security and resilience of remote military installations because of the exceptional load stability and predictability.

This article will review the main ocean power technologies and assess their potential for renewable and resilient electric power production. The review will start with presenting established and prototype technologies using tidal movement and wave power, explore the vast potential of ocean thermal energy and discuss electric power generation from salinity gradients.

TIDAL POWER

Tides are mainly caused by the moon's gravitational force but are also influenced by the sun. Their occurrence, strength and range is defined by astronomic constellations and topographic features and can be calculated many years in advance for every point of the global coastlines. This allows predictable energy production from tidal power plants. Tidal power plants can add a controllable electricity source to the global renewable power production mix. They are most effective at latitudes above 40° in both hemispheres because the Coriolis-force deflects water to higher latitudes.(Lewis et al. 2011)

Electricity generation in tidal power plants is performed by hydro-kinetic turbines which are using either the gravitational gradient of temporarily stored ocean water (tidal range power) or directly by immersion into the tidal flow of water (tidal stream power). They operate in harsh conditions, as sea water is corrosive and the kinetic power of the water is immense and sometimes destructive. Submerged turbines are also difficult to access for maintenance and repair work.(IRENA 2020)

TIDAL RANGE POWER

Tidal range power stations are preferably situated on coasts with a high tidal range and typically at rivers, estuaries, or inlets, which can easily be blocked by a dam. Rivers are preferable sites because the river influx adds to the storable quantity of water for power generation during low tide. They generally consist of an artificial water reservoir to store the water from the high tide, usually via a dam, a sluice to fill the water reservoir and another sluice to direct the water to the turbine which is often installed within the dam. The potential energy difference of water levels between the two sides of the dam drives water through a turbine and transforms it into rotary energy which in turn drives an electric generator. The higher the potential energy difference, the higher the amount of electricity produced.(Roberts et al. 2016; Lewis et al. 2011; Boretti 2020)

Tidal range powered plants are an old technology. The first known tidal mill for grinding grain was built in the 7th century by monks on Ireland's NE coast. (Charlier et al. 2004) The century long usage of tidal power demonstrate the simplicity and effectiveness of this technology.

Worldwide, only three tidal range power plants are currently operational, two of them have a capacity of >200MW: the Rance plant in France and the Shihwa Lake power station in South Korea. Both plants are discussed with their technical details and the associated social and environmental costs and benefits.

ELECTRICITY PRODUCTION AND SOCIAL CONNECTIVITY: THE RANCE TIDAL POWER STATION IN FRANCE

At the estuary of the river Rance in Brittany (France) several tidal water mills were in operation from medieval times onwards because of the favourable topographic conditions and the high tidal range of 8.2m on average. There, the French power company Électricité de France (EDF) inaugurated in 1966 the first modern tidal power plant (Figure 3C).

The dam of the Rance power plant is 700m long spanning the entire width of the mouth of the river Rance where it flows into the British Channel. It holds 24 reversible turbines with a combined capacity of 240MW. Its long-term annual power production is on average 500GWh which amounts to 0.12% of the annual energy consumption of France.

Electricity production in the Rance Tidal Power Station is versatile. During high tide (Figure 3A), the water level on the seaside is higher than on the river side, pushing water through the turbines at the bottom of the estuary. During low tide (Figure 3B) the water level in the river is higher, pushing water through the turbines to the ocean. Sluices can be closed at high tide and therefore the electricity production can be reduced, stopped or postponed. In practice, most of the power generation is done during low tide.

The estimated Levelized Cost of Electricity (LCOE) is 7.98 or 4.56 €-ct kWh^{-1} for an assumed service time of 25 or 50

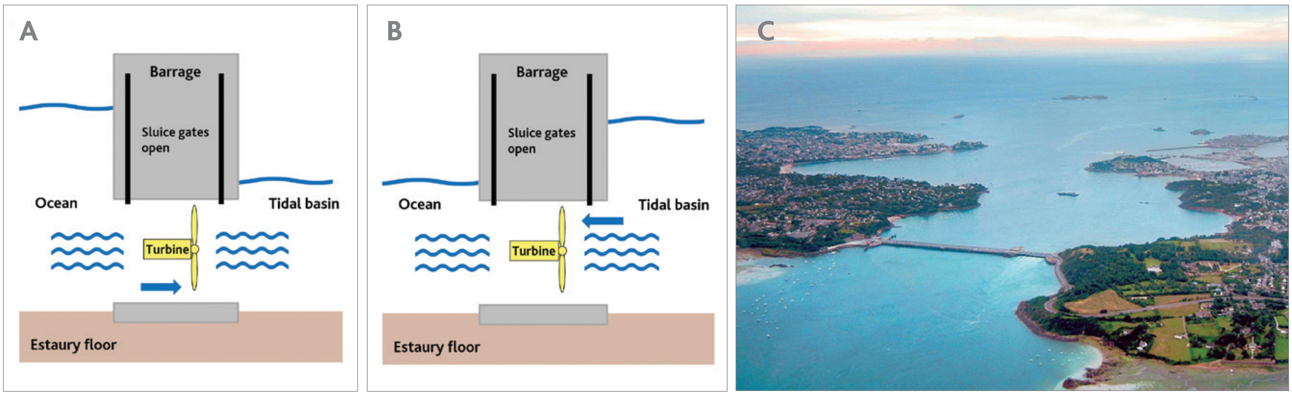

Figure 3: The Rance tidal power station. Configurations for electricity production during (A) High tide: Water from the ocean is pushing through the turbines into the river Rance. (B) Low tide: Water from the river Rance is pushing through the turbine into the sea. (C) Aerial photo of the Rance Tidal Power Station (Brittany, France). Visible in the background is the British Channel in the front the Rance river. Centre: Barrage (dam) with integrated turbines to generate electricity. The dam also serves as a road connection across the river.(EDF 2024)

years, respectively. The 50-year service time was reached in 2016. No official data from EDF are available and currently no plans for decommissioning the plant are known which will result in even lower LOCE in the future.(Boretti 2020; Statista 2020)

The effects of the dam on the region are various. Local residents valued the dam more for its integrated road rather than for the cheap power production. The shortcut over the dam considerably reduced the travelling time between communities on both sides of the bay while the power plant itself and the reservoir behind the dam became a tourist attraction.(Électricité de France 2025) The dam caused an increased silt deposition behind the barrage and the fish population in the Rance was affected by the local extinction of some native fish as well as the remigration of formerly locally extinct fish species into the Rance. (EDF 2024; Boretti 2020)

FRESH SEAWATER EXCHANGE AND ELECTRICITY SUPPLY: THE SHIHWA LAKE POWER STATION IN SOUTH KOREA

The Shihwa Lake Tidal Power Station in South Korea was built in 2011 and surpassed the Rance Tidal Power Plant with 254MW of installed capacity.

The Shihwa Lake is an artificial lake claimed from the ocean. Its construction was completed in 1994. A 12.7km long seawall created a 56.6km² lake and generated land gains of 33km² with three new cities and large industrial complexes. The Shihwa Lake was intended to become a freshwater lake fed by several small rivers and should provide water for agriculture. However, due to an imbalance of fresh and wastewater influx, it transformed into a highly polluted lake void of living organisms.(Park and T. S. Lee 2021; K-Water 2024)

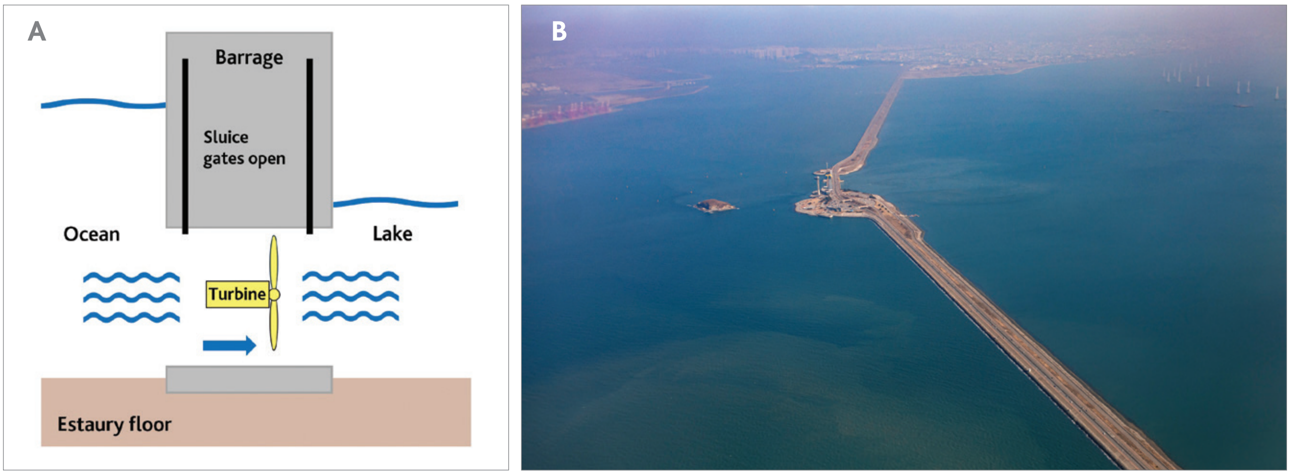

Figure 4: The Shihwa Lake tidal power plant. (A) High tide electricity production. (B) Aerial photo of the Shihwa Lake power station. Left is the ocean side; right is the lake side of the plant. In the centre of the dam the sluice gates and turbines are visible. Photo by Arne Müseler / arne-mueseler.com / CC-BY-SA-3.0 / https://creativecommons.org/licenses/by-sa/3.0/de/deed.de (Müseler 2020).

In 2000 the government begun a project to improve the water quality of the lake. The official status of the lake was changed from a freshwater to a saltwater body and a tidal power plant was planned to be integrated into the existing embankment with two objectives: To allow the exchange of water between the newly established saltwater lake and the ocean and to produce electricity. (Park and T. S. Lee 2021; K-Water 2024)

The Shihwa power plant was inaugurated in 2011 with the primary goal of improving the water quality in the lake. Since it was designed for electricity generation during high tide only when water flows into the lake (Figure 4A), it operates only twice per day for 4h and 25min each time. The sluices are closed before the flood tide, and when the sea level raises to approx. two meters above the lake level, the turbine gates are opened, allowing the turbines to produce electricity. When the ocean and the lake water level become balanced, the turbine gates close and the sluice gates are opened, allowing the lake water to flow to the sea. In this way approx. half of the total volume of the lake is exchanged twice per day, improving the water quality considerably. This "one-way-flow" tidal power generation mode results in a relatively low-capacity factor of 25%, but was chosen for environmental purposes of allowing efficient sediment and pollution drainage. (Park and T. S. Lee 2021; K-Water 2024)

Ten turbines with a capacity of 25.4MW each (total: 254MW) produced between 2011 and 2024 approx. 550GWh per year. The LCOE of the Shihwa plant is estimated to be as low as 2.28 to 4.56 €-ct kWh^{-1} depending on the assumed service life of 50 or 25 years respectively, but actual data are not yet available (Boretti 2020; Statista 2020).

The Shihwa tidal power plant is an excellent example of the versatile technology of tidal range electricity production as it solves two problems in one take: First the previously ecologically "dead" freshwater lake was transformed into an intact seawater ecosystem and second, electricity is produced from a renewable source in a predictable manner.

TIDAL STREAM POWER

A second possibility to use the energy of the tides is by transforming the kinetic energy of the water flow during the change of the tides. This technology does not dependent on specific coastal landforms. While using tidal stream power has no technological history, groundbreaking developments have been made over the past years.

Tidal stream plants are favourably situated on coasts with a high tidal gradient. Topography can enhance the induced tidal currents and narrow straits e.g. between islands or narrow inlets are a preferred location.(IRENA 2020; Lewis et al. 2011)

Tidal stream plants require the possibility to install turbines on the sea floor or submerged on floating scaffolds which are anchored. The tides rush water through the turbines and the kinetic energy of the current is transferred to the turbines which drive a power generator. The stronger the current, the higher the amount of electricity to be generated.(IRENA 2020; Lewis et al. 2011)

Tidal stream turbines are approaching a mature technology level and may become more prominent than tidal barrage plants. Several turbine technologies are under investigation such as horizontal- and vertical-axis turbines, oscillating hydrofoils, Archimedes spirals and tidal kites.

Horizontal-axis turbines and tidal kites have been preferred in recent years in developing projects. The turbine development started with 100kW capacity models and has now reached 1.5MW. Smaller turbines like tidal kites may have a market of their own for remote islands and isolated facilities while big stationary turbines could be the future for large-scale applications.

Tidal induced water flow can reach up to 5.5m s^{-1} (19.8km h^{-1}) but varies widely depending on the location. Wind turbines require at least 5m s^{-1} of wind speed to generate electricity, while the energy harvest of water turbines starts at much lower values because the energy harvest of a turbine is primarily determined by three factors: the flow speed of the medium, its density and the width of the turbine rotor. The density of water is approx. 1000 times higher than that of air, which means that compared with wind turbines, high electricity harvests from water turbines can be achieved at low water flow speeds and with short turbine wingspans.

A COMMERCIAL TIDAL STREAM PLANT: THE MEYGEN PLANT IN SCOTLAND (UK)

Since 2018 four 1.5 MW turbines are operational between the northernmost coast of Scotland and the uninhabited Stroma Island (Pentland Firth). Each 150-ton turbine has three blades with a rotor diameter of 18m. The turbines include a module which rotates the turbine at each slack tide to face into the subsequent low or high tide flow. They are mounted on a 1450-ton gravity foundation that supports the turbine with its own weight. The water flows with a speed of up to 18.5km h^{-1} (5.1m s^{-1}) which is among the highest flow speeds globally. Until the end of December 2023 61GWh electricity were generated. In the final state 398MW of capacity should be installed in several project phases. (SAE Renewables 2024; Tethys 2025a)

The generated tidal stream electricity can easily be fed into the national grid because the existing grid infrastructure from the now decommissioned nuclear plant in Dounreay, located at a distance of 20km from MeyGen, will be used.

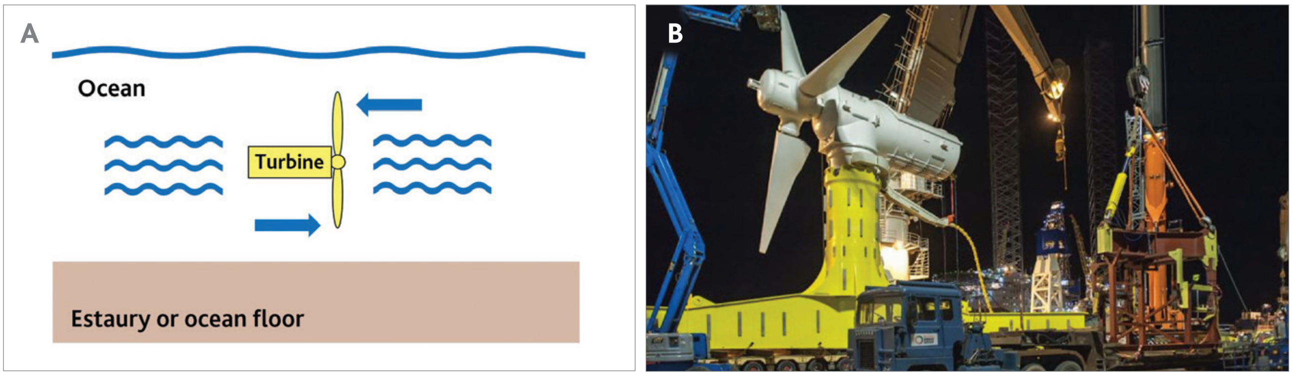

Figure 5: Horizontal-axis turbine. (A) Configuration of a horizontal-axis turbine. (B) One of the MeyGen Power Plant horizontal-axis turbines before loading on the ship for installation in the Pentland Firth (Scotland, UK).(Deign 2020)

ISLAND ELECTRICITY SELF-SUFFICIENCY: THE TIDAL KITE PLANT AT THE FAROE ISLANDS (DENMARK)

The Faroe Islands are inhabited by 50 000 people and are a self-governed part of Denmark. The archipelago is located in the North Sea halfway between Scottland and Iceland. The Faroe Islands want to reach 100% of renewable electricity production by 2030. (Barney et al. 2022)

In 2022 a tidal kite with a capacity of 0.1MW was installed as proof of concept at the Vestmannasund. It delivered reliable electricity to the national grid and was considered a success, so that in February 2024 a larger 1.2MW tidal kite was installed at the same location. The deployment of an array of 24 tidal kites with a total capacity of 30MW at the Hestfjord is planned during the next years. (Minesto 2024; Offshore 2024)

The wings of tidal kites use the hydrodynamic lift force created by the underwater current to move the kite. With an onboard control system, the kite is autonomously steered in a predetermined figure-of-eight trajectory (Figure 6A), pulling the turbine through the water at a speed several times higher than the actual current flow. Therefore, even low water speeds can be used for power generation. When the tide turns, the kite is re-aligned and starts to "fly" again as soon as the current is strong enough. The tidal kite consists of a turbine mounted on wings which are stabilised and controlled by rudders as well as a control unit for "flight" trajectories. The kite is tethered to an anchor on the seafloor (Figure 6B) (Minesto 2024).

The 1.2MW kite has a wingspan of 12m and a and a weight of 28 tons. (Minesto 2024) The low weight allows a cost-effective operation of the kites. Actual LCOE for tidal kites are not available yet, but Barney et. al. calculated LCOE for a tidal kite array of the Faroe Islands to be 8.79 €-ct kWh^{-1}. (Barney et al. 2022) Only after several years of electricity production and a sufficient number of plants installed, a robust value of LCOE can be determined. The comparably high LCOE may be attractive for remote island and installations in comparison to using fossil fuels for electricity production which have to be shipped there, thus increasing the LCOE of fossil fuel plants significantly.

WAVE POWER

Wind action, while having a low energy density, can accumulate energy in the top surface layer of the ocean over vast distances in the form of waves and can be used for electric power generation.

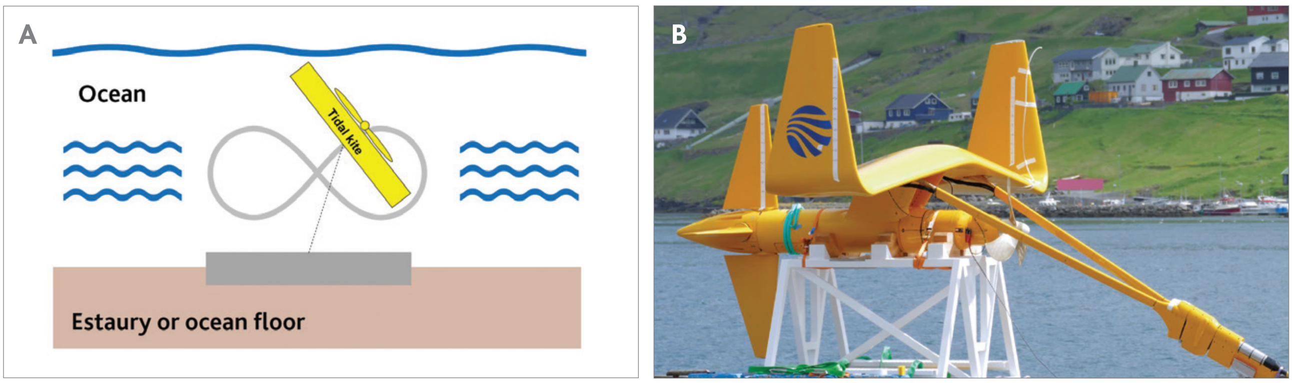

Figure 6: Tidal-kite turbine. (A) Configuration of a tidal kite turbine with schematic flow pattern. Modified after IRENA 2020 (IRENA 2020). (B) One of the 100kW capacity tidal-kites installed on the Faroe Islands (Denmark) (Frangoul 2020).

Generally, waves do last longer than the wind itself, as water – due to its higher density – reacts slower than air to changes in wind speed. Waves can also be regularly caused by tides, and ocean currents while wave-wave interactions, episodic landslides or tectonic movement can cause extremely large "freak" waves or tsunamis. In these cases, a wave power plant is automatically shut down to avoid damage, comparable to wind turbines in high wind-speed situations.

Wave energy contains kinetic and potential energy, and both can be harvested to produce electricity. Kinetic energy is mostly absorbed by moving bodies e.g. attenuators which stay on the surface of the water and move with it on a horizontal axis, while potential energy is used by "overtopping devices" which move up and down along their vertical axis. Some technologies use both energy sources e.g. point absorbers (IRENA 2020).

The energy content of waves is influenced by wave height, wave speed, wavelength (or frequency) and water density. Wave energy resources are spatially more evenly distributed than tidal sources, which is reflected in wave energy's large production potential. (IRENA 2020)

The theoretical global potential of wave energy is 30TWh per year which is approx. 10% of the current global electricity use of 30 800TWh. (Ritchie and Rosado 2020) Although varying in the short term as well as seasonally, waves can be forecasted from wind patterns and are widely considered a reliable and predictable energy source. (IRENA 2020)

Wave energy technologies have not seen a convergence towards one type of design which is a sign of early technology development stages. Over the years several working principles in all stages of technology readiness level (Tzinis 2012) have been developed (TRL values range from 1 to 9, the higher the number, the more commercialized is the product).

HAWAII'S (USA) EFFORTS TO BECOME INDEPENDENT FROM FOSSIL FUEL IMPORTS: THE OE35 OSCILLATING WATER COLUMN PLATFORM

Hawaii is the most petroleum-dependent state of the USA. The state government has set itself the goal of using 100% renewable energy by 2045. Additionally, the US-military is looking for ways to increase the energy efficiency and resilience of its deployed forces in the Pacific Ocean (Knodell 2021; OceanEnergy 2024; The Maritime Executive 2019).

The OE35 floating platform (Figure 7) could help to meet this goal. It is constructed by a cooperation of the US Navy, the US Department of Energy, and the Sustainable Energy Authority of Ireland. It's oscillating water columns technology funnels a discontinuous air stream driven by the movement of the waves through a one-way air turbine (Wells turbine). The special blade design turns the turbine in one direction only, regardless of the direction of the air flow (Figure 7A). The technology has reached TRL 8.(Knodell 2021; OceanEnergy 2024; The Maritime Executive 2019)

The OE35 barge was deployed in the Navy test site off Oahu (Hawaii) in 2019. The platform was designed by the Irish company OceanEnergy and constructed by a US shipbuilding yard. The barge is 38 by 18m large and weighs 825 tons, comparable in size to a small Navy vessel such as a mine sweeper. All moving parts are above water and therefore easily accessible for repairs and maintenance. It is expected to generate annually 1.25 – 1.75MWh which sounds reasonable for a 1MW turbine.(Knodell 2021; OceanEnergy 2024; The Maritime Executive 2019)

MEGAWATT-SCALE FLOATING WAVE ENERGY PLATFORMS: THE NANKUN PLANT IN ZHUHAI (GUANGDONG, CHINA) STARTS TRIAL OPERATIONS

The Nankun energy platform works on the oscillating bodies energy converter technology (Figure 8). The up/

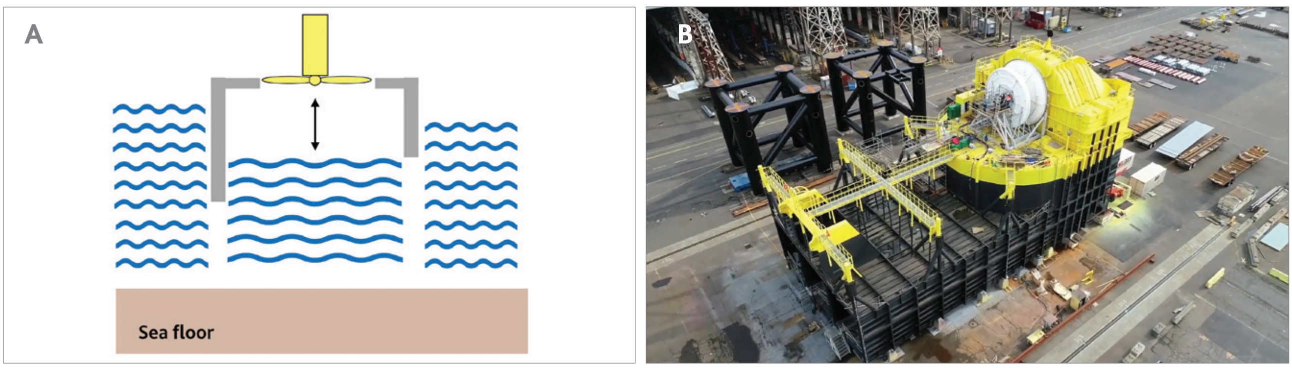

Figure 7: Oscillating water column technology. (A) Configuration of a typical setup. The water surface level changes caused by wave action push air through a wind turbine which works only in one direction. Modified after IRENA 2020 (IRENA 2020). (B) Picture of the OE35 barge, developed by OceanEnergy (Ireland). Submerged parts of the barge are painted black, yellow painted parts are above the water surface (OceanEnergy 2024)

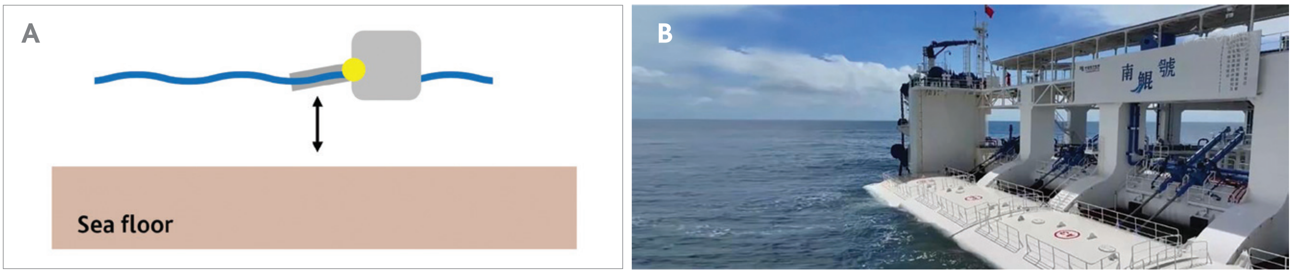

Figure 8: The Nankun wave energy platform. (A) Working principle of the floating wave energy platform. A large floating platform with smaller floating sides converts the up-down movement of the waves via hydraulic power to electricity. (B) Photo of China's first megawatt-scale floating wave energy generation device, called Nankun, in Zhuhai, Guangdong province (Yukun 2023).

down movement of moveable floating plates relative to a larger floating engine platform pushes and pulls pistons, which drive electric generators via a hydraulic engine. The technology has reached TRL 8.

The large triangular wave energy platform started its trial operation in June 2023. It has a length of 300m covering an area of 3 500m². The platform is semi-submersed and has a displacement of approx. 15 000 tons. The structure consists of a power generation platform, a hydraulic system, a monitoring system, and an anchor chain system that will allow it to be deployed in water depths between 30 and100m. The structure – labelled as a vessel – was built by the Chinese COSCO Shipping conglomerate (Braid Maritime 2023; Yukun 2023).

Each of the three sides of the main vessel body has five floating plates connected to it that are driven up- and downward by the movement of the waves (Figure 8). No crew is needed, as the platform is remotely controlled. Solar panels are also installed to generate additional energy. The device can generate up to 24MWh of electricity per day (Braid Maritime 2023; Yukun 2023).

The Nankun platform is a commercial prototype with emphasis on the commercial aspects. The successful establishment of the platform, three times bigger than a mid-sized frigate, shows that the stage of proof of concept for several constructional topics has been passed. The question to be answered is not whether it will generate electricity, but how much. The electricity production from movement of waves, transformed via the movement of pistons into hydraulic pressure and afterward with a turbine into a stable and continuous electrical current is the most essential and impressive aspect of the Nankun platform. (Braid Maritime 2023; Yukun 2023)

BUOY POINT ABSORBER ARRAY AT THE WEST COAST OF IRELAND: THE SAOIRSE WAVE ENERGY PROJECT AS A PRE-COMMERCIAL DEMONSTRATION PLANT

Point absorbers in the form of buoys can use both the kinetic and the potential energy of the waves. They are moored to the sea floor and can be arranged into arrays, forming multi megawatt plants. A combination with offshore wind farms seems favourable, as the grid connecting infrastructure can be used.

The Saoirse Wave Energy Project at the west coast of Ireland is a pre-commercial test and demonstration plant. At this location waves are created by wind and the tides. The plant uses an array of point absorber buoys from the Swedish manufacturer CorPower. They have successfully

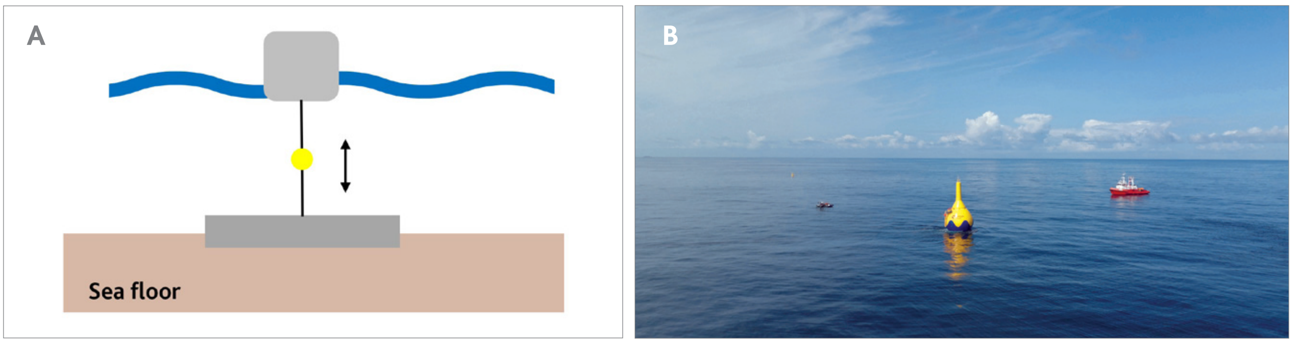

Figure 9: (A) Point absorbers use kinetic and potential energy for electricity generation from movement in all directions of the buoy relative to the mooring by a mechanical drive. The up/down motion is transformed into rotation which drives a generator. Modified after IRENA 2020 (IRENA 2020). (B) Newly installed point absorber as used in the Saoirse Wave Energy project. The vessel serves for size comparison and is used to fix the buoy to the seabed mooring (Saoirse Wave Energy 2024).

passed the test on Portugal's Atlantic coast, one of the most challenging marine environments.

The buoys use the kinetic and potential energy of the waves for electricity generation. The movement - up/down und sideways - relative to the mooring of the buoy is transformed by a mechanical drive into rotation energy which drives a generator inside the buoy. Each buoy is 9m wide and 19m tall and has a capacity of 300kW (Figure 9).(Saoirse Wave Energy 2024; CorPower Ocean 2021) If waves exceed a given maximum height, the internal mechanism is automatically disengaging to protect the system.

The power plant is deployed 4km off the coast of County Clare in Ireland. A capacity of 5MW is planned to be deployed until 2026, and an additional capacity of 25MW until 2028. Expected operation time is 15 years intended as a pre-commercial project. (Saoirse Wave Energy 2024; CorPower Ocean 2021)

The electricity producing network of buoys is in a pre-commercial development stage. The technology is mostly placed under water in a challenging high-wave environment. Whether the many moving parts of the technology will prove to be of low maintenance can only be evaluated after a significant running time. The same holds true for the mooring on the seabed which typically has a low impact on the ocean floor.(Saoirse Wave Energy 2024; CorPower Ocean 2021)

OCEAN THERMAL ENERGY CONVERSION

Oceans absorb the irradiation of the sun and store the energy as heat mainly in the epipelagic (sunlight) and mesopelagic (twilight) zones extending down to approx. 200m and 1000m depth, respectively. Ocean Thermal Energy Conversion (OTEC) uses the temperature difference between the warm surface (down to 50m depth) and the cold deep-sea (starting below 800m to 1000m depth) and converts it into electricity. The minimum temperature difference of the two ocean water bodies must be >20°C. Because deep sea ocean water is at a constant temperature of 4°C, the ocean surface temperature must be at least 25°C without significant seasonal variations and the sea must be at least 800m deep to reach the deep-sea layers. Such conditions are only present in tropical regions between latitudes of less than 30 degrees north and south. (IRENA 2020; Tethys 2025b)

Even though restricted to the tropics, the global potential of OTEC is the largest of all ocean energy sources with 44 000TWh per year of continuous power. Besides it's uniquely large potential, OTEC's main advantage is the ability to provide a non-intermittent, continuous power supply. (IRENA 2020)

In the simplest technical configuration, warm surface water is used in a closed-cycle system to heat a working fluid with a very low boiling point (e.g. butane or ammonia). The gas then drives a generator and is condensed by coming into contact with cold, deep-sea water in a condenser and is pumped back into the closed system (Figure 10A). (IRENA 2020) More sophisticated versions of the technology are available. Globally, several test plants at universities and research centres are operational. Six OTEC plants were globally in operation in 2021 and another twenty are currently in various planning stages in all tropical oceans. (Kim et al. 2021)

RESEARCH AND DEVELOPMENT COOPERATION FOR NEW TECHNOLOGIES AND ENERGY INDEPENDENCE: THE KAILUA-KONA OTEC TEST PLANT IN HAWAII (USA)

The OTEC facility in Kailua-Kona (Hawaii, USA) has been

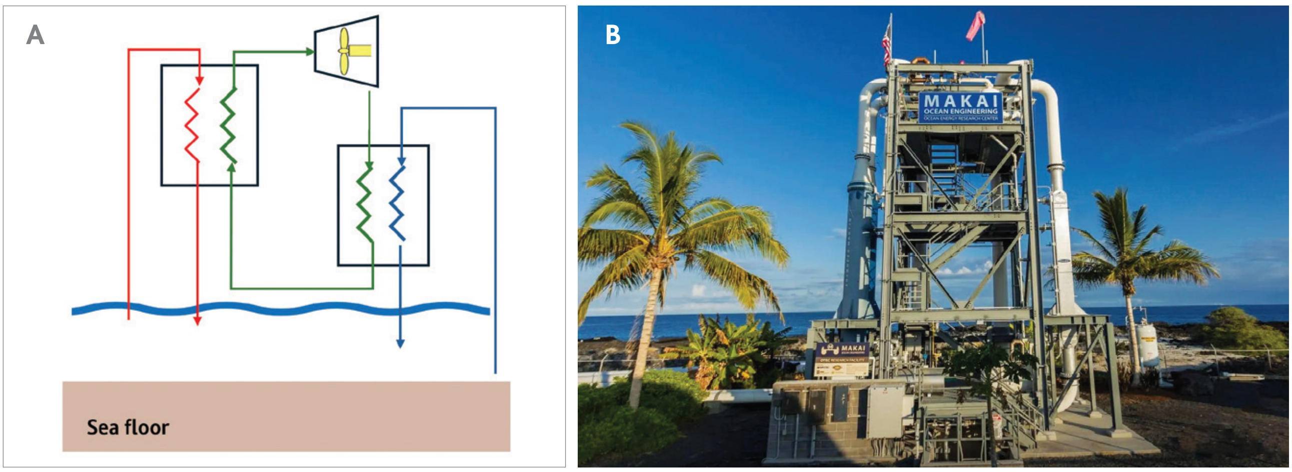

Figure 10:Ocean thermal energy conversion (OTEC) (A) Working principle of a closed-cycle system. The working fluid (green) is heated and vaporised (left) by warm surface sea water. The vapor drives a turbine (top) which drives a generator. The working fluid is cooled by cold deep-sea water in a condenser (right). Modified after IRENA 2020 (IRENA 2020), (B) On-shore OTEC test facility in Hawaii with a capacity of 100kW (Makai Ocean Engineering 2024).

in operation since 2015. It is run by a cooperation of the private company Makai Ocean Engineering, the U.S. Navy's Office of Naval Research, and the University of Hawaii. It has a capacity of 100kW and is also capable of providing thermal energy for heating and cooling in addition to producing electricity.(Makai Ocean Engineering 2024; U.S. Energy Information Administration 2024)

SALINITY GRADIENT

Energy from the sun not is not only stored as heat in the oceans but also stored as chemical energy in form of a concentration of ions. While freshwater influx from rivers has a low concentration of ions, the continuous evaporation over the oceans results in an ion-free water vapour flow to the atmosphere and an increase of the ion concentration in the ocean water.

The mean salinity of the oceans is 3.5% with some variations across the globe. It is lower in regions with freshwater influx from rivers or glaciers and low evaporation e.g. in the proximity of the poles. Regions with a lack of precipitation or river influx and high evaporation show higher salinity. As the amount of retrievable electricity is proportional to the salinity gradient, freshwater-seawater systems are most efficient for electricity production. Salinity plants can produce electricity continuously. However, the geographical requirements are significant and therefore, the estimated global potential of 1 650TWh yr^{-1} is small in comparison is small in comparison to the other ocean power technologies (IRENA 2020; ESA 2019).

Currently two technologies are being tested and applied: Pressure retarded osmosis (PRO) and reversed electro-dialysis (RED). Both technologies are on low TRL levels and need ion selective membranes to separate the salty from the freshwater to allow ions to move from the higher to the lower concentration. Such membranes are currently not commercially available in the needed quantities. The technology remains in conceptual and test stages and is significantly less mature than tidal, wave or OTEC.

The RED system makes direct use of the salt ions in the seawater and bypasses the need for a turbine and any moving parts. Energy losses due to friction are non-existent, which is why the technology shows a high efficiency. In seawater the dominant ions are sodium (Na+) and chloride (Cl-). The RED system contains ion selective membranes for both, positively charged cations (e.g. Na+) and negatively charged anions (e.g. Cl-). A pair of electrodes bridges the membranes. When sea water flows between a positive and a negative selective membrane with freshwater on the other side of the membranes, the ions from the sea water will migrate through the respective membrane to the fresh water. One side will become positively charged, the other side negatively thus creating an electrochemical cell (Figure 11A).

THE FIRST SALINITY GRADIENT PLANT IN OPERATION SINCE 2014: THE RED POWER PLANT ON THE AFSLUITDIJK FLOOD PROTECTION DAM IN THE NETHERLANDS

In 1932 the 20km long Afsluitdijk dam located between the Dutch provinces of Friesland and North Holland next to the North Sea was built to protect the country from storm surges. The detached water body quickly became a freshwater lake because of a river flowing into it and was named IJsselmeer. In 2014 the dam was enlarged to host the first RED technology salinity gradient electricity plant

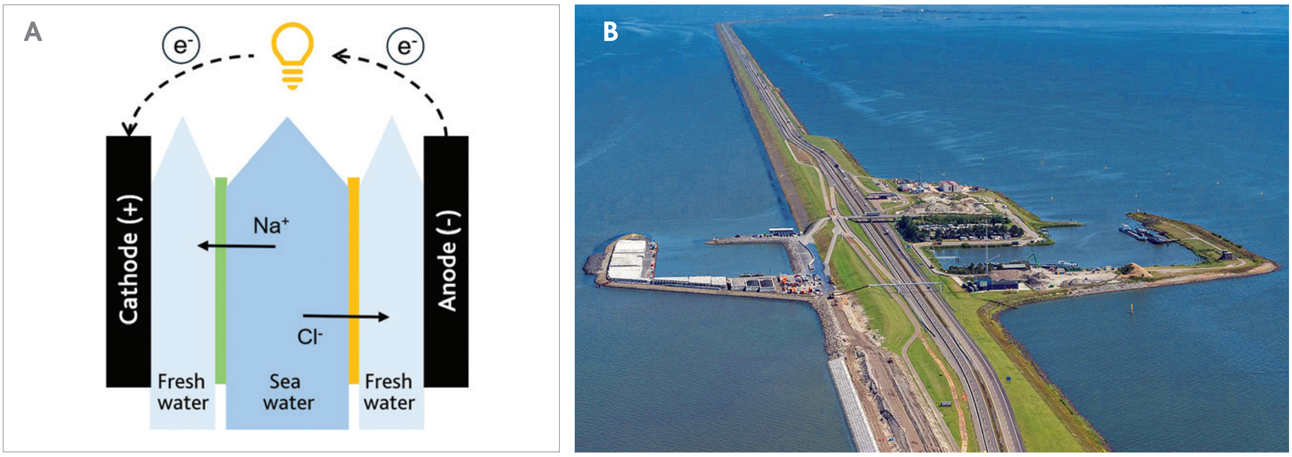

Figure 11: Salinity gradient plant. (A) Schematic diagram of the RED-technology with two differently selective membranes. Green: Cation selective membrane. Orange: Anion selective membrane. Black: Pair of electrodes. The Cathode is positively charged and the place of reduction, respectively the uptake of electrons. The anode is negatively charged and the place of oxidation, respectively the loss of electrons. Modified after IRENA 2020 (IRENA 2020). (B) RED plant on the Afsluitdijk dam in the Netherlands. Left in the picture is the saltwater side of the North Sea, right is the IJsselmeer freshwater lake. The power plant is located at the freshwater side of the dam. Sea water is pumped via a pipeline to the plant and the brackish waste water is pumped back to the seaside by a separate pipeline (IRENA 2020; REDstack 2024).

with 50kW capacity. Using the existing dam reduced the investment costs of the plant significantly (Figure 11B). The plant is theoretically able to run on a permanent basis (8760 h yr^{-1}); however, all power plants are at least one month per year shut down for maintenance and repairs which results in this case in a capacity factor of 90%. Although the plant is running successfully, funds to build a larger plant are currently not available (REDstack 2024; IRENA 2020; Encyclopaedia Britannica 2025).

ENERGY SECURITY AND RESILIENCE

Several technologies for using the energy potential of the oceans are currently in use with the majority of them in a more or less advanced prototype or experimental phase of application. There is no doubt that some of these technologies will reach maturity. The key to further success of ocean power will be to secure the capital investment needed to reach TRL 9. Governments may invest in such technologies because they provide strategic energy security and thus resilience for nations and help reducing the environmental impact of power generation while private investors must be sure that the technology promises a return on investment. In a best-case scenario, all aspects can be addressed by ocean power technologies and national and private interests are covered.

In the following we discuss the challenges and options for strategic energy security, resilience and environmental impacts. In a second article we will then address the question of costs, investments and best locations for large-scale integration of ocean power into the electricity grid and the global energy mix.

OCEAN ENERGY TECHNOLOGIES AND THE NEED FOR BASELOAD CAPABILITY

Modern societies have high energy demands and need sources of very flexible electricity supply because the instant electricity demand varies hugely on a daily (day/night), weekly (working days/ weekends) and seasonal basis (winter/summer). This requires the presence of plants which can be operated on demand and on response timescales reaching from seconds to hours. Electrical grids dominated by renewable energies without storage capabilities generally lack plants with so called base-load capabilities. These plants operate constantly with response times of hours and cannot be shut down completely on a short time scale (e.g. coal plants).

To demonstrate the temporally varying electricity demand and the need for a baseload capability the energy production vs. consumption in Germany is shown for a full week during summer and Winter in 2024 with the latter covering a period of dark doldrums also known as "Dunkelflaute" days (Figure 12). During the summer of 2024 the production of renewable electricity exceeded the demand significantly, especially around noon, while during calm periods at night the electricity production was low. In winter – especially during the dark doldrums – the electricity demand of Germany could not be covered domestically. Dark doldrums occur for a few days annually. Longer periods of several weeks may happen every 3 to 5 years, when neither wind nor solar power plants produce sufficient electricity.

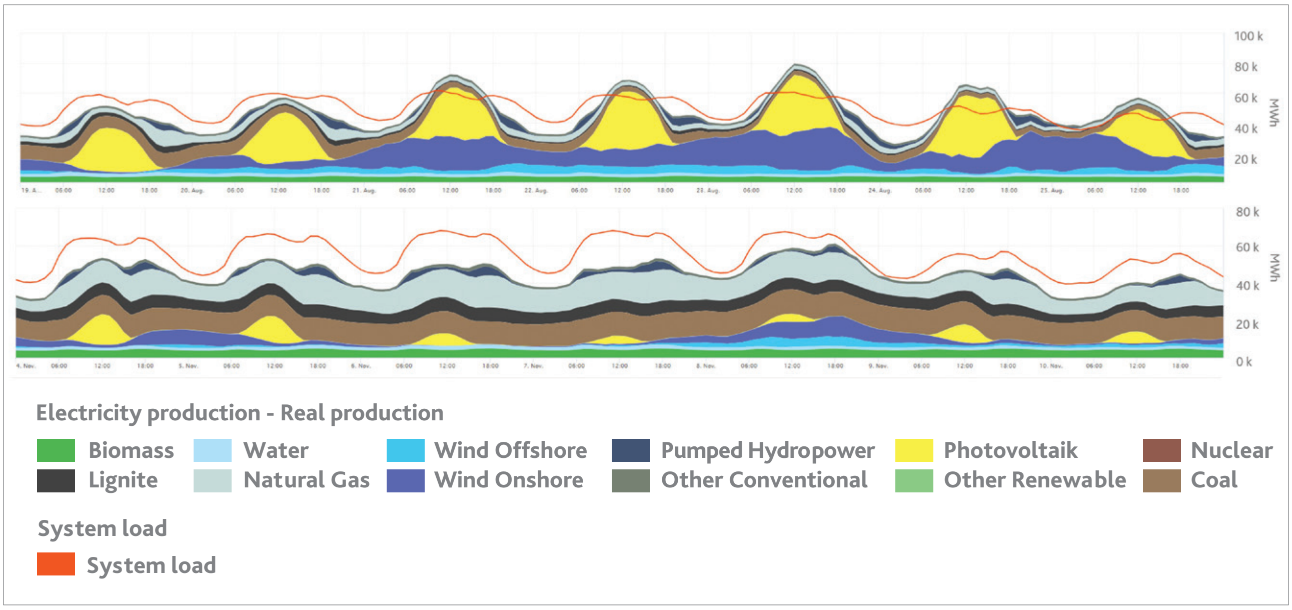

Figure 12: Energy production and consumption within Germany during a week in summer and winter of 2024. (A) Week from Monday 19th to Sunday 25th of August (summer in the northern hemisphere) and (B) Week from Monday 4th to Sunday 10th of November 2024 (winter in the northern hemisphere and including some days of dark doldrums)(Bundesnetzagentur 2025). The electric power demand (system load) is during most days higher than the power produced by German power plants and must be covered by imports.

DARK DOLDRUMS AND BASELOAD CAPABILITY IN GERMANY

Especially in winter during the dark doldrums, Germany imports large quantities of electricity. During these periods electricity costs in Germany as well as in the European synchronized grid zone, (ENTSO-E 2022) can increase dramatically. During summer, when solar power production is huge, Germany becomes an electricity exporter especially to Norway through the NordLink Power line (Fischer 2021; TenneT TSO GmbH 2020) and to France when cooling capacity for the French nuclear power plants is diminished (Comptes Rendus de la Commision des Finances 2023).

In the case of highly industrialised countries a non-wind and non-solar predictable and controllable renewable power sources integrated into the electricity mix - such as ocean power- (Table 2) could allow the decommissioning of "reserve power plants". These are generally fossil fuel based with high productions costs per kWh because of their low annual running time.

Excess electricity from wind and solar during peak production in summer could be directed to e.g. the production of green hydrogen (Lauf 2020; Lauf and Zimmerman 2022).

Baseload capacity in electrical grids dominated by renewable power plants without storage capabilities such as wind and solar-PV is minimal. In contrast, some ocean power technologies can provide a predictable and sometimes even controllable 24/7 power production and are discussed with respect to their electrical grid stabilizing potential.

Ocean thermal energy conversion (OTEC) and Salinity Gradient technologies are potential baseload technologies because both provide electricity permanently and are at the same time controllable and flexible in responding to varying electric demands. OTEC, while limited to the tropics and a sea depth of >800m has the environmental advantage that it can be installed offshore and thus does not compromise shallow water ecosystems and the coastline.

While tidal power technologies are also long term predictable, only tidal range power plants with a reservoir provide storage, controllability and flexibility and thus fulfil the requirements for baseload power plants.

Tidal stream and tidal range plants without reservoir lack energy storage capability and thus controllability. While they can serve as a valuable energy source for predictable temporal energy production, tidal range and tidal stream power technologies do not fulfil the requirements for baseload applications unless connected to large mid- to long- term electric power storage facilities which are still extremely expensive.

Wave power lacks all features mentioned above and might be useful as an additional energy source if the baseload capacity is provided by other technologies.

In spite of the still high investment costs, ocean power technologies are already used successfully on islands and small or remote coastal communities because they reduce the dependence on expensive fuel imports and associated supply logistics.

GLOBAL USABILITY OF OCEAN POWER TECHNOLOGIES

All described technologies rely on specific physical environmental conditions and on water in its liquid state of aggregation.

In the high latitudes and the arctic regions icebergs and pack ice endanger ocean power plants. Icebergs may reach heights above water of more than 100m and below water up to 700 meters. Pack ice is much shallower, both

Technology	Predictability of production	Storage capacity	Controlability	Flexibility
Ocean Thermal Energy Conversion (OTEC)	Permanently available	Thermal energy	Yes	Yes
Salinity gradient	Permanently available	Salinity	Yes	Yes
Tidal range with reservoir	Long-term	Reservoir	Yes	Yes
Tidal range	Long-term	No	Yes	No
Tidal stream	Long-term	No	No	No
Wave power	Short-term	No	No	No

Table 2: Characteristics of renewable ocean power technologies for electricity production sorted in descending order from the best to the least fit.

above and below the water level and may be driven as drift ice by waves, wind, tides and currents towards power plants and thus damage or destroy them. As a consequence, arctic regions and the drift ice areas of the oceans appear unsuitable for ocean power plants. This excludes at last 12% of the global ocean areas from ocean power technologies.

OTEC plants have the highest prognosed power production potential and need a minimum surface water temperature of 25°C and access to water of 4°C in about 800 to 1000m depth.(IRENA 2020) The tropical zones of the Indian and the West Pacific Ocean have the highest seas surface temperatures. Some locations outside of the tropics e.g. the coastlines of Mexico and the Caribbean or the Chinese Sea are also apt for OTEC (Figure 13). This area will certainly increase further poleward due to the warming climate.

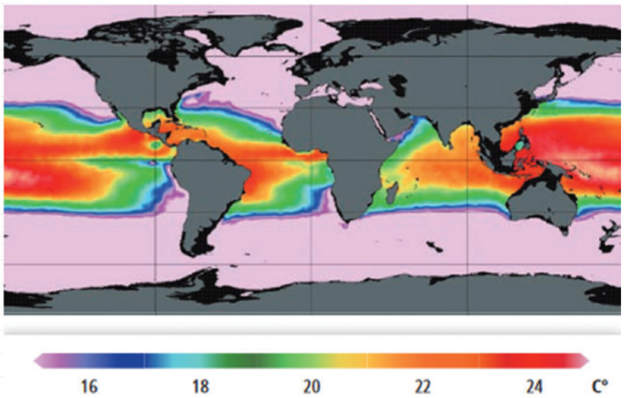

Figure 13: Global Sea Surface temperatures averaged for 2003–2011. Areas with an ocean surface temperature all year round above 25°C are potentially apt for OTEC technologies.(Lewis et al. 2011)

Most challenging are suitable locations for building salinity gradient plants. Fresh and saltwater sources must be available in close proximity to each other, and these conditions are normally found on coastlines with large rivers. Conflicts over freshwater use is difficult to avoid which is problematic in dry and hot regions. These coastal locations also tend to be densely populated. Installing salinity gradient plants is theoretically possible near artificial saline systems e.g. using high salt content brine from desalination plants or high salt content brine from lithium extraction plants, but environmental concerns might be difficult to overcome.

For military applications, small autonomous offshore power systems which offer electric power in the 10W to 1MW range can provide communication and data services for underwater vehicles and open-ocean environmental sensors (Figure 14). Also, remote military bases may profit from ocean power systems providing electricity, but the need for resilience will allow only a supportive role for the energy generation.

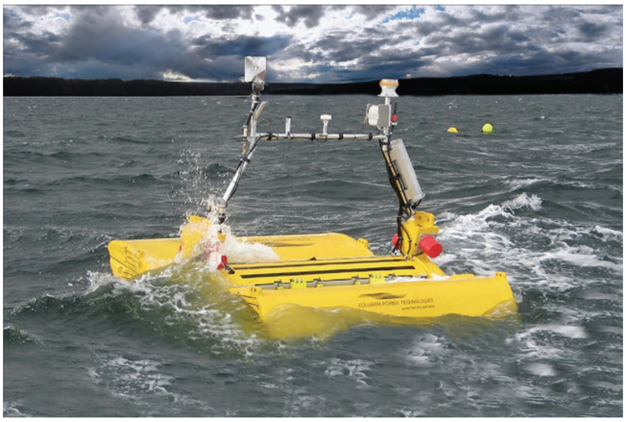

Figure 14: The SeaRAY offshore wave power system designed for localized power-generation and data services connecting to unmanned underwater vehicles and ocean-dwelling environmental sensors.(Schmitz 2025)

ENVIRONMENTAL CONSIDERATIONS AND IMPACTS OF OCEAN POWER TECHNOLOGIES

Any human activity has implications for the environment. Electricity production from renewable sources helps to prevent the release of greenhouse gases from fossil sources into the atmosphere. However, this advantage in mitigating the current global warming trend must be balanced with negative effects on the ocean's ecosystems.

Many of the described technologies only exist as prototypes or in small commercial numbers. Therefore, environmental studies evaluating their environmental impact on a larger scale have not yet been performed for all the technologies presented in this article. In the following the already proven side effects of technologies described in this article will be discussed, while large scale implementation of ocean power plants may cause further, often unintended environmental problems.

Large-scale ocean power infrastructure may interfere with activities such as fishing and shipping, endanger marine wildlife via risk of entanglement, or cause debris and pollution as pump material malfunctions and maintenance services to fix broken pipes may transport invasive alien species. (Barboza et al. 2018; National Academies of Sciences 2022; Röschel and Neumann 2023)

Specifically, the creation of magnetic fields by electricity generating and transporting devices can disorient organisms which rely on the magnetic field of the earth for orientation while low frequency noise from machinery is a general problem for many marine organisms (as well as military sonars) and not limited to ocean power generation technologies. The oscillating water column wave power technology as described in the OE35 is noisy and may not be tolerated near settlements.(Tethys 2025c)

Tidal range technologies require large barrages and change the sedimentation dynamics and the ecology of the blocked river, inlet or bay In the case of a lake forming dam with sufficient influx of freshwater and turnover of the lake water, the waterbody can turn from salt water into a freshwater ecosystem, as had happened with the IJsselmeer. (Encyclopaedia Britannica 2025) However, without sufficient freshwater but high waste water influx the lake can turn into an ecological disaster zone as was the case of the South Korean plant. Only after severe interventions following the completion of the dam and a change in perspective in terms of the kind of the ecosystem, a viable salt water ecosystem was created. (Park and T. S. Lee 2021; K-Water 2024) In the case of dams on river outlets (AIP Conference Proceedings 1850; Schneider et al. 2017) the sedimentation patterns are changed and the migration of fish may be obstructed, as was the case of the river Rance in France. (EDF 2024; Boretti 2020) Often these artificial water bodies attract tourists which can cause additional environmental problems.

Tidal stream and wave power technologies must be anchored to the ocean floor which locally destroys the seabed ecosystem. Tidal stream technologies rely on relatively slow-moving rotors or kites submersed in the water. While no casualties of large fish, seals, dolphins or whales have been reported, other possible disturbances such as altered water flow patterns are under investigation.(Tethys 2025a)

The most significant environmental impacts might evolve from a large-scale use of OTECs. Cold, nutrient rich deep-sea water is pumped to the ocean surface (artificial upwelling) while warm, carbon enriched surface water will be pumped to the deep sea (artificial downwelling). This will change the density structure of the ocean and the ocean circulation over tens of kilometres.(National Academies of Sciences 2022)

The artificial downwelling causes an (un-)intentional transport of dissolved CO_2 and the transport of surface heat, nutrients and oxygen into sub-surface water (Stigebrandt et al. 2015) with so far unknown changes in the deep-sea biodiversity. Artificial upwelling on the other hand fertilizes surface waters and stimulates phytoplankton growth. A potential positive effect of this is the long term (centuries to millennia) storage of photosynthetically fixed atmospheric carbon when the dead phytoplankton sinks to the deep-sea ocean floor. Also, the enhancement biological production (Oschlies et al. 2010) could impact fishing or mussel farming. (Handå et al. 2013; Casareto et al. 2017; Ortiz et al. 2022) Artificial upwelling leads to cooler surface water temperatures and might reduce the stress on thermally sensitive ecosystems like, coral reefs (Sawall et al. 2020; Schneider et al. 2017) but cold deep-sea water also lowers the pH value of surface water and could endanger marine ecosystems by acidification.(Pan et al. 2016)

OUTLOOK

As many as 2.4 billion (109) people, representing 40% of the global population, live within 100km distance from ocean coasts or on islands (IRENA 2020). Supplying them with renewable energy from the ocean is possible. The largest, almost untapped renewable energy source is the thermal energy of the oceans which can be converted to electric power by Ocean Thermal Energy Conversion technologies. The second largest ocean energy source is energy stored in waves.

Both technologies can be deployed offshore and in the open sea, thus not being limited to the vicinity of coastlines and shores. Thermal energy conversion in the ocean is limited to tropical and subtropical areas, while wave energy can be exploited in most ice-free areas, thus providing a much larger geographic potential.

Future large-scale application of these two technologies faces two major challenges: power transmission and environmental concerns. The generated electric power must be transmitted from the producing devices in the open ocean to the consumers at the coast, often across large distances. This involves huge investment and maintenance costs for energy transmission.

Especially for thermal energy technologies, the environmental concerns reach from immediate negative effects on fishery and marine life to concerns of irreversibly by the authors changing the ocean water thermal properties of surface and deep-sea regions.

The implementation of any ocean-based installation, whether floating or fixed, must be approved by the governmental authorities with respect of environmental and navigation safety. Power plants and transmission lines may obstruct existing and potential new shipping routes as well as the environment.

Power production plants are typically run by private companies and are connected to a larger electric grid system. Aspects of choosing the best locations and a comparison of electricity production costs for the different ocean power technologies will be covered in a separate publication.

However, for such installations each nation also must decide whether these plants and power lines are considered as Critical Infrastructure and require additional protection provisions against cyber or kinetic attacks. Deep-sea cable security and protection has come recently under increased scrutiny.

This involves not only the costs of security measures against potential terrorist attacks but also the need for planning military protection of this energy infrastructure if deemed critical for a nation in a conflict situation.

Additional issues may arise from the regulatory and legal framework which can present challenges in the high seas due to legal uncertainties, regulatory gaps, jurisdictional disputes and limited protection against sabotage of offshore installations and subsea cables.

Nations located in higher latitudes, namely many members of NATO will not be able to cover their future renewable energy demand by wind and solar power generated within their own territory alone. Importing electric power from other regions or open oceans located at lower latitudes will not only pose additional costs and risks for their nation's energy security but will inevitably create new geostrategic and geopolitical dependencies.

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