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Review

Harvesting Energy from Ocean: Technologies and Perspectives

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Abstract: The optimal utilization of renewable energies is a crucial factor toward the realization of sustainability and zero carbon in a future energy system. Tidal currents, waves, and thermal and salinity gradients in the ocean are excellent renewable energy sources. Ocean tidal, osmotic, wave, and thermal energy sources have yearly potentials that exceed the global power demand of 22,848 TWh/y. This paper extensively reviews the technologies related to energy harvesting from waves, tidal, ocean thermals, and the salinity gradient. Moreover, the socio-economic, social, and environmental aspects of the above technologies are also discussed. This paper provides a better picture of where to invest in the future energy market and highlights research gaps and recommendations for future research initiatives. It is expected that a better insight into ocean energy and a deep understanding of various potential devices can lead to a broader adoption of ocean energy. It is also clear that further research into control strategies is needed. Policy makers should provide financial support for technologies in the demonstration stage and employ road mapping to accelerate the cost and risk reductions to overcome economic hurdles. To identify traditional and online sources on the topic, the authors used electronic databases and keyword searching approaches. Among them, the International Renewable Energy Agency data were the primary database utilized to locate sources.

Keywords: wave energy; salinity gradient; tidal energy; tidal current; tidal turbine; conversion technology

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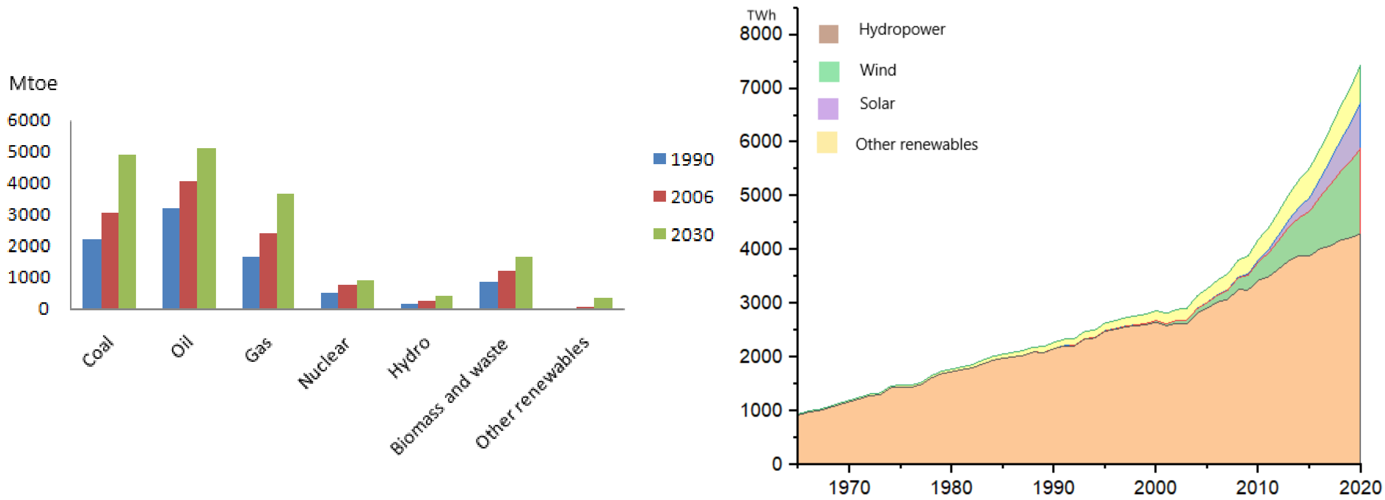
1. Introduction

The future of energy is a hotly discussed topic, particularly with regard to which energy source we can rely on in the future. We need energy sources that are safe, economical, and environmentally friendly. The influence of the COVID-19 pandemic on numerous living sectors and the declining usage of energy in the industrial and transportation sectors dominate the short-term outlook for solid and liquid fuel consumption [1] as well as the environment [2,3]. Furthermore, gaseous fuels including natural gas and biogas are considered to be more resistant to the effects of COVID-19 than oil [4]. As a result, the usage of gaseous fuels in power, industry, and buildings decreases, while their consumption in other sectors increases. In addition, combined utilization of natural gas and the adoption of carbon capture, utilization, and sequestration (CCUS) can be employed to make blue hydrogen, especially during the energy transition period. As a result, the rising gas consumption, particularly liquefied natural gas (LNG), may help bridge the gap between our current coal dependency and the shift to renewable energy, particularly in Asian regions [5,6].

As the global energy transition moves toward lower-carbon energy systems [7], renewable energy is believed to dominate the primary energy growth in the future energy outlook (see Figure 1a,b), which shows the detailed generated power from various renewables including hydro, solar, wind, and others. It is clear from this figure that hydropower is the most popular and widely adopted renewable energy resource up to today [8]. However, both wind and solar-based power generation plants are quickly expanding, especially over the last decade. As a result, the total share of renewable energy including wind, solar, geothermal, and biomass has increased significantly from 5% in 2018 to over 40% and almost 60% by 2050 in the rapid transition (significant increase in carbon prices supported by more-targeted sector-specific measures) and net-zero (rapid transition scenario plus significant shifts in societal behavior and preferences, leading to larger carbon emission reduction) scenarios, respectively [9,10]. The growing importance of renewable energy comes at the expense of hydrocarbons, whose primary energy contribution falls from about 85% in 2018 to roughly 40% and 20% in rapid transition and net-zero scenarios by 2050, respectively [10].



(**a**) (**b**)

Figure 1. Renewable energy worldwide: (**a**) Global total primary energy consumption by fuel and (**b**) renewable energy generation worldwide.

Oceans are massive alternatives to fossil fuels that are preserved in different forms including thermal energy (temperature difference), kinetic energy (in the forms of tides and waves), chemical energy (chemicals from the ocean), and biological energy (ocean biomass). Some studies predicting the annual potential energy that can be harvested from the ocean have shown several different results. Derakhshan et al. [11] forecasted the potential as ranging from 4 to 18 million tons of oil equivalent (mtoe), while Wahyudie et al. [12] estimated that about 32 TW of electricity could be harvested globally. Furthermore, de Andres et al. [13] mentioned that the potential for deploying a power converter from ocean energy could reach 337 GW with the produced annual electricity of 885 TWh. Furthermore, a more detailed potential of annual harvested energy was estimated by Khan et al. [14], who found that the tidal, wave, osmotic, and thermal difference had potentials of 800, 2000, 8000–80,000, and 10,000–87,600 TWh, respectively.

Kinetic energy is harvested by tidal current or wave generators, while salinity and temperature gradients are harvested by osmotic power plants and thermoelectric generators [15–18], respectively. The energy of a wave is related to the square of its amplitude and the motion's period. Energy flows with a 40–50 kW per meter width of oncoming wave are prevalent in significant duration (7–10 s) and high amplitude (2 m) waves [19]. The gravitational pulls of the Moon (68%) and Sun (32%) generate 7 m tides in some coastal locations throughout the world, which can be harnessed by low-headed hydropower [20]. In addition, an osmotic head of 240 m can be caused by changes in the concentration of salt between the freshwater (rivers) and the ocean. The Great Salt Lake and the Dead Sea have a 3000 m osmotic head, and oil-trap salt domes have more energy in the salt than in the oil field [21]. One-third of the ocean and seawater surface are significantly warmer than 25 °C, whereas three-quarters of its volume (deep water at 500–1000 m) is 4 °C, which is sufficient to run a low-efficiency heat engine. The available power capacity produced by ocean thermal energy conversion systems in the ocean is predicted to reach about 30 TW [22].

This review study was performed based on the relevant literature and desk-based research analysis. The areas that are discussed in this study have also been determined partially in several references [23–25]. However, it is challenging to find comprehensive works that have comprehensively discussed all aspects including the technologies, economy, and policies correlated to ocean energy. Therefore, this work is dedicated to reviewing the technologies adopted to harvest energy from waves, tidal, ocean thermals, and the salinity gradient. In addition, socio-economic, social, and environmental aspects of the above technologies were also investigated. Later, essential policies and regulations are also discussed in this paper. The rest of the study is arranged as follows: Section 2 examines the potential of different ocean energy sources. The various technologies and energy extraction devices are described in Section 3. The latest developments on wave and tidal energy projects are presented in Section 4. The impact of ocean energy on the ecosystem is depicted in Section 5. Section 6 presents a comprehensive overview of developing ocean energy sources including grid integration, societal influence, design, and, most crucially, policies and regulations. Finally, Section 7 brings the article to a close.

2. Ocean Energy Potential

2.1. Potential of Tidal Energy

Tidal energy was first adopted more than ten centuries ago to drive the grain mills in Europe, while presently, it is mainly converted to electricity [26]. The generated power is mostly linear to the surface area and the square of the water head difference. Moreover, the generated power from tidal energy can be approximated using the following equation [27,28].

$$P = \frac{C_p \rho A U^3}{2} \quad (1)$$

where P, Cp, ρ, A, and U are the generated power (W), power generation efficiency, water density (kg/m^3), cross-sectional area intercepted by the device (m^2), and current velocity (m/s), respectively.

Figure 2 shows the global distribution of tidal energy resources (shown as energy density in kW/m). In addition, Table 1 lists the potential tidal locations worldwide that have been identified as technically feasible (summarized from [29–31]). For example, in the northwestern region of Europe, there is a potential tidal energy resource that can generate a large amount of electricity [32]. Excessive tidal fluctuations and forces are caused by resonant interactions such as basin configuration, Coriolis forces, and extreme tidal fluctuation, which are primarily driven by the coupled Earth–Moon system. The increase or fall in deep water far out at sea is only about 0.5 m, which is ineffective. In general, the generated power is more predictable and less fluctuating compared to other renewables including solar and wind. However, tides fluctuate dramatically to the southeast of Boston between high and low tides, reaching a global maximum of 16 m [33].

Tidal energy technologies can be divided into three categories. Tidal range technologies form the first group, and they capture energy from the height difference between high and low tides using a barrage—a dam or another barrier. Some of the novel methods developed for tidal range power generation include tidal lagoons, tidal reefs, tidal gates, and low-head tidal barrages. The tidal current or tidal stream technologies fall within the second category. The main distinctions between the devices (ducted) are the turbines, which might be based on vertical or horizontal axes and are sometimes enclosed. The last category, hybrid applications, is a type of tidal range technology with many potentials, if its design and deployment can be integrated with the planning and design of new coastal infrastructure.

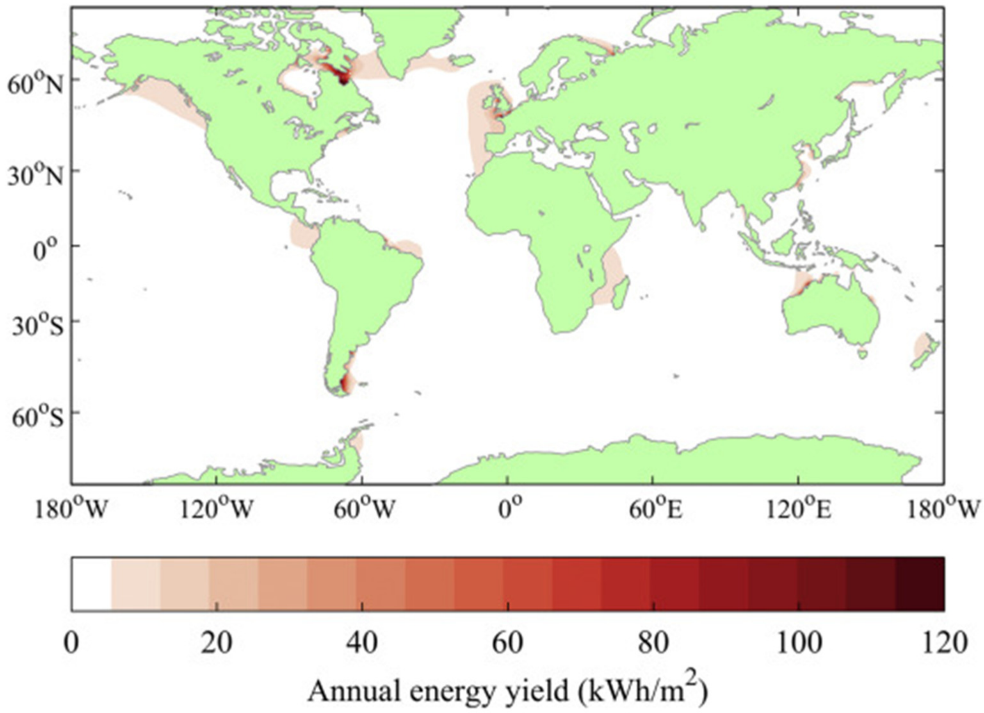


Figure 2. Worldwide distribution potential of the major tidal power computed in kWh/m^2 (adopted from [34] under CC BY-SA 4.0 license).

Table 1. Potential locations of tidal energy across the world (summarized from [29–31]).

Country	Site	Type	Mean Tidal Range (m)	Basin Area (km^2)	Proposed Capacity (GW)	Estimated Annual Output (TWh)
Argentina	San Jose	Barrage	5.9	-	6.8	20
Australia	Secure bay 1	Barrage	10.9	-	-	2.4
	Secure Bay 2	Barrage	10.9	-	-	2.4
Canada	Cobequid	Barrage	12.4	240	5.34	14
	Cumberland	Barrage	10.9	90	1.4	3.4
	Shepody	Barrage	10	115	1.8	4.8
India	Gulf of Kutch	Barrage	5.3	170	0.9	1.7
	Gulf of Cambay	Barrage	6.8	1970	7	15
South Korea	Garorim	Barrage	4.7	100	0.48	0.53
	Cheonsu	Barrage	4.5	-	-	1.2
Mexico	Rio Colorado	Barrage	6.7	-	-	5.4
	Tiburon	Barrage	-	-	-	-
UK	Severn	Barrage	7.0	520	8.94	17
	Mersey	Barrage	6.5	61	0.7	1.5
	Wyre	Barrage	6.0	5.8	0.047	0.09
	Conwy	Barrage	5.2	5.5	0.033	0.06
	Swansea	Lagoon	-	-	0.32	-
	Newport	Lagoon	-	-	0.75	-
	Bridgewater	Lagoon	-	-	2	-
	Cardiff	Lagoon	-	-	1.8–2.8	-
	Colwyn Bay	Lagoon	-	-	1.5	-
	Blackpool	Lagoon	-	-	1.0	-
U.S.	Passamquoddy	Barrage	5.5	-	-	-
	Knik arm	Barrage	7.5	-	2.9	7.4
	Turnagain	Barrage	7.5	-	6.5	16.6
	Arm	Barrage	-	-	-	-
Former Soviet Union	Mezen	Barrage	9.1	2300	15	50.0
	Tugur	Barrage	-	-	10	27.0
	Penzhinskaya	Barrage	6.0	-	50	27.0
	Cauba	Barrage	-	-	-	-

The extent of tidal energy potential is determined by the ocean's rising and decreasing waters. Along with the beach, neap and spring tides with a range of 4–12 m can produce 1–10 MW/km of electricity [35]. There are now only a handful of tidal power plants in operation worldwide. The world-first commercial level tidal power plant has been constructed in Europe. In addition, the United Kingdom was the first country that proposed harvesting tidal energy to generate electricity in 1920 [36].

2.2. Potential of Wave Energy

The combination of prevailing winds and huge regions of the open sea produces waves. Due to interaction reinforcement and interference, strong storm-force winds produce a disordered and chaotic localized wave field, resulting in a more regular series of swells propagating from the storm zone. The generated power from wave energy can be approximated by using the following equation [37].

$$P_w = \sqrt{P_x^2 + P_y^2} \tag{2}$$

$$P_x = \rho g \iint C_{gx} E(f,\theta) df d\theta \tag{3}$$

$$P_y = \rho g \iint C_{gy} E(f,\theta) df d\theta \tag{4}$$

where P_w, g, C_g, and $E(f,\theta)$ are the generated power from wave energy (kW/m), gravitational acceleration, component of absolute group velocities, and energy density spectrum in each different axis, correspondingly. Moreover, f and θ are the wave number frequencies and direction, respectively. Furthermore, wave energy flux (E_f) can be calculated using the following equation [38].

$$E_f = \left(\frac{\rho g^2}{64\pi}\right) H_s^2 T_m \approx 0.49 H_s^2 T_m \tag{5}$$

where H_s and T_m are the significant wave height (m) and mean wave period (s), respectively.

With 2% of the world's 800,000 km of coastline, which has a wave power density of higher than 30 kW/m, the wave current's estimated global technical potentials are about 500 GW of electricity (with 40% of conversion efficiency). Large wave energy resources can be found across the globe. Simultaneously, regimes vary significantly between places, resulting in a wide range of technologies [39].

Figure 3 depicts the global map of the wave power density. The map shows the wave and tide trends, and the colors show the maximum amount of wave energy extracted. Despite the modest fetch, the monsoon significantly impacts the wave environment in the South China Sea and the Arabian Sea [40,41]. In the Southern Hemisphere, swells generally travel northeast, whereas, in the Northern Hemisphere, swells propagate southeast, causing the wave period in each basin to rise from west to east. The resource is typically situated offshore, given the substantial force of westerly wind waves. However, the surges might reach further to coastlines where there are dense populations. The southern coastlines of Australia and New Zealand are the most appropriate places for wave energy development since they have year-round wave energy [42]. However, the challenge is related to the power transmission to transfer the harvested power to the continent. Considering this point, wave energy is generally extracted in the coastal areas of countries.

Table 2 shows the wave energy resources distributed across the oceans of different countries. Some coastal areas showed very high wave energy density such as the Argentine Sea (61.3–69 kW/m), Los Lagos (71–87 kW/m), and Magallanes (about 78 kW/m). However, some countries also showed relatively low wave energy density including China, Malaysia, and Japan.

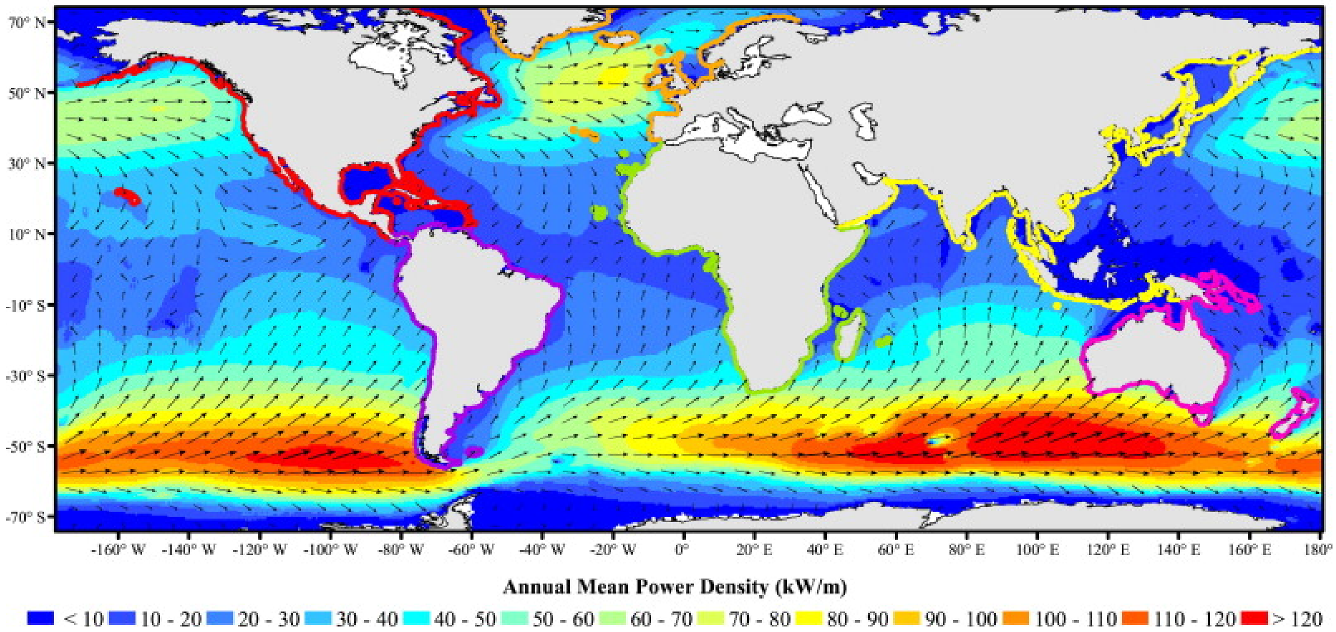


Figure 3. Annual average power per meter of wave crest (adopted from [43] with license number 5235061405721).

Table 2. Wave energy resources in different coastal areas across different countries.

Country	Location	Wave Resources (kW/m)	Reference
South Africa	South African and southwest Africa Coast	40–50	[44]
Argentina	Argentine Sea	61.3–69	[45]
Australia	Southern Australian shelf	25–30	[46]
Belgium	Belgium Continental Shelf	4.64	[47]
Brazil	North East region	2–14	[48]
Canada	North Pacific Ocean (Vancouver Island)	25	[49]
	North Atlantic Ocean (Sable Island)	25	
Chile	Los Lagos	71–87	[50]
	Magallanes	78	[51]
China	Bohai Sea	7.73	[52]
	Yellow Sea	6.29	
	East China Sea	6.36	
	South China Sea	5.32	
Denmark	North Sea	9.8	[53]
France	Bay of Biscay	24.3	[54]
Greece	Crete Island	4–11	[55]
India	Indian Coast	5–10	[56]
Ireland	West of Malin Head	30–40	[57]
	Donegal Bay	20–40	
	Sherkin Island	20	
Italy	Mediterranean Sea	8.91–10.29	[58]
Japan	Japan Sea Coast	7.2	[59]
	East Coast	6.3	
	Entire Coast	6.4	
Malaysia	East Peninsular Malaysia	<6.5	[60]
	West Peninsular Malaysia	0.5–2.0	[61]
	Sarawak Ocean	3.1–4.5	[62]
	Sabah Ocean	6.5	[63]
Norway	Norwegian Sea (Runde Island)	40–50	[64]
Portugal	Portuguese nearshore	30–40	[65]
Sweden	Skagerrak Strait	2.8–5.2	[66]
United Kingdom	Celtic Sea	15–32	[67]
United States	Hawaii	15–25	[68]
	California Coast	10–32	[69]
	Pacific Northwest	36	[70]
	Southeast Atlantic Coast	9–15	[71]

2.3. Potential of Ocean Temperature Difference

Ocean thermal energy conversion (OTEC) technologies generate energy by converting the temperature gradient between the hot saltwater at the ocean's surface and the cold seawater at depths of around 800–1000 m. Warm saltwater is utilized to create vapor (as a working fluid), which drives the turbines. On the other hand, cold water condenses the vapor and guarantees that the vapor pressure difference is sufficient to drive the device. Figure 4 shows the global distribution of the temperature difference between the warmer seawater at the surface and colder deep seawater. It is shown that tropical areas around Southeast Asian countries have the highest temperature difference; hence, these countries have a higher potential for the application of OTEC.

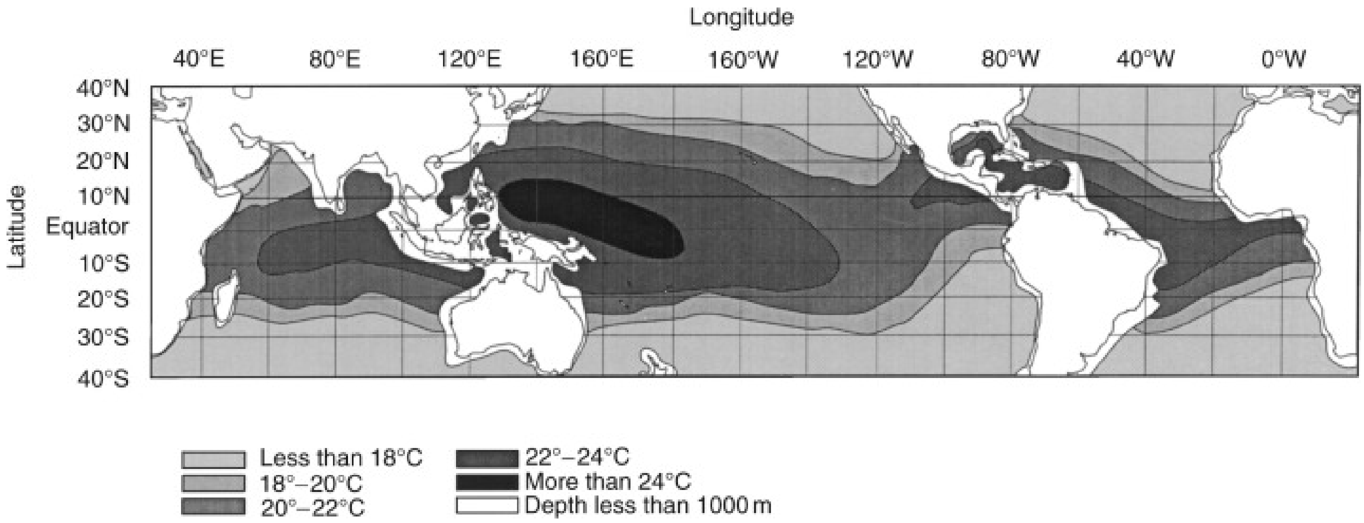


Figure 4. Temperature differences between the ocean surface and deep water across the globe (adopted from [72] with license no. 5240581259275).

The temperatures at the source and the destination (T_h and T_c, respectively) remain constant when hot and cold water are supplied rapidly to a heat engine, where the energy handled by the engine is low in contrast to the total throughout. Theoretically, Carnot's theorem provides the greatest efficiency of heat-to-work conversion (η_c), which is written as:

$$\eta_c = {}^{W}/_{Q} = 1 - \left({}^{T_c}/_{T_h}\right) \tag{6}$$

Driving water at a high rate through the warm and cold reservoirs, on the other hand, wastes a significant amount of energy in the current situation. Therefore, several researchers have tried to optimize the performance [73–75] and acquired power when the temperature of the source and sink water is allowed to fluctuate. When defining the heat transfer that occurs in the heat exchangers, the link between the two elements of thermal efficiency and thermal energy signifies the upper bound of the thermal efficiency at the highest power output of the heat engine in finite-time thermodynamics (FTTs) [76–79]. At that time, the ideal thermal efficiency η_{th}, CA (Curzon–Ahlborn) is expressed as follows:

$$\eta_{th,CA} = \eta_{pc} = 1 - \sqrt{\left(\frac{T_c}{T_h}\right)} \tag{7}$$

When the heat transfer performance is infinite and the seawater has a constant temperature, the heat transfer performance is unlimited in the heat exchange process. However, because a finite volume of seawater is injected into the heat engine in the power plant for power generation using standard OTEC procedures, an increase in seawater flow rate results in a considerable rise in seawater intake pumping power. As a result, a temperature shift in the saltwater is unavoidable. Under typical OTEC circumstances, which are a temperature difference (T_h–T_c) of about 24 °C and surface seawater temperature (T_h) of 27 °C, the calculated η_c and η_{pc} generally have values of 8% and 4%, respectively. Carrying cold water to the surface from a depth of 1000 m and other internal loads will typically require 1% of the total output of work per unit of heat energy. Therefore, the final net η_{pc} ($\eta_{pc,\ net}$) is around 3%.

This efficiency is about one-twentieth of the efficiency of the most advanced modern combined-cycle unit and about 10% of the nuclear or coal-fired power plants. The large physical size per MW of OTEC results in a high specific cost, even though the fuel is free. Furthermore, the expense of operating and maintaining a ship at sea is higher than on land.

When all ocean energy technologies are compared, OTEC shows the highest potential [80,81], and 98 nations and territories have been recognized as having feasible OTEC resources in their exclusive economic zones. According to recent research, OTEC may provide all of the world's power generation capacity while not affecting the ocean temperature profiles. Furthermore, OTEC resources are also available within 10 km of the Caribbean and Pacific Ocean coast with many island countries. OTEC appears to be particularly well-suited and economically feasible for distant tropical islands where generation may be coupled with other sources such as air cooling and freshwater generation [82].

2.4. Potential of Salinity Gradient

Salinity gradient power energy is the energy generated by the difference in salt content between two fluids, most commonly freshwater and saline, such as when a river flows into the sea. Figure 5 shows the average global sea surface salinity. Globally, the entire technological potential for salinity gradient power is projected to be approximately 647 GW, equivalent to about 5177 TWh annual electricity production or 23% of the energy consumption in 2011 (worldwide power capacity in 2011 was 5456 GW). However, this potential does not consider any biological or legal restrictions on the deployment of salinity gradients, therefore, the real potential is lower [83]. Canada, Colombia, Germany, the Netherlands, and Norway are among the countries that have conducted extensive research on the ecological and legal implications of water extraction. Salinity gradient power generation employed in hybrid applications is not included in the current estimations. Because waste streams from wastewater and desalination facilities often have greater salt concentrations than the surrounding seawater, the technological and economic possibilities for these applications might be significant. As a result, the amount of energy generated per volume (kW/m^3) of brine would be larger, with lower total costs. Extensive research works are necessary to identify the potential of hybrid solutions, land-based saltwater lakes, and other forms of saltwater reserves.

Two membrane-based technologies are now being tested in demonstration projects. In a pressure retarded osmosis (PRO), a membrane is utilized to separate a concentrated salt solution (such as seawater) from freshwater. Through a semi-permeable barrier, freshwater flows toward the seawater, raising the pressure within the seawater chamber. The pressure is regulated, and electricity is generated by a rotating turbine. In reversed electrodialysis (RED), membranes are utilized to transport salt ions. RED is made from a stack of alternating cathode and anode swapping permselective membranes. Seawater and freshwater alternately fill the compartments between the membranes. The salinity gradient acts as a driving force for ions to move, resulting in an electric potential that can be converted to power [83].

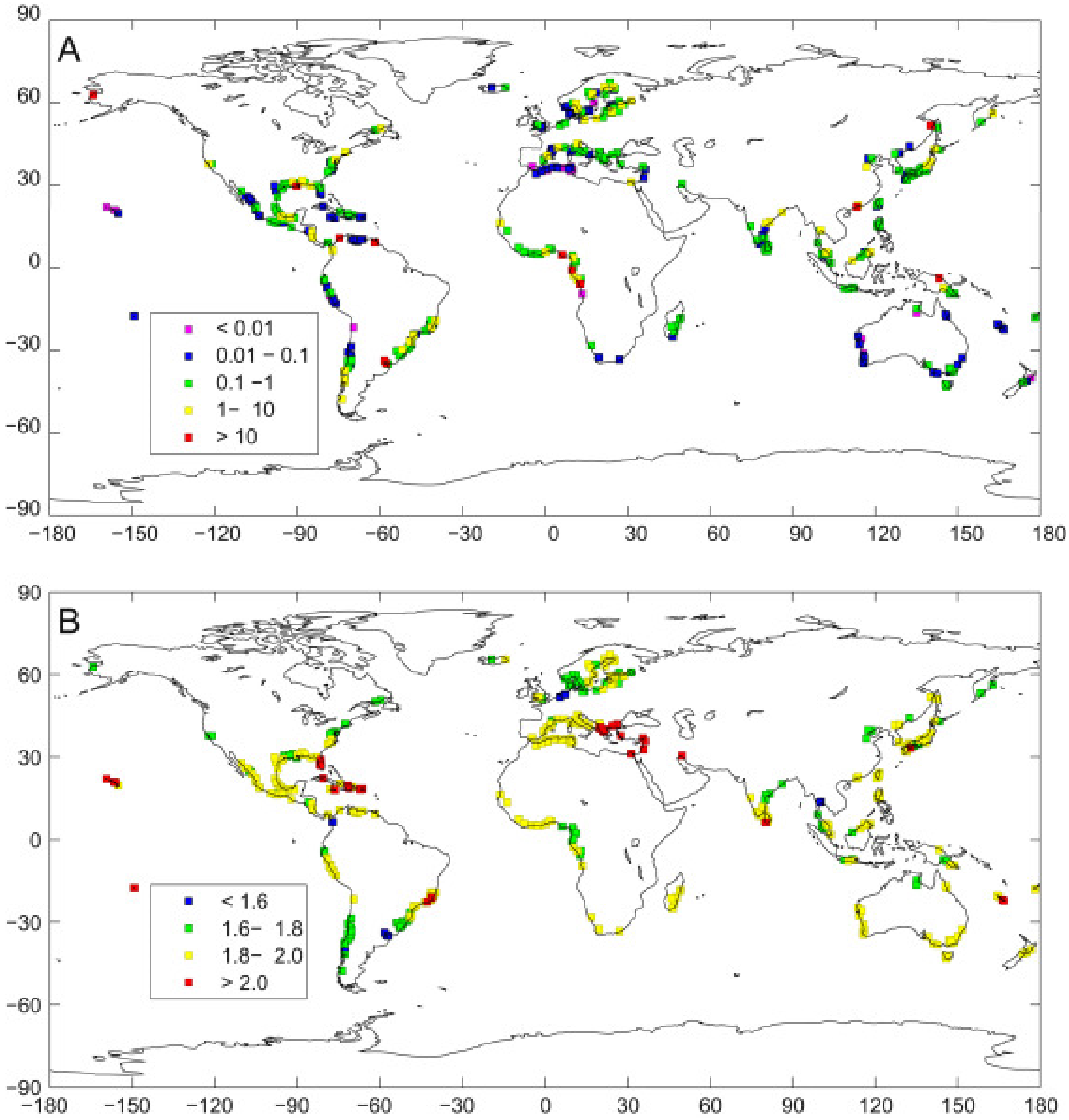
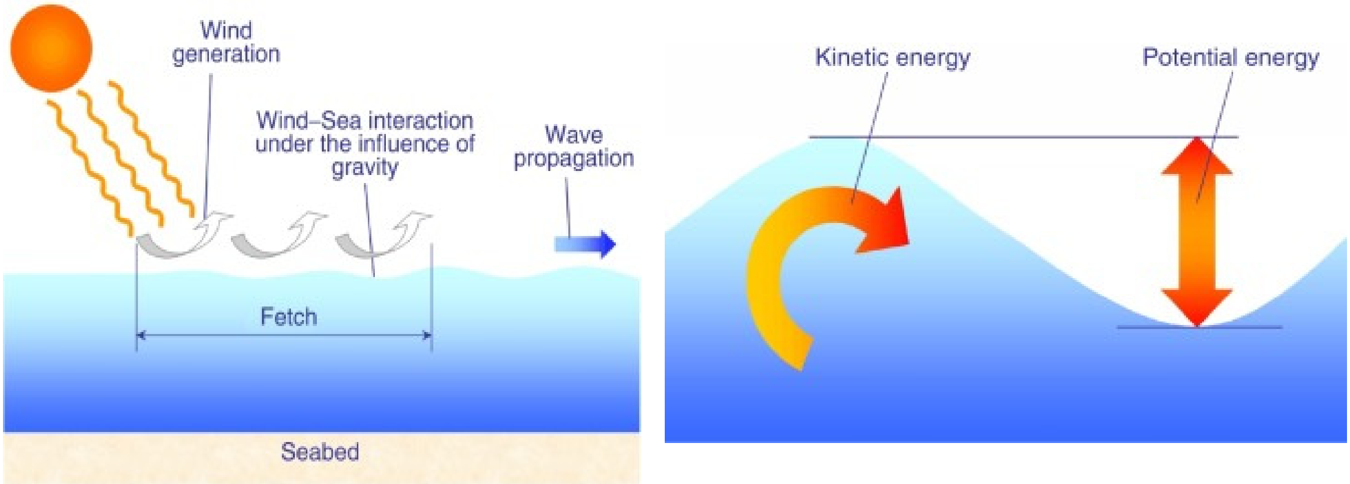


Figure 5. Average global sea surface salinity: (**A**) Energy that can be extracted (TWh/a) and (**B**) energy density (MJ/m^3) (adopted from [84] with license no. 5240621253046).

3. Energy Harvesting Technologies from Wave/Tidal

Wave energy converters (WECs) convert the energy from the kinetic and potential energy of ocean surface waves into another kind of energy. Two major turbines are adopted: horizontal and vertical axes turbines. The rotating axis of a wind turbine is horizontal or parallel to the ground when it has a horizontal axis, while it is vertical or perpendicular to the ground in vertical axis wind turbines. The wind itself causes this turbine to rotate. When the wind goes to the surface of the water, the waves are generated because of the different viscosity of the two fluids. Despite the complexity of air–sea interactions and energy transfer pathways, ocean surface wave generation is essentially governed by wind speed, duration, and fetch. The size depends on the air quality, airspeed, and period. Figure 6 shows how the waves are generated. Moreover, tides are generated due to the celestial motion of the Earth, Sun, and Moon. The wavelength of these tides is of various kilometers, while the biggest can reach up to the Earth's radius. They travel in a fashion more streamlined than the wind resource, and as their direction is more uniform, they can exert greater power. Therefore, if we translate it inside the water and place it on the ocean's surface, we would be able to extract more power for a more sustained period, which is what tidal turbines do. This turbine is connected to the shaft, which is connected to the gearbox and power generator [85].



(a) (b)

Figure 6. Ocean wave generation: (**a**) Wave generation induced by wind and (**b**) energy components in the wave (adopted from [86] with license no. 5240591291694).

Toward this aim, many technologies based on wave-induced pitching, heaving, or surging action have been proposed [82]. Hydraulic pistons are generated using oscillating water column (OWC) devices, and the air is propelled through the turbine, rotating the power generator (explained in Section 3.1). However, when the wave-power devices must resist linear wave-power densities over 200 kW/m, one of the design difficulties is related to their fragility. Hence, intensive and expensive design criteria should be used because of this constraint.

3.1. Wave Energy Extraction Devices

Ocean waves are basically generated by the wind blowing on the ocean surface. The extraction of ocean wave energy can be performed directly from surface waves or by utilizing the pressure fluctuations under the wave [26]. Therefore, depending on the area of installation, it can be categorized into nearshore, offshore, and far offshore. The wave energy is initially converted to mechanical energy, which is further converted to electricity.

3.1.1. Oscillating Water Columns (OWCs)

OWCs are energy converters with a semi-submerged chamber that keeps a trapped air pocket above the water column. When the wave approaches, it forces the column to move up and down like a piston, causing the water to rise and fall. Moreover, the air is sucked out of the chamber, then sucked back in. Finally, water is channeled via rotor blades and drives the air turbine-generator group. As a result, energy is generated. The significant benefits of these systems are their simplicity (there is no moving part, except for the air turbine) and reliability. However, the performance is relatively low. Therefore, new control techniques and turbine ideas are being developed, which are expected to significantly improve the power generation performance.

Figure 7A shows the working principle of the OWC. First, the waves cause the buoy (yellow bit) to move up and down. The fluid, which can be liquid or even air, is immersed inside the column and constrained in a channel. Therefore, when the float moves up and down, it pushes the fluid through the system. Finally, the turbine in the base is rotated whenever any fluid passes through, generating the electricity [87]. Moreover, Figure 7B shows the wave energy extraction using multi OCW units with different structures including array, segmented, and modular.

It is expected that this kind of wave energy extraction device can harvest the electricity of 15–25 kW/m annually [88]. In addition, according to Liu et al. [89], this kind of device has the highest commercialization opportunity compared to other wave energy converters. Furthermore, Table 3 lists some of the active wave energy harvesting systems based on OWC including both fixed and floating systems.

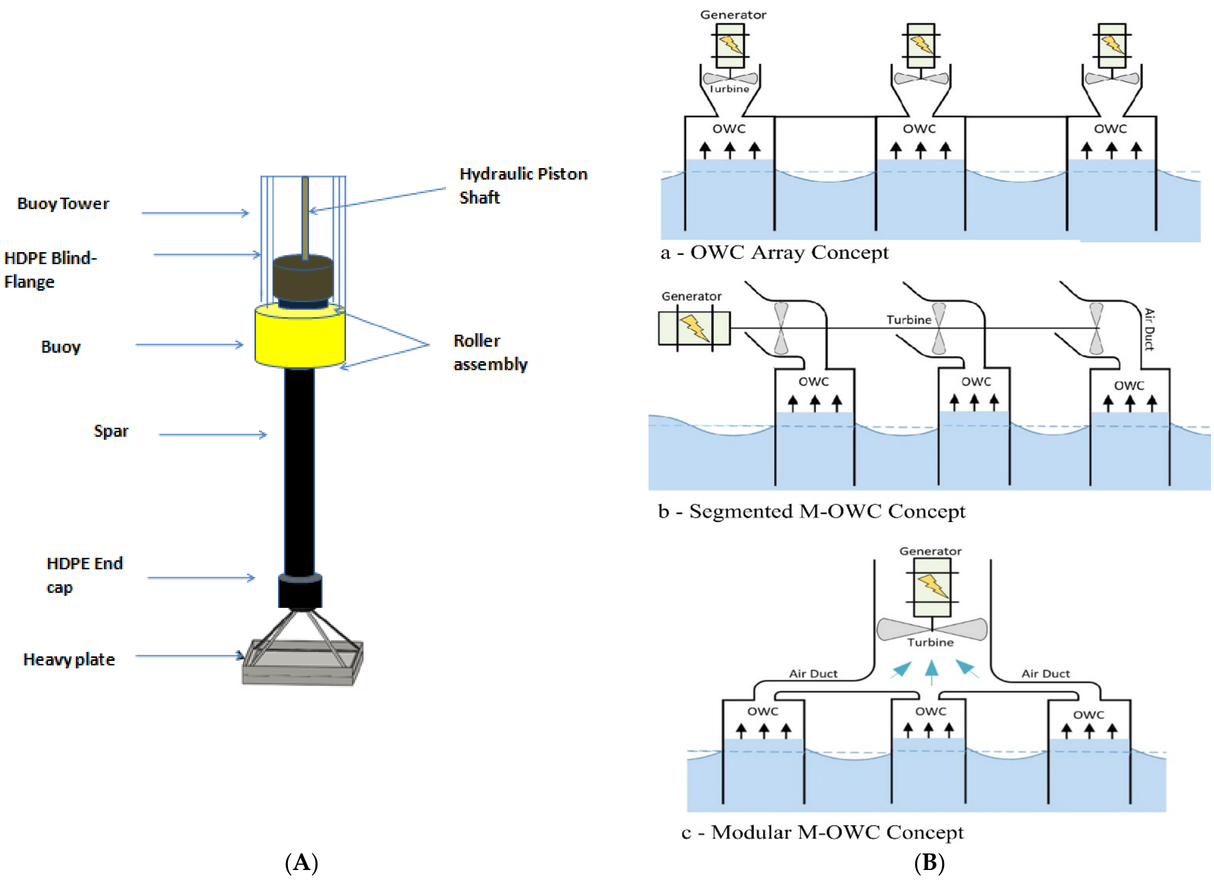


Figure 7. Electricity generation employing OCW: (**A**) Working principle of the point absorber (authors' own illustration) and (**B**) multi OCWs with different configurations (adopted from [90] with license no. 5240610225589).

Table 3. Running demonstration projects for OBC in several countries.

Type	Project and Place	Capacity (kW)	References
Fixed	Mutriku, Spain	296	[91]
	REWEC3, Italy	20 (potential of 2500)	[91]
	King Island, Australia	200	[91]
	Yongsoo OWC, Korea	500	[91]
Floating	MARMOK-A-5, Spain	30	[91]
	Ocean Energy Buoy, Ireland	500	[91,92]

3.1.2. Oscillating Body Converters (OBCs)

OBCs are either submerged (occasionally anchored to the bottom) or floating (typically). They utilize the stronger wave regimes that often occur in deep seas at a depth of more than 40 m. OBCs are generally more sophisticated than OWCs, especially their power take-off (PTO) systems. Indeed, several PTO systems have been produced due to the numerous concepts and methods for converting the oscillating movement into electricity.

As shown in Figure 8, a system of hydraulic rams converts the oscillating (rectilinear or angular) motion of a floating body (or the relative motion between two moving bodies) into a high-pressure (HP) flow of a liquid (water or oil) in vast devices (or equivalent devices). A hydraulic motor (or a high-head water turbine) operates an electric generator at the other end of the hydraulic circuit. A gas accumulator system can smooth out the highly variable hydraulic power provided by the reciprocating piston (or pistons), allowing for more consistent electricity production. The smoothing effect naturally grows in proportion to the accumulator volume and working pressure [93].

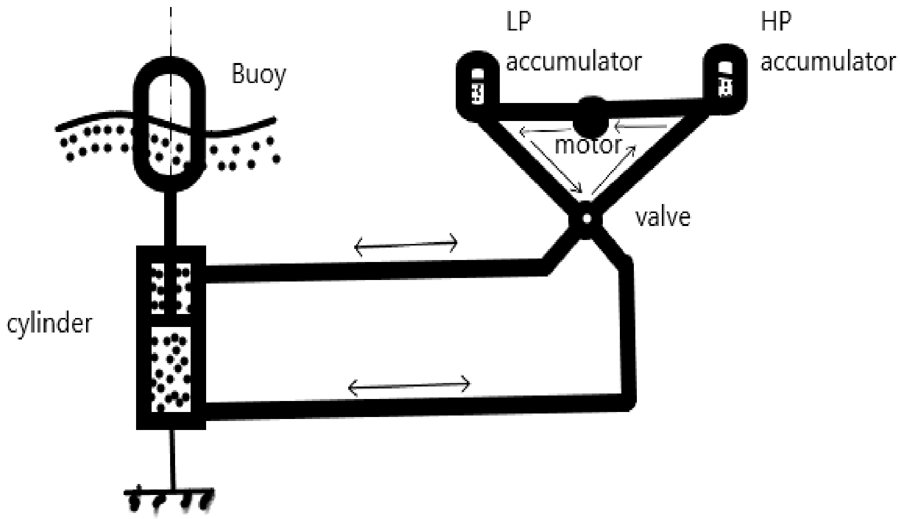


Figure 8. The OBC working principle.

Furthermore, Table 4 displays several running projects employing OBC to harvest energy from the ocean including Columbia Power Technologies Power Buoy, Oyster (Scotland), Seatricity (Cornwall), Pelamis (Scotland), and Wave Star (Denmark). Because most OBCs are floating devices, they have the benefit of being small and versatile. However, a separate technology has yet to be developed, and further study is needed to improve the PTO's performance and prevent certain mooring system difficulties.

Table 4. Running demonstration projects for the OBC in several countries.

Type	Project and Place	Capacity (kW)	References
Heaving	PB3 PowerBuoy, USA	3	[94]
	CET06, Australia	1000	[95]
	Atmocean, USA	10	[96]
	Seabased, Sweden	30	[97]
	Oceanus, UK	162	[98]
	Corpower, Sweden	300	[95]
	BOLT LifeSaver, Norway	30	[95]
	Neptune 6, Canada	20	[95]
	Archimedes Waveswing, UK	16	[91]
Horizontal	Wavepiston, Denmark	100–200	[95]
	40South Energy H24, Italy	50	[95]
Flap	WaveRoller, Finland	350	[99]
	CCell-Wave, UK	-	[100]
	LAMWEC, Belgium	200	[95]
	bioWAVE, Australia	250	[95]
Articulated	SeaPower Platform, Ireland	-	[101]
	SeaRay, USA	5	[91]
	Blue Horizon, UK	-	[91]
	Blue X, UK	2–4	[91]
	M4 WEC, UK	-	[95]

3.1.3. Overtopping Converters

Overtopping converters are made up of a water reservoir construction that is either floating or attached to the ground and, in some cases, reflecting arms that ensure that as waves approach, they pour over the top of the ramp structure and are confined in the device's reservoir. The potential energy is turned into electricity using ordinary low-head hydro turbines due to the height of the collected water above sea level (equivalent to the mini-hydro plants).

The primary benefit of this system is its basic concept: it holds water and then lets it run through a turbine when it is full. The low-head (to the order of 1–2 m) and vast proportions of a full-scale overtopping device, on the other hand, are two key disadvantages. Figure 9 depicts an overtopping wave energy converter. Currently, the overtopping breakwater (OBREC) [91] is one of the operating overtopping types of wave energy converter. It was developed by the University of Campania Luigi Vanvitelli and installed in the Thyrrenian Sea, Napoli, Italy, with a capacity of 8 kW.

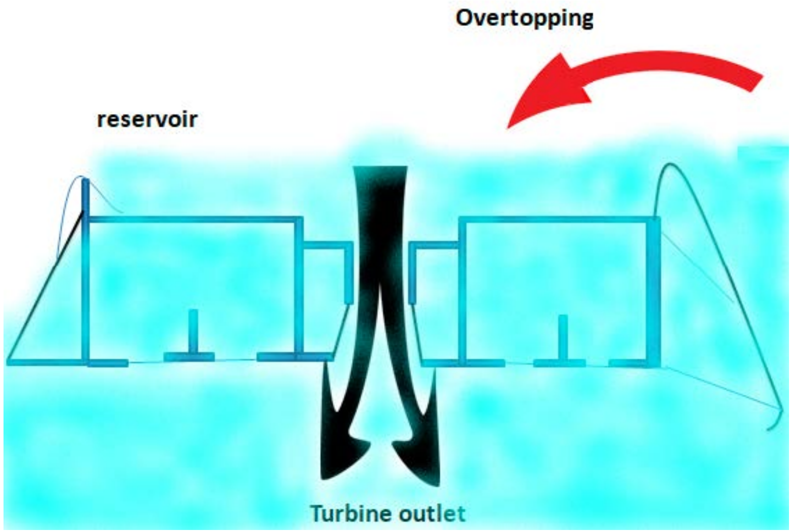


Figure 9. Overtopping wave power converter.

3.1.4. Wave-Activated Bodies (WAB)

Wave-activated bodies (WABs) extract energy when the wave interaction drives a floating body. WAB is set up in a partially floating configuration, in which the device is aligned with the prevailing wave direction. The body follows the contour of the passing wave, as shown in Figure 10. As the wave travels through the WAB, this occurrence occurs repeatedly and perpetually [102]. The movement enables the conversion of kinetic energy to electricity via hydraulic or mechanical transmission. The floating bodies are securely joined in an array utilizing universal joints, which hold and allow bodies to move. The design is straightforward, consisting of a chain of rafts [103] coupled to the hydraulic piston and capable of serving as a hinge mechanism as well as a PTO system. The best number of raft trains was determined to be three [104], which resulted in high overall efficiency. In addition, the authors in [105,106] made improvements leading to higher overall efficiency, ranging from 10 to 35% [107]. The power output of one system tested in the North Sea was 150 kW [108].

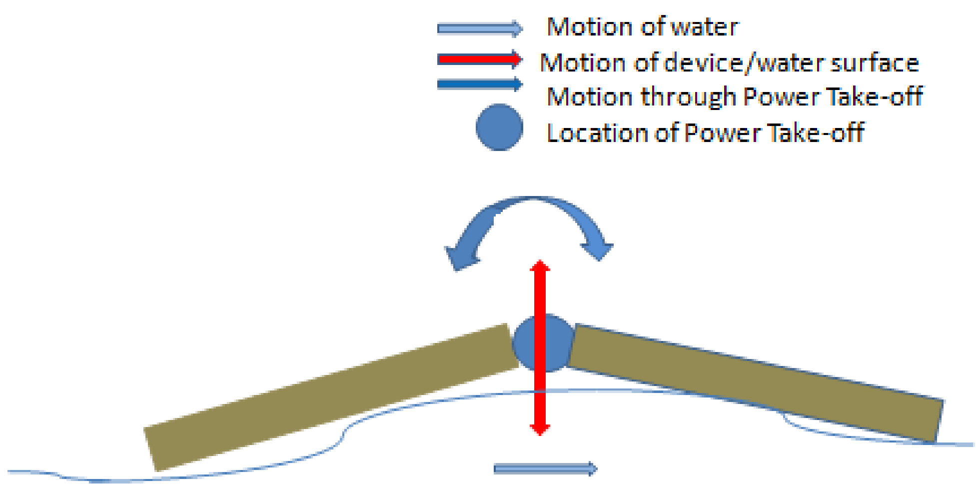


Figure 10. The concept of a wave-activated body.

3.1.5. Point Absorber

In relation to the rotational wave motion, a point absorber is defined as a floating or submerged body oscillating in a mix of heave, sway, and pitch. This type of point absorber can typically catch waves coming from various directions. In most cases, the point absorber device comprises the floater (floating buoy) and the absorber (also called as PTO) units. Figure 11 depicts a typical setup of point absorbers. As wave crests and troughs pass through the floater unit, the floater unit will concurrently react in a heavy direction due to the pressure difference effect. This heaving motion is then used to rotate the generator, generating electricity [109].

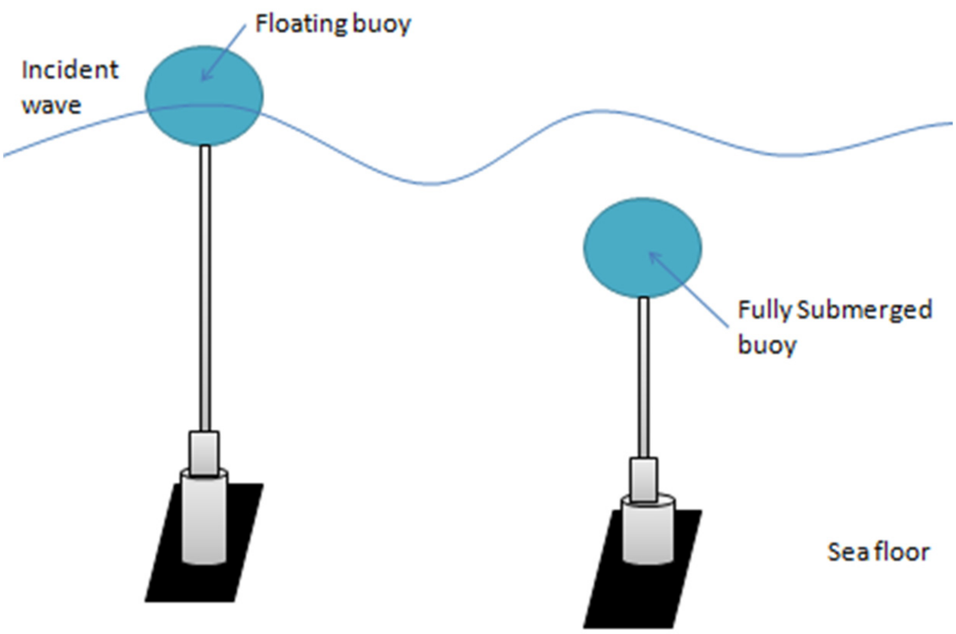


Figure 11. Two types of point absorber: submerged body and floating body.

An Archimedes wave swing device is an example of a submerged point absorber [110]. The idea of the floating-point absorber is based on the movement of a partially submerged buoy. As shown in Figure 11, the wave surface fluctuation drives this movement. The partially submerged buoy typically has a tiny diameter compared to the ocean wavelength, and it can act alone or in an array. The Ocean Power Technologies (OPT) power buoy [111] is an example of a floating-point absorber. This contraption creates electricity by causing the floating buoy to move vertically in relation to the vertical spare motion; heavy mass on the vertical spar unit is necessary to improve its mass moment of inertia. The OPT device with a power rating of 40 kW has been successfully tested in the Pacific and Atlantic Oceans [112].

3.2. Tidal Energy Extraction Devices

Tidal energy is a type of fresh energy that is both renewable and pollution-free, and has become more popular throughout the world. Tidal energy has many potentials in terms of dependability, superior energy density, certainty (predictability), and durability [113]. The energy extracted from the tides is dependent on predictable and consistent vertical water motions. The water's predictable vertical movements, which cause tidal currents, can be turned to kinetic energy and used to generate electricity. Tidal energy has two different forms: tidal range (potential) and tidal current [114]. The first is to use barrages to take advantage of the cyclic rise and fall of sea levels by extracting energy from the potential head of the water, comparable to hydropower generation. The second option is to use local tidal currents in a similar way to wind power. This technology uses tidal current energy converters such as tidal turbines to extract the kinetic energy of moving water [115].

3.2.1. Tidal Range Technologies

The potential energy generated by the difference in the head between the ebb and flood tides is harvested by tidal range devices. Such resources exist in places where enormous water volumes flow into compounding areas, bays, and estuaries due to geological and biological factors. Furthermore, tidal range energy is predictable. It is controlled mainly by cyclical constellations and the gravities of the Moon, Sun, and Earth, rather than meteorological circumstances, resulting in a predictable bi-weekly, biannual, and yearly cycle.

Most tidal power generation plants basically originated from tidal barrages, which were constructed from 1966 to 2011 using bi-directional tidal flows [116]. From the modes of operation, tidal barrage can be categorized into one-way using ebb only, one-way using flood only, and two-ways using ebb-flood [117]. Tidal barrages can channel mechanical energy, while tidewater river turbines can seize the energy from tidal currents. The blade is made to be very streamlined, and the fluid flows and hits this blade. As a result, different types of force are produced. The lifting force causes the blade to move up, while the drag force leads the blade to move in the other direction, and the combination of lifting and drag forces produces torque. Finally, the torque causes the rotor to rotate around its axis to be further converted to electricity.

Many demonstration projects employ tidal range technologies such as 1 MW twin-rotor turbines (Devon Marine Current Turbine) and the 400 MW tidal-power station at San Francisco Bay (PG&E) [118]. As shown in Table 5, many designs are still in the conceptual stage with no quantitative data available [119–121]. More research is needed using a combination of advanced computational fluid dynamics (CFD) and scale model testing to properly determine whether any of them might feasibly replace bulb turbines [29].

Furthermore, contemporary tidal range projects have significant advantages in situations when existing dams or complexes are employed. In this case, energy generation is linked with water quality improvement. Aside from the Sihwa barrage in South Korea, the Netherlands is working on a project in Grevelingen Lake, while Canada is working on projects in British Columbia to convert historically closed impoundments into energy-producing impoundments [122]. The greatest concerns related to tidal energy power generation plants is the high construction cost for barrages and dams. In addition, it also potentially has high environmental impacts such as the change in original characteristics, alteration of the tidal flushing regime, and diminishing the aquatic habitat [117]. Therefore, due to these concerns, the technological trend is directed toward the adoption of tidal turbines as a promising option.

Table 5. Studies and projects related to tidal range technologies.

Technology	Case Studies	Mean Tidal Range (m)	Output (MW)	Notes, Operation Type	Turbine Used
Tidal barrage	La Rance (France)	8.5	240	Two-way generation with pumping, firstly operated in 1966, basin area of 22 km^2	Bulb
	Sihwa Lake (South Korea)	5.6	254	Flood generation, first operated in 2015, basin area of 56 km^2	Bulb
	Kislaya Guba (Russia)	2.3	1.7	Two-way generation, firstly operated in 1968, basin area of 1.1 km^2	Savonius
	Annapolis Royal (Canada)	7.0	20	Ebb generation, firstly operated in 1984, basin area of 15 km^2	Rim
	Jiangxia (China)	5.1	3.9	Two-way generation, firstly operated in 1980, basin area of 1.4 km^2	Bulb
	Severn Estuary (UK)	7.8	8640	Two-way generation, basin area of 450 km^2	Bulb
	Incheon (South Korea)	5.3	1320	On hold, basin area of 110 km^2	-
	Mezen (Russia)	9.1	19,200	Proposed, basin area of 2300 km^2	-
	Penzhin (Russia)	9.0	87,000	Proposed, basin area of 20,530 km^2	-
	Solway Firth (UK)	5.5	-	-	-
	Bay of Fundy (Canada)	11.7	-	-	-
	Gulf of Cambay (India)	6.1	-	-	-
	Maluanwan (China)	2.58	24	Proposed	-
	Bachimen (China)	3.1	36	Proposed	-
	Jiantiaogang	2.63	21	Proposed	-
Tidal lagoon	Swansea Bay	-	320	Firstly operated in 2019, Two-way generation with pumping, basin area of 11.5 km^2	Bulb
Tidal reef	No existing locations	-	-	-	-
Tidal fence	No existing location	-	-	-	-

3.2.2. Tidal Current Technologies

In the last five to seven years, tidal current or tidal stream technologies have made tremendous progress toward commercialization. Almost 40 new devices are being developed right now, and only a few of them have been thoroughly tested in the UK's waters. The kinetic energy in tidal current or tidal stream technologies is converted into usable energy (electricity). The advancement of technology is analogous to the advancement of wind turbines. The tidal current energy converters can be categorized into horizontal axis tidal current turbines (HATCTs), crossflow or vertical axis tidal current turbines (VATCTs), and other non-turbine devices [115].

Figure 12 shows the working principles of three types of tidal current technologies. Blades, which are parallel to (horizontal) or perpendicular to (vertical) water flow, are used in tidal turbines with horizontal (HATCT) and vertical (VATCT) axes, respectively. The turbines are designed similarly to wind turbines; however, the blades are smaller and move more slowly due to the increased water density. They must also be able to withstand adverse situations.

Blades are generally connected to a central rotor shaft connected to a generator shaft. An open-center turbine's blades are mounted on an inner shaft, which is an open-centered shaft enclosed in a static tube. As the water passes through the shaft, it spins, generating electricity. The benefit of this design is that it eliminates the need for a gearbox. The blades of horizontal or vertical turbines can also be encased in a duct. Moreover, enclosed, ducted, and shrouded turbines are later types of turbines (Figure 12).

According to an extant tidal current project assessment, HATCTs account for 76% of all turbines, while vertical axis turbines account for 12% [25]. This is due to the fact that HATCT has simpler operating principles as well as its ability to realize higher energy efficiency (over 35%) [123]. Furthermore, horizontal axis turbines received 76% of all research and development spending on tidal current technology in 2011, while the enclosed and vertical axis turbines received 4% and 2%, respectively [124]. On the other hand, VATCT seems to be preferable under weaker current conditions because of its performance in generating higher torque at lower current velocity and tip speed ratio [125].

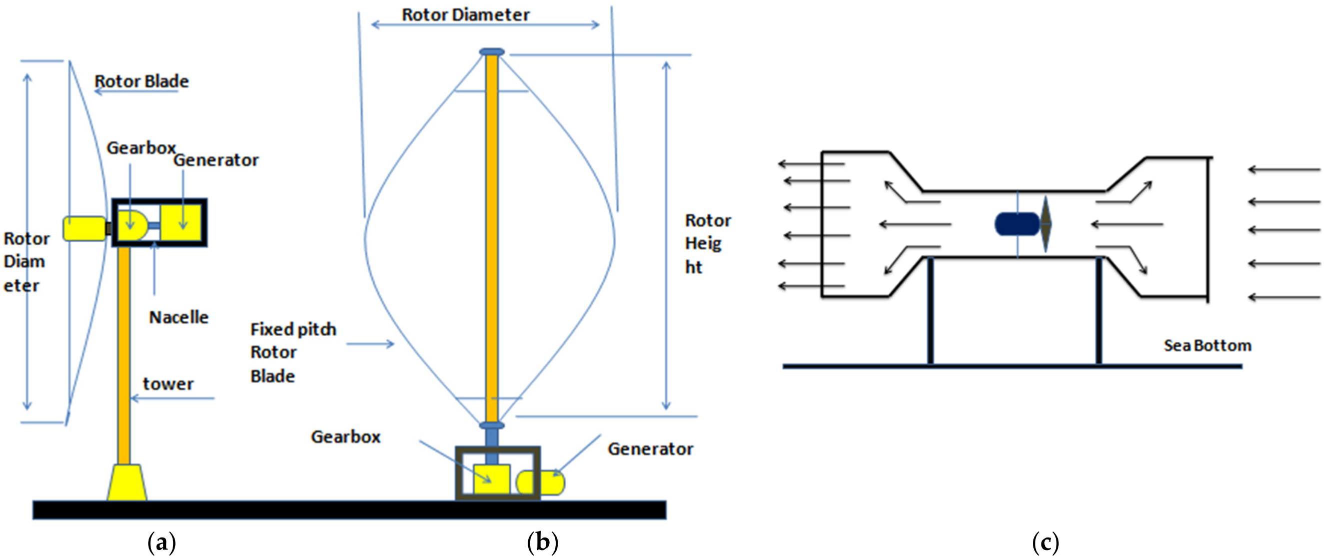


Figure 12. Working principles of different tidal current technologies: (**a**) HATCT, (**b**) VATCT, and (**c**) enclosed turbines.

Other non-turbine devices consist of diversified design concepts including oscillating hydrofoil, tidal kites, flutter vane, hydro venture devices, and piezoelectric [126,127]. Figure 13 shows the representative non-turbine devices including oscillating hydrofoil and tidal kite. A tidal kite developed by Minesto (one of spin-out from Saab) is an example of non-turbine technology, which was developed to match the conditions of low current velocity [128].

Furthermore, regarding the platform used for the power generation plant adopting tidal currents, Sheng et al. [125] classified it into three different systems: (a) a floating moored system, which has simpler maintenance, easy installation and removal, and is preferred to be adopted in areas where the sea-bed is deep and mostly stone; (b) a pile mounted system, which is appropriate for sea-bed with depth of about 30–60 m; and (c) a sea-bed mounted system, which is efficient for shallow sea-beds and conditions when the wave and wind effects are small.

Tidal turbines need to be designed to be robust and reliable as they face several severe challenges including cavitation, bio-fouling, sedimentation, stall, and fluctuating Reynolds number [129]. The technologies for tidal turbine are basically developing, covering wide aspects of the hydrodynamics, operating parameters, and environmental issues [130]. Comprehensive measurement data and monitoring should be conducted, especially related to the flow field characteristics including the wake behind the turbine [131]. Moreover, the economic performance is still the biggest problem for the adoption of tidal current technology. To increase its economic performance, it has been suggested that the turbine should be able to evenly harvest bi-directional flows [132].

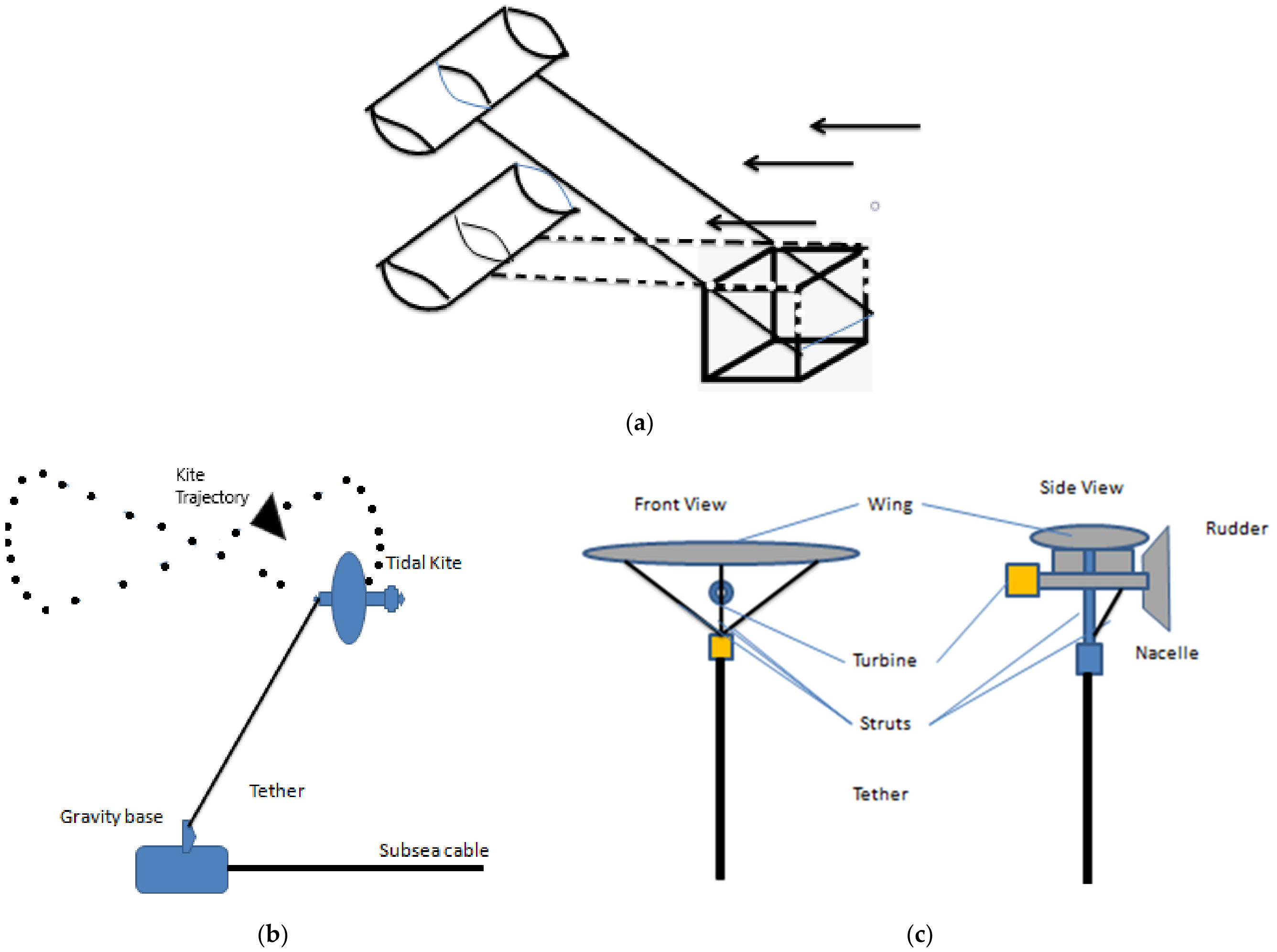


Figure 13. Other non-turbine devices to harvest the energy from tidal currents: (**a**) oscillating hydrofoil and (**b**) general working mechanism of a tidal kite, and (**c**) operating method and schematic of Minesto's Deep Green tidal kite.

3.3. Ocean Thermal Energy Converter (OTEC)

The OTEC is a method of producing energy from the temperature difference between the surface and the deep ocean in a sustainable manner. In 1881, J. A. D'Arsonval proposed the OTEC, and in 1930, G. Claude tested an OTEC concept off the coast of northern Cuba. [133]. In collaboration with the Hawaiian Government, the first floating OTEC facility was built off the western coast of Hawaii in 1979 by Lockheed Missiles and Space Company and Dillingham Corporation [133]. Around 1996, the Pacific International Center for High Technology Research (PICHTR) operated an OTEC plant in Hawaii that produced 255 kW gross and 103 kW net electricity [133]. This PICHTR-operated OTEC system is an open-cycle OTEC system [133]. Using this method, the temperature difference from the ocean surface to deeper depths turns the thermal energy into electricity. When there is a temperature difference of at least 20 °C, the OTEC can operate sufficiently [134].

OTEC systems come in a variety of shapes and sizes including open- and closed-cycle systems [133]. As shown in Figure 14, OTEC can be used in a desalination system, to supply cold water for ventilation and watering, and offer nutrient-rich water for marine culture, in addition to producing electricity for the grid [133,135]. Furthermore, Table 6 shows some projects related to OTECs in different countries.

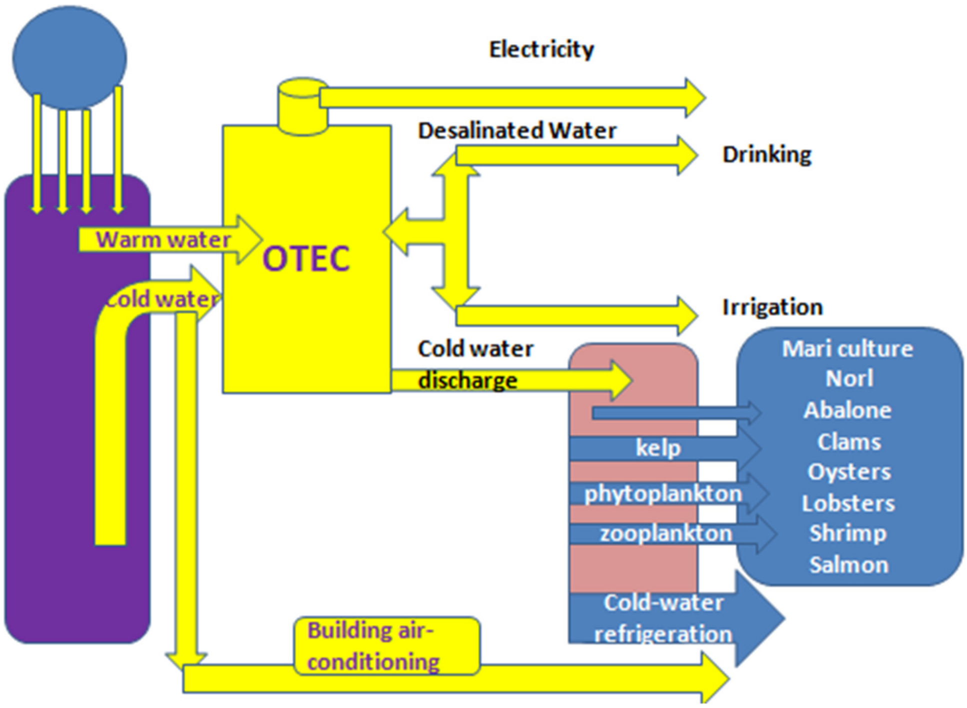


Figure 14. Byproducts from an open-cycle OTEC.

Table 6. Running demonstration projects for OTECs in several countries.

Project and Place	Capacity (kW)	Ref., Notes
Kavaratti, Lakhshadweep Islands, India	60	[91], under development
KRISO, Goseong, Korea	20	[91], operational
KRISO, Korea	1000	[91], under development
Nauru, Japan	120	[136], constructed in 1982
Okinawa, Japan	50	[136], constructed in 2013, a land based plant
NELHA, Hawaii	50	[136], constructed in 1979
OTEC International LLC, Hawaii	1000	[136], operated between 1993–1998
Lockheed Martin naval facility, Hawaii	10,000	[136]
Tuticorin, India	1000	[136], a floating closed cycle
Southern China	10,000	[136]
Martinique, Bellefontaine	10,000	[136], a floating type

3.3.1. Closed-Cycle OTEC

The initial concept of a closed-cycle OTEC [133] was developed by D'Arsonval. Heat transfer from the warm saltwater in the evaporator is used to evaporate the working fluid. The vapor expands in the turbo generator and condenses in the condenser due to the heat transfer to cold saltwater. Figure 15 shows the conceptual diagram of a closed-cycle OTEC system.

Closed-cycle OTEC power systems require smaller turbines than open-cycle systems because they run at higher pressures [14,137]. The temperature of the warm seawater evaporates the working fluid in a closed-cycle system, and the vapor then expands via the turbo generator, producing energy [133]. The expanded vapor passes into the condenser, where the cool seawater condenses the steam, which is then pressured by a boiler feed pump to complete the cycle [133]. Most of the parasitic power usage comes from the seawater supply system [133]. Working fluids with a low boiling point such as ammonia, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs) are ideal for a closed-cycle OTEC system [133]. However, CFCs and HCFCs are being pushed out of manufacturing (or have already been) due to the Montreal Protocol. As a result, the list of possible working fluids has been reduced to ammonia and HFCs.

The quality of the working fluid and the susceptibility of heat exchangers to biofouling are also disadvantages of using a closed-cycle OTEC [133]. In addition, HFCs are a greenhouse gas (GHG), and ammonia is toxic, even in low amounts [133]. Therefore, Claude proposed using steam as the working fluid generated by warm seawater to address these difficulties. Therefore, the first open-cycle OTEC system was established [133].

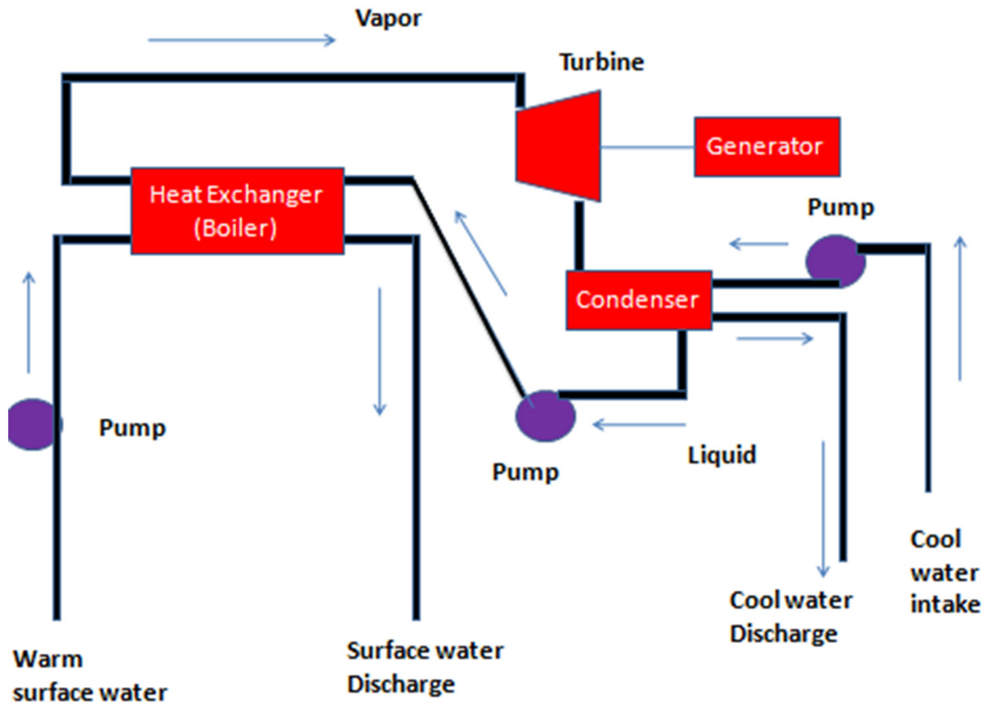


Figure 15. Conceptual diagram of a closed-cycle OTEC system.

3.3.2. Open-Cycle OTEC

Warm saltwater is utilized directly as the working fluid in an open-cycle OTEC. In the evaporator, warm seawater is flash-evaporated in a partial vacuum. The vapor expands and condenses with the cold saltwater as it passes through the turbine (see Figure 16) [138]. The main disadvantage of an open-cycle OTEC is the low working pressure, which demands substantial major components to meet the high volumetric steam flow rates [137]. The first step in an open-cycle OTEC is to flash/evaporate the warm saltwater in a partial vacuum at pressures varying from 1% to 3% of atmospheric pressure [133]. The steam then expands through the turbine, generating energy before condensing as it comes into contact with the cool ocean. Finally, any remaining condensate and non-condensable gas are squeezed and expelled [133]. The two types of condensers that can be utilized in an open-cycle OTEC system are direct contact condensers (DCC) and surface condensers. The DCC oversees squirting cool seawater onto the water vapor. Because the varied temperature fluids are in direct contact, it is both affordable and efficient [133]. As it uses a bodily barrier between the hot and cool water, the surface condenser is more expensive and more difficult to maintain; however, it provides freshwater as a byproduct [133]. One of the downsides of open-cycle OTEC systems is that they are susceptible to air-in-leakages and stimulate the formation of non-condensable gases when operated at partial vacuum. As a result, the process of pressurizing and releasing these gases consumes energy [133]. Furthermore, a greater volumetric flow rate is required due to the low steam density to create a unit of power. The equation below can be used to calculate the seawater flow rate (Q).

$$Q = \frac{P}{\eta \rho C p \Delta T} \quad (8)$$

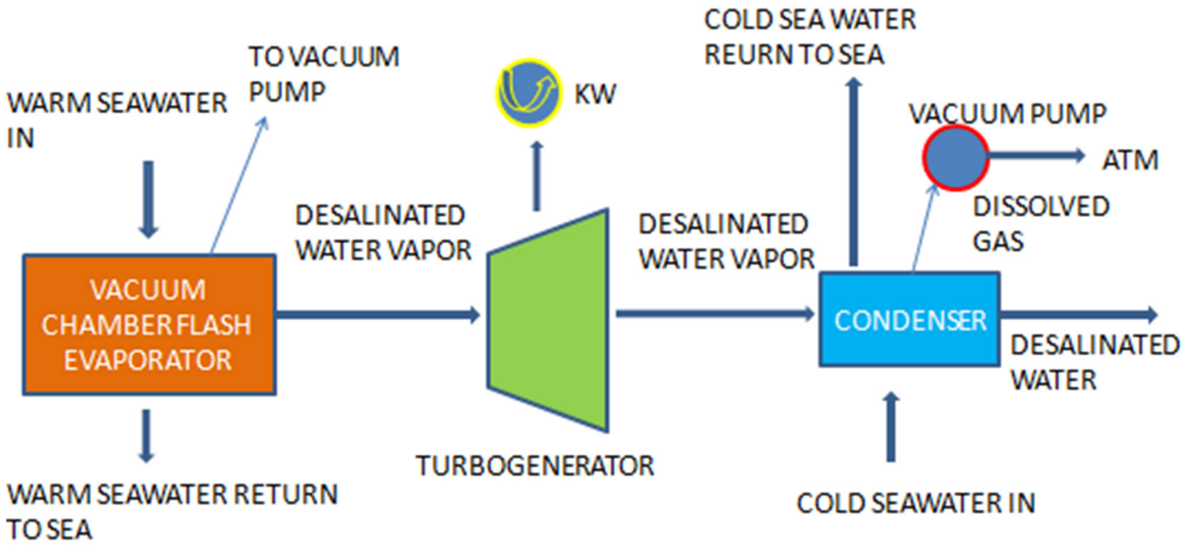


Figure 16. Conceptual diagram of an open-cycle OTEC.

The parameters in the equation are power (P); the system's overall efficiency (η, 0.061 for an 85% efficient turbine); density (ρ, 1000 kg/m^3 for seawater); specific heat of the seawater (C_p, 4.2 J/g·°C); and temperature difference between hot and cool seawater (ΔT) [133]. For example, a 255 kW open-cycle OTEC plant has a seawater flow rate of 0.046 m^3/s, which is equivalent to 46 L of seawater being flown per second. This may not seem like much, but as the OTEC plant's power requirement rises to hundreds of megawatts, the seawater flow rate also rises considerably.

3.3.3. Kalina Cycle OTEC

The Kalina cycle is a closed-cycle OTEC that uses a blend of water and ammonia as the working fluid instead of pure ammonia. Instead of having a boiling point, such a mixture has a boiling point trajectory. During evaporation, more of the given heat is taken into the working fluid, allowing for a larger amount of heat to be converted, resulting in improved efficiency [139]. A binary combination has the advantage of evaporation or condensation occurring over a wide temperature range at a given pressure; a pure Suid, on the other hand, changes the phase at a fixed temperature. Thanks to this extra degree of freedom, heat transfer-related irreversibility in the evaporator and condenser can be decreased. The Kalina cycle requires more capital equipment and may place significant demands on the evaporator and condenser, even though it enhances efficiency. Higher heat transfer coefficients, larger heat transfer surface area, and higher seawater flow rate are required to boost the efficiency. Each has a cost or a power penalty connected with it. Additional research and testing are needed to determine whether the Kalina cycle and its variants are feasible options [137].

3.3.4. Hybrid System

Hybrid cycles combine the potable water production capabilities of open-cycle OTECs with the closed-cycle's potential for huge electricity generation capacities. The steam generated by flash evaporation is used as heat to drive a closed-cycle in hybrid systems, which incorporate both open- and closed-cycles [140,141]. First, as previously stated, power is generated in a closed-cycle system. Following that, the heated seawater discharged from the closed-cycled OTEC are flash evaporated and cooled with the cold-water discharge, like an open-cycle OTEC system, and it results in the production of freshwater. A typical closed-cycle OTEC system that produces electricity and downstream flash-evaporation-based desalination technology makes up the hybrid cycle. Both water and electricity production can be modified independently and can function if one of the subsystems fails or requires maintenance [137]. However, warm saltwater is directly used in the ammonia evaporator and additional equipment such as a potable water surface condenser is necessary to prevent biofouling, resulting in higher capital costs [137].

3.3.5. Ocean Thermoelectric Generators (OTEG)

Thermoelectric technology has been widely employed for decades, from satellites to wristwatches, from climate-controlled seats to the ingenious Mars rover. The thermoelectric effect, also called the Seebeck effect, is the electric potential created by a temperature difference in thermoelectric materials such as positively and negatively charged semiconductors [14]. A thermoelectric generator (TEG) can transform the waste heat from thermal power plants, vehicle exhaust, and flue gases into electricity. The thermoelectricity (V) generated by thermoelectric materials with the Seebeck coefficient (α, unit of μV/K) under the temperature gradient (ΔT) can be approximated as,

$$V = \alpha(T_H - T_C) \tag{9}$$

In practically-adopted thermo-electric generators, typical values of α range from −200 to +200 μV/K [14].

The OTEG usually needs over a 100 °C temperature differential to produce significant electricity [14]. However, recent advancements in nanotechnology have created new thermoelectric possibilities. The effectiveness of a TEG is determined by a non-dimensional figure-of-merit (ZT), expressed as follows,

$$ZT = S^2\sigma T/K \tag{10}$$

where S represents the Seebeck coefficient; σ denotes the semiconductor's electrical conductivity; K denotes the thermal conductivity; and T denotes the absolute temperature. Increasing the electrical characteristics ($S^2\sigma$) or decreasing the thermal conductivity (K) are the two main ways to improve thermoelectric performance. According to [142], new nanotechnology-developed materials enable ZT efficiency to exceed 1. For example, a novel thermoelectric material, bismuth antimony telluride (BiSbTe), demonstrated laboratory performance with a ZT of 1.4 at 100 °C [143]. However, their commercial applications have been limited for many years due to low efficiency and high startup costs. Although present commercial TEG units have a limited performance, this technology has many potentials to become a leading concept of deep-sea energy generation with the growing number of research and development initiatives. Furthermore, thermoelectric materials are dependable power sources that have been used in a variety of applications requiring autonomy and dependability.

3.4. Salinity Gradient Energy

The salinity gradient energy (SGE), often called blue energy, is a type of energy that was initially discovered in the 1950s [143]. As an alternative and sustainable energy source, salinity gradient energy has many advantages. It generates electricity using the Gibbs energy created by mixing two salt solutions of different concentrations. Figure 17 shows the main principle of SGE, which is a brackish (saline) solution made of a concentrated and diluted solution. It is a pollutant free (no CO_2, SO_2, or NO_x emissions) and environmentally friendly method of generating energy by mixing water streams with varying salinity. Submarine and surface current motions cause global salinity variances, as shown in Figure 5. Salinity gradient-based power is accessible where various salinity salt solutions mix such as when fresh river water runs into the sea or industrial brine is discharged. Estuaries alone are predicted to have a global energy potential of 2.6 TW [144], which is around 20% of the global energy demand [145] and more than the global electricity consumption (2.0 TW).

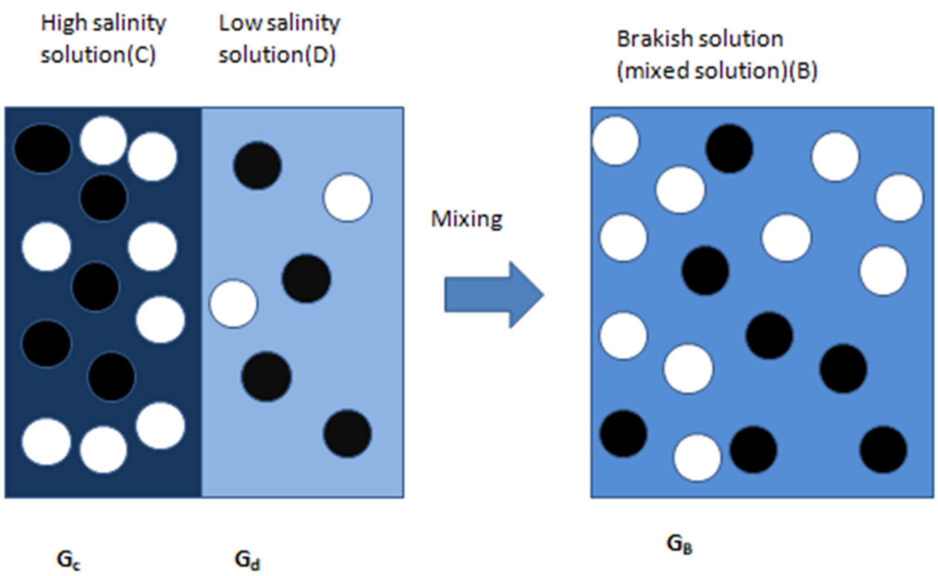


Figure 17. The combination of a concentrated and diluted solution to a brackish solution.

The SGE can be better understood by looking at the definition of the Gibbs free energy of mixing. The Gibbs free energy of mixing can be stated for an ideal dilute solution ($\Delta_{mix}H = 0$).

$$\Delta G_{mix} = G_b - (G_c + G_d) \tag{11}$$

where ΔG_{mix} represents the change in the Gibbs energy (J/mol), while G_b, Gc, and G_d are the Gibbs energies of the brackish, the concentrated, and the diluted solution, respectively (J/mol).

Equation (11) can be expressed in the following fashion to achieve the link with the entropy of mixing $\Delta_{mix}S$:

$$\Delta_{mix}G = -(n_c + n_d)T\Delta_{mix}S_b - (-n_cT\Delta_{mix}S_c - n_dT\Delta_{mix}GS_d) \tag{12}$$

where n denotes the amount of particles (mol); T represents the temperature (K); and $\Delta_{mix}S$ denotes the molar entropy of mixing (J/mol·K), which can be expressed as:

$$\Delta_{mix}S = -R\sum_i x_i \ln x_i \tag{13}$$

where R represents the universal gas constant (8.314 J/mol·K); x_i denotes the molar fraction of component i. It is feasible to compute the potential energy that can be recovered from any river mouth using these equations [146]. Several technologies have been considered for the use of SGE, based on the huge energy source's potential output. However, only two approaches have made it to the pilot stage thus far [146].

3.4.1. Pressure Retarded Osmosis (PRO)

In PRO, two solutions with different salinities are brought together through a semipermeable membrane that only enables the solvent (water) to pass through while keeping the solute in place (dissolved salts). Water transmission from the diluted solution to the concentrated solution across a semipermeable membrane converts the free energy of mixing from two solutions with different salinities into energy in PRO. Much of the pioneering works were published by Loeb et al. [147–152] and Metha et al. [35,149,153,154] and their coworkers. They presented the notion and published the initial results of their experiments. Loeb et al. [147] studied not just the mixing of sea and river water, but also the idea of using PRO to mix high-saline solutions such as Dead Sea water with seawater. Lee et al. [35] constructed a theoretical model based on osmosis and reverse osmosis (RO) measurements to describe the PRO performance of a membrane. They stated that "if PRO is to become a financially viable technology for power production employing seawater–freshwater as a resource for the salinity gradient, membranes with much-enhanced performance will be required". The economics of a brine/freshwater system, on the other hand, appears to be comparable to those of conventional power generation methods." Because the membranes, which are the fundamental component of PRO, are ineffectual, there has not been much work to establish this technology [146].

3.4.2. Reversed Electrodialysis (RED)

Several anion exchange membranes (AEMs) and cation exchange membranes (CEMs) are placed in an oscillating arrangement among an anode and a cathode in RED, allowing only salt ions to be transported. Through an alternating set of AEMs and CEMs, a concentrated salt solution and a less concentrated salt solution are mixed together in RED. An oscillating set of AEMs and CEMs separates the concentrated and dilute salt solution [155]. The AEM has fixed positive charges and only allows anions to be transported to the anode. In contrast, the CEM has set negative charges and only allows cations to be transported to the cathode. A spacer controls the hydrodynamics in both the concentrated and diluted feed compartments. The electrons released at the anode are then delivered to the cathode via an external circuit with an external load [156], as shown in Figure 18. The ions transport charge in the internal circuit of the stack, while electrons carry charge in the external circuit. Redox processes occur at the electrodes on the stack's outer surface, converting the ionic current to electrical current. The redox pair is used to reduce the number of transferred electrons [155].

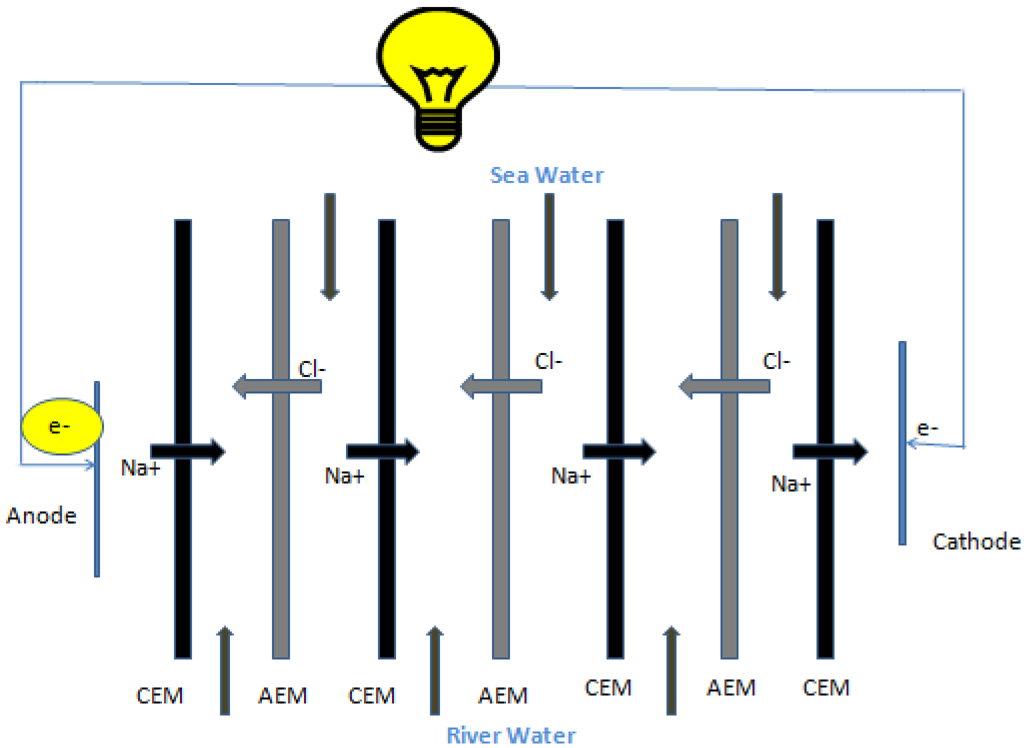


Figure 18. Functioning of energy production by the RED process.

The most challenging aspect of RED technology is adapting it to a real-world context where water-based solutions have more complicated compositions than the simple NaCl solutions utilized in the lab. In addition, the compositions of real-world solutions are less predictable, resulting in fluctuations in concentration and temperature over time. Furthermore, natural sea or river water contains numerous contaminants that might seriously impede the operation of a RED system [146].

4. Current Updates on the Wave and Tidal Energy Projects

Technology development, finance and markets, environmental and administrative difficulties, and grid availability are the four key barriers to ocean energy solutions [25,157–165]. Further intensive research and development and state policy are required to achieve essential cost reductions and massive deployment. At the moment, technological barriers are believed to be the most challenging and important issues that the ocean energy sector need to tackle in the short- to medium-terms. Technological issues are considered to account for about 35% of the crucial priorities for the wave and tidal energy industries [166], and should be addressed with high priority in the next few years [167]. Furthermore, overcoming these technological issues is fundamental to determining and finding the appropriate solutions to the other barriers, particularly the economic and investment hurdles [168].

The European Marine Energy Center (EMEC) acts as a hub for the development of tidal and wave energy, where various prototypes are being built and tested at sea [115,169]. Other well-known tidal current turbines such as Seagen and Andritz Hammerfest have previously been connected to the grid [170,171]. Other pre-commercial devices in development include the 2 MW Open Hydro, 1 MW Atlantis AR1000, and 2 MW Scots renewable SR2000, all of which are being tested at the EMEC. In 2019, the amount of electricity generated from marine sources increased by 13% [172]. Nonetheless, the condition of marine power remains off track, since it falls short of the Sustainable Development Scenario's (SDS) requirements of a 23% annual growth rate through 2030 [173] (see Figure 19). Several countries including Canada, the United Kingdom, China, and Australia have advanced marine energy projects with capacities ranging from 10 kW to 1 MW in operation [173]. Furthermore, countries such as Canada, Australia, and the United States have substantial representations, whereas eastern Asia is still seeking greater activity [174,175], as shown in Figure 20.

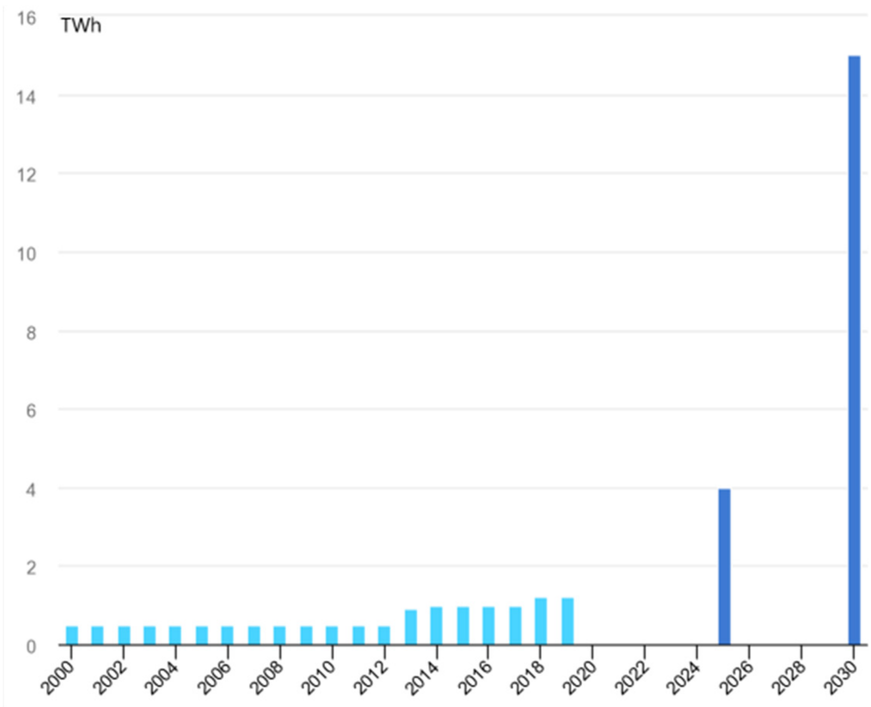
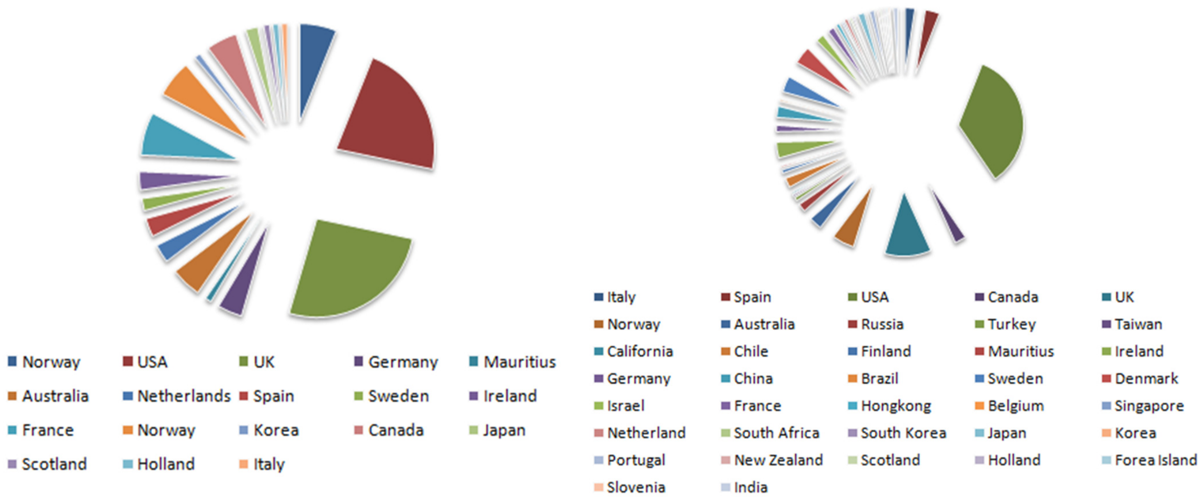


Figure 19. Ocean power generation scenarios from 2000 to 2030.



(**a**) (**b**)

Figure 20. Distribution of companies worldwide focusing on: (**a**) tidal energy and (**b**) wave energy.

Tables 7 and 8 show the technical and site specifications of major tidal (summarized from [176–180]) and wave (summarized from [181–188]) power plants worldwide. According to recent studies, the OTEC may provide all of the world's power generation capacity while not affecting the ocean temperature profiles. Furthermore, many Caribbean and Pacific Ocean Island republics have OTEC resources within 10 km of their beaches. The OTEC appears to be particularly well-suited and economically viable for distant tropical islands where power generation can be integrated with additional activities including air conditioning and freshwater production [139].

Table 7. Operational tidal power plant.

Power Plant	Country	Year	Installed Capacity (MW)	Annual Capacity (GWh)	Reference
Annapolis Royal Station	Canada	1984	20	30	[177]
Jiangxi Tidal Station	China	1980	3.2	4.4	[177]
Kislaya	Russia	1968	1.7	1.8	[189]
Rance Tidal	France	1966	240	480	[189]
Sihwa Lake	South Korea	2011	254	552	[121]
Strangford Lough	UK	2008	1.2	-	[121]
Uldolmok	South Korea	2009	1.5	2.4	[190]
Eastern Scheldt	Netherlands	2015	1.25	-	[34]

Table 8. Power stations that run on wave power.

Plant	Country	Capacity (MW)	Type	Year	Reference
Ada Foah Wave Farm	Ghana	0.4	Point absorber	2016	[181]
Agucadoura Wave Farm	Portugal	2.25	Surface-following attenuator	2008	[182]
Azura	United States	0.02	Point absorber	2015	[183]
BOLT Lifesaver	United States	0.03	Point absorber	2016	[184]
Islay Limpet	United Kingdom	0.5	Oscillating water column	2000	[185]
Mutriku Breakwater Wave Plant	Spain	0.3	Oscillating water column	2009	[186]
Orkney Wave Power Station	United Kingdom	2.4	Oscillating wave surge converter	Proposed	[191]
Pico Wave Power Plant	Portugal	0.4	Oscillating water column	2010	[192]
SDE Sea Waves Power Plant	Israel	0.04	Oscillating wave surge converter	2009	[192]
SINN Power wave energy converter	Greece	0.02	Point absorber	2015	[192]
Sotenäs Wave Power Station	Sweden	3	Point absorber	2015	[192]

The IEA Energy Technology Perspectives (ETP) has aided our understanding of global deployment. The ETP model combines energy supply and demand analysis to create a bottom-up, technology-rich study of the global energy system. The ETP scenarios are set until 2050 and clearly refer to the average worldwide rise in degrees centigrade (DS) in anthropogenic climate change: 2 DS (there is at least a 50% possibility of keeping the average temperature rise below 2 °C); 4 DS (taking into consideration climate and energy initiatives that are being planned or discussed, assuming a 3.7 °C temperature increase); and 6 DS (anticipating no GHG mitigation efforts beyond existing policy measures, which might result in a 60% rise in yearly energy and process-related CO_2 emissions, resulting in a 5.5 °C temperature increase). Under these three scenarios, Figure 21a shows the expected generation level from ocean energy. Overall, the forecast for ocean energy is brighter, with 52 TWh generated under 6 DS, 92 TWh created under 4 DS, and 144 TWh generated under 2 DS, for the year 2040. By 2050, the total installed ocean energy capacity will have increased from around 1 GW in 2013 to 37 GW under 6 DS, 71 GW under 4 DS, and 178 GW under 6 DS [193,194]. Despite this, ocean energy represents less than 1% of total renewable electricity generation in all three scenarios. By 2050, this estimation predicts a total capacity of 101 GW of tidal stream and 236 GW of wave energy [195] (see Figure 21b).

More than 100 wave energy projects have been announced in Europe alone since 2009, with a total planned capacity of 1.2 GW. Unfortunately, more than 0.77 GW has been canceled. However, it was expected that the additional wave energy project could achieve about 26 MW in Europe by 2018 (see Figure 21b), increasing the total installed capacity to 57 MW. Although this amount was significantly smaller than the previously planned total capacity, it can be considered as a significant development in the tidal energy market [168].

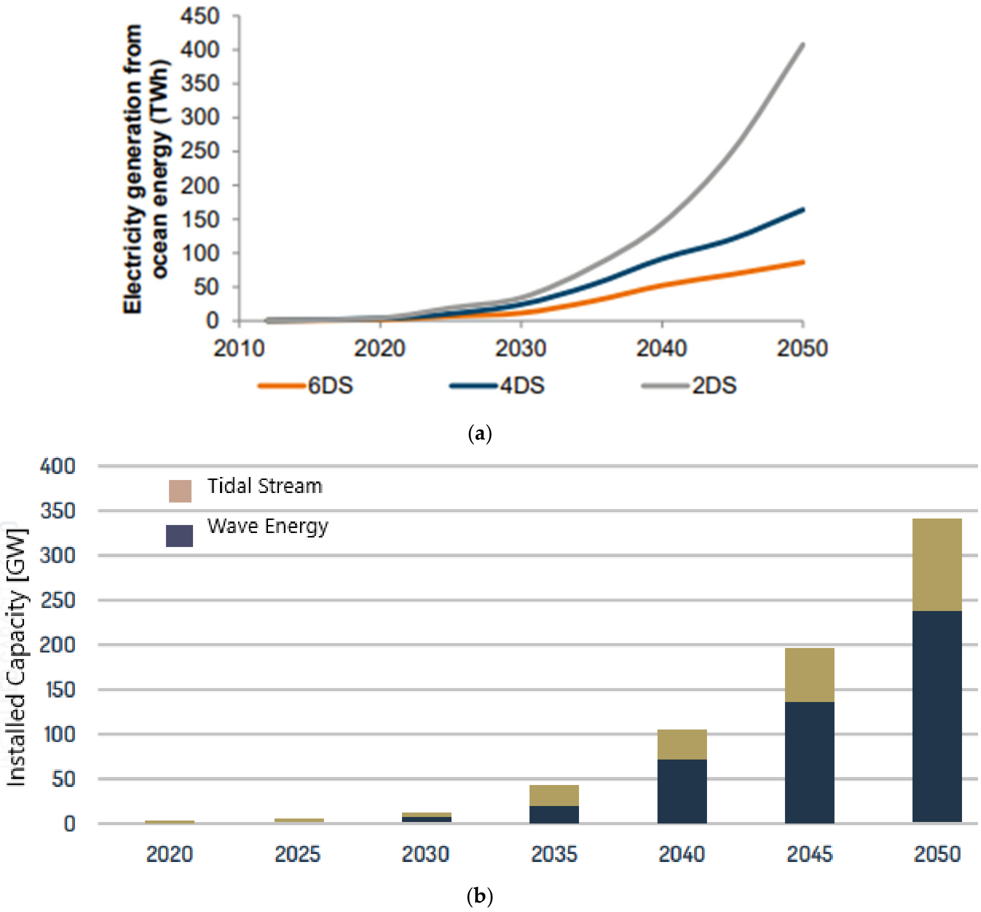


Figure 21. Projected electricity generation and installed capacity: (**a**) electricity generation from ocean energy between 2013 and 2040, and (**b**) ocean energy capacity forecast to 2050 by ETP.

5. Environmental and Other Impacts

The flip side of this energy has been presented well by the Scottish Association for Marine Science (SAMS) [196]. Ocean energy technologies have three different types of environmental consequences [197]. The first is about how the device interacts with aquatic life. Animals could be harmed if they collide with the operating parts of an ocean energy gadget. The second source of concern is underwater noise pollution created by ocean energy devices including wave energy and tidal stream devices. This kind of noise potentially disturbs the life of marine species including whales, dolphins, seals, sea turtles, migratory fish, and invertebrates. Since these marine species utilize underwater sound rather than light to chat, navigate, and communicate, any background noise can interfere with their ability to perform these tasks [198]. Given the small number of devices that have been deployed thus far, empirical data on how these devices affect marine species are scarce. The fourth category concerns the potential effects of ocean energy devices on water movement caused by tides, waves, ocean currents, and density as a result of energy removal from the marine environment or interruptions to normal water flow. Table 9 summarizes several environmental and other impacts of energy harvesting from ocean tidal and waves. Figure 22 shows the potential noise pollution in the ocean generated by tidal and wave energy converters.

Table 9. The possible impacts of ocean tidal and wave energy harvesting on the environment and others.

Type of Impact	Description
Noise pollution	This is one of the biggest problems. However, sound travels faster in a denser medium; hence, the sound inside water is faster than that in air. As a result, marine life is highly disturbed by the amount of sound produced by these devices.
Collision	The animals in the sea are move frequently and wildly, and when there are barriers in the sea, collisions may occur. In addition, the visibility under the sea is worse than on land, and some marine animals have limited vision capability. This collision endangers marine life as well as possibly damages the devices. Therefore, design, operating conditions (e.g., speed and depth), materials, and location selection are essential in avoiding marine mammal collisions.
Electromagnetic fields (EMFs)	These are generated by subsurface wires that transport electricity to the shore. EMF is detected by various marine creatures including bony fish, sharks/rays, and marine mammals. A few sensitive species [199] are attracted to cable EMF, which can be detected up to 295 m away. There is little indication that offshore power cables have a broader influence [200]
Chemical effects	The expected risks connected with maritime vessel operations will be encountered during deployment, routine maintenance, and decommissioning. Spills can happen in routine operations, especially in systems that use hydraulic fluid. Continuous chemical leaching may occur if anti-fouling coatings are applied to decrease the biological fouling of devices. OTEC is involved in a one-of-a-kind circumstance that presents fresh challenges. It is possible that the working fluid in a closed system (typically ammonia, which is highly deadly to fish) could leak or spill [201].
Hydrodynamics	Hydrodynamic aspects include the seabed form and type, erosion and scouring produced by current device modifications, and unique sediment transport and deposition patterns. Wave and tidal stream projects will be located in areas with high ambient energy. Therefore, there are site-specific challenges that must be addressed. Osmotic and permanent OTEC plants must be carefully sited, especially near their output pipe locations [202].

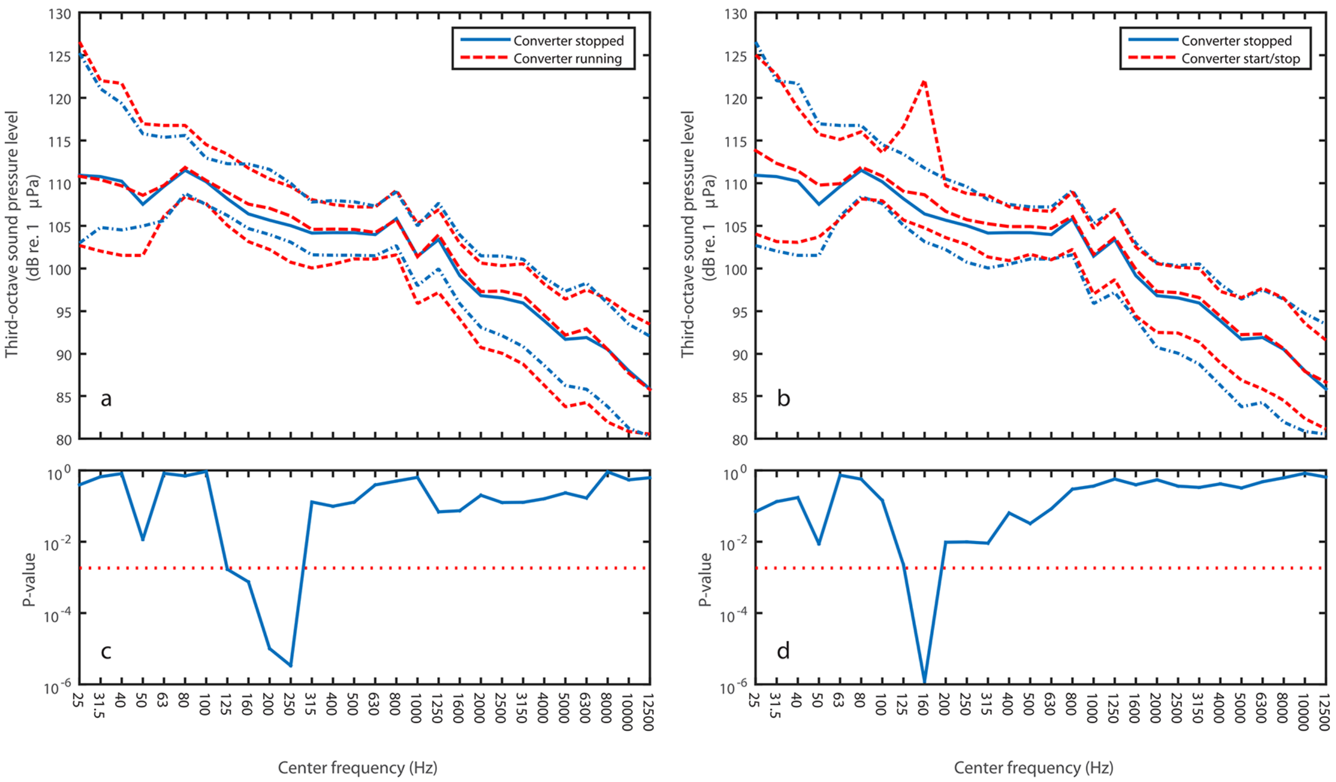


Figure 22. Noise pollution in the ocean generated by tidal (**a**,**c**) and wave energy converters (**b**,**d**) (adopted from [203] under CC BY-SA 4.0 license).

6. Opportunities and Challenges in Developing Ocean Energy Sources

6.1. Socio-Economic Performance

The growth and emergence of ocean energy could result in more employment opportunities, notably in linked industries such as in oil and gas, maritime, and offshore energy [204]. Knowledge and skills transfer from one industry to another could help establish a stable and reliable ocean energy supply and value chain within the region. This local supply chain would assist in building the sector and could reduce the initial costs of harvesting the energy from the ocean. Ocean energy is also more price stable than its competitors oil and gas. As a result, long-term employment and job stability can be predicted once the sector has matured [205]. Ocean energy is a renewable source of electricity; however, it faces various hurdles, ranging from technological issues to issues impacting its operation and maintenance [206], in a hostile ocean environment characterized by high salinity and extreme weather [207].

The technological difficulties stem from the high cost of the deployment and maintenance of offshore equipment. Due to the plethora of marine space users and environmental effects issues, space on offshore platforms is restricted. As a result, ocean energy devices and systems must be modular and resistant to tropical sea conditions. There is a push to reduce the cost of deployment and maintenance by ensuring that devices can survive for a long period in the water with minimal repair and replacement [205]. The environmental implications of wave energy converters may be difficult to assess due to the still low and limited deployment; however, it has been long enough to fully assess the environmental implications both on land and at sea.

The cost of generating electricity from ocean energy is significantly higher than that of traditional energy sources [26]. In addition, the multiplicity of components necessitates industrial cohesion and constrained supply networks. Therefore, synergies with other offshore businesses would benefit and strengthen the ocean energy industry in terms of planning and technology development. Similarly, additional dedicated infrastructure such as ports and transmission grids might be built to support the installation, operation, and maintenance of ocean energy converters [82].

Furthermore, because ocean energy is still a novel technology, project estimations and estimates (including planning, installation, maintenance, and repair) are confined to laboratory-scale deployment rather than commercial-scale implementation [21]. Even in places such as the EU and the UK, where ocean energy technologies are more established, the accuracy of capital and operational cost projections is an issue. This is because ocean energy harvesting is comprised of several technologies, the bulk of which are still under development. In 2015, Ocean Energy Systems (OES) published a landmark study on the levelized cost of energy (LCOE) of the wave, tidal, and OTEC technologies at various levels of development. Table 10 shows the various cost projections for distinct ocean technologies such as wave, tidal, and the OTEC, based on the OES study, at various deployment stages. Furthermore, Table 11 presents the globally proposed tidal power stations (summarized from [208–210]).

Table 10. Summary data averaged for each deployment and technology type, based on the International Levelized Cost of Energy for the Ocean Energy Technologies report by the International Energy Agency-Ocean Energy Systems (IEA-OES) [211].

Deployment Stage	Variable	Wave		Tidal		OTEC	
		Min	Max	Min	Max	Min	Max
First array/first project	Project capacity (MW)	1	3	0.3	10	0.1	5
	CAPEX (USD/kW)	4000	18,100	5100	14,600	25,000	45,000
	OPEX (USD/kW·y)	140	1500	160	1160	800	1440
Second array/second project	Project capacity (MW)	1	10	0.5	28	10	20
	CAPEX (USD/kW·y)	3600	15,300	4300	8700	15,000	30,000
	OPEX (USD/kW·y)	100	500	150	530	480	950
	Availability (%)	85%	98%	85%	98%	95%	95%
	Capacity factor (%)	30%	35%	35%	42%	97%	97%
	LCOE (USD/MWh)	210	670	210	470	350	650
First commercial-scale project	Project capacity (MW)	2	75	3	90	100	100
	CAPEX (USD/kW)	2700	9100	3300	5600	7000	13,000
	OPEX (USD/kW·y)	70	380	90	400	340	620
	Availability (%)	95%	98%	92%	98%	95%	95%
	Capacity factor (%)	35%	40%	35%	40%	97%	97%
	LCOE (USD/MWh)	120	470	130	280	150	280

Table 11. Globally planned tidal power stations.

Name	Capacity (MW)	Country	Primary Cost (B USD)	References
Garorim Bay Tidal Power Station	520	South Korea	1	[208]
Incheon Tidal Power Station	1320	South Korea	3.4	[209]
Tugurskaya Tidal Power Plant	3640	Russia	-	[209]
Mezenskaya Tidal Power Plant	24,000	Russia	22.76	[209]
Skerries Tidal Stream Array	10.5	UK	0.07698	[209]
Tidal Lagoon Swansea Bay	320	UK	1.3	[212]
Gulf of Kutch Project	50	India	0.15	[212]
Alderney Tidal Plant	300	Alderney	-	[212]

6.2. Social Influence

There is a social divide between public support for renewable energy development, which leads to local job creation, reduced electricity costs, lower carbon emissions, enhanced energy security, and successful planning and application approval. Power plants for renewable energy are frequently met with low public approval, which at the very least slows down, if not completely prohibits, initiatives. The visual effects, denial of climate change, a desire to avoid commercialization of coastal waterways, and harm to tourism, fisheries, recreation, and navigation operations are all factors [176,213].

6.3. Design, Installation, and Operation

Compared to land-based structures, the design, operation, and installation of any structure or facility in an ocean environment is always a problem. The importance of design in the case of ocean energy is much greater, as ocean energy is anticipated to actively interact with the ocean waves in a precise way to harvest energy from them. In addition to being able to handle operating pressures, the performance and survivability of ocean energy during extreme loading circumstances such as hurricanes and storms are critical.

Biofouling (moorings and floating or submerged components of the device) and corrosion are the most typical difficulties that ocean energy devices will confront [174,214–236]. Seawater's corrosive character [237–239] can also be a challenge for several aspects of ocean energy. Therefore, at the design stage, complete operation and maintenance strategies for ocean energy systems must be well-planned and devised, which will undoubtedly add to the lifecycle cost. Accessing the facility offshore is another critical concern for operation and maintenance planning [237–241]. Offshore energy industry knowledge such as experiences in offshore wind, oil, and gas industries [242] can help to understand the risks and costs associated with sustaining an offshore plant. As a result, a system with well-spaced maintenance activities will be a suitable option, lowering the expenses involved with repeatedly mobilizing staff to the plant.

Some studies are attempting to model the reliability of ocean energy devices and prospective failure rates. Thies et al. devised a system for simulating component reliability and failure rates under specified operational settings [243]. Device testing in environments that may simulate real-world situations is a requirement for determining device and component reliability [244]. Annual running and maintenance costs for ocean energy devices can be as high as 3.4–5.8% of capital expenditure, compared to 2.3–3.7% for offshore wind [227]. There have only been a few full-scale devices deployed; hence, there is limited practical experience. Installation of ocean energy devices must be simple and quick to reduce the installation costs [244]. In the case of tidal devices, this is also necessary because installation must take place at slack tide, which is short.

6.4. Grid Connection and Integration

Grid concerns, on the other hand, may not be a major concern in all markets. Because the grid infrastructure is adjacent to ocean energy resources along their coasts, many European countries such as France, Portugal, Spain, and the Netherlands may have an edge in building ocean energy projects [25]. Many countries see marine energy as a possible electricity source, as indicated in [245], in order to cut carbon emissions and diversify their electricity sources. Ireland, for example, has set a goal of 500 MW of ocean energy in its energy portfolio by 2020 [246]. Blavette et al. [245] summarized some important points and advice. The wind energy industry may have viewed the introduction of additional grid code criteria for wind as unfair or unjustified [247]. However, in the case of ocean energy, a close working relationship between grid operators and developers in the development of grid code requirements should benefit both sides [219,248] (see Figure 23). Grid operators may find it challenging to understand the possible grid impact of all the many brands of ocean converters because of their diversity. More communication with the ocean energy business may result in the establishment of more appropriate criteria that will satisfy both parties. Involvement of the ocean energy sector in the establishment of these specifications, on the other hand, would also increase developer acceptance. Furthermore, it may improve the industry's grasp of the whole range of power system stability challenges.

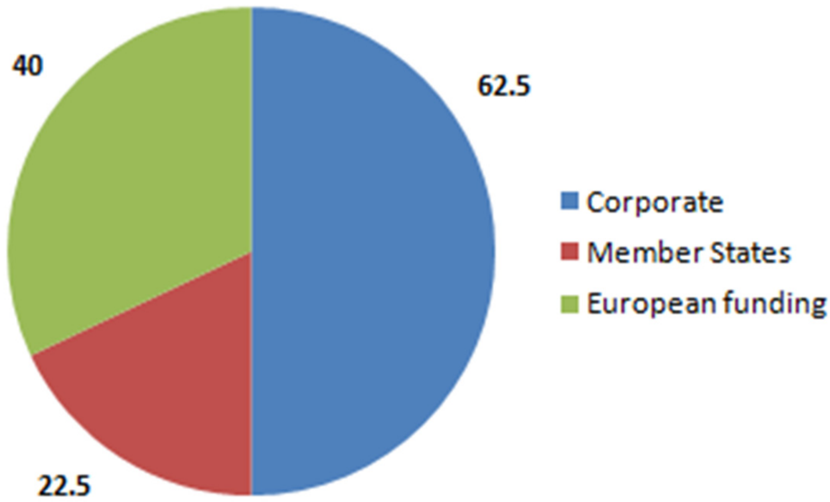


Figure 23. Total research and development investment in wave and tidal energy projects in 2011 (in M EUR).

In order to integrate new energy sources, requirements must evolve. In the case of ocean energy converters, it is proposed that this evolution be broken down into multiple steps that will be defined in partnership with industry and grid operators. Future requirements are recommended to grow in the same way that wind turbine requirements do (i.e., based on the experience gained at each stage of the grid integration process and the level of penetration of ocean energy in the energy mix). Developing fixed requirements to be applied from low to high penetration levels would be unreasonable and irrelevant [168].

At the initial stage, the first phase of grid integration is concerned with the time when the ocean energy's contribution to the energy mix is low and hence does not pose a danger to the stability of the power system. Soft grid requirements are proposed during this time; therefore, the developers can enhance their technology by testing it in real-world scenarios with a grid connection [245]. In the following phases, when wind energy becomes a large part of the energy mix in some areas, tighter criteria are imposed such as low voltage fault ride-through or frequency control requirements. Similarly, harsher limitations will need to be adopted later, depending on the extent of the penetration of ocean energy [245].

6.5. Policy and Regulations

Many countries with ocean access are planning to develop ocean energy as part of their long-term energy goals. The EU has put in place support mechanisms to help with the development of ocean energy, with 66 MW of projects expected to be operational by 2018 [168]. Table 12 lists some of the governmental policy instruments for ocean energy in the EU [202].

Ocean energy offers a unique utilization that can support various energy networks. It enables the Global Renewable Energy Islands Network (GREIN) clusters on islands, which include water desalination [25]. Capacity or generation targets; capital grants and financial incentives including prizes; market incentives; industry development; research and testing facilities and infrastructure; and permitting, space, and resource allocation regimes, standards, and protocols are the six categories of policies that apply to ocean technology [249]. In addition, creating resource mapping, increasing capital grand funding, expanding international collaboration, and fostering research, development, and demonstration are all policies that can assist in overcoming the technological hurdles for ocean energy [25]. To overcome the economic barriers, policymakers might provide financing support for technologies in the demonstration stage and use road-mapping to speed cost and risk reductions [25]. Because tidal stream energy cannot currently be funded purely through commercial means, public subsidization measures such as feed-in tariffs (FIT) can help promote its development [26].

Table 12. Governmental policy instruments for ocean energy.

Policy Instrument	Country	Example Description
	Targets	
Legislated targets, aspirational targets, and forecasts	United Kingdom Ireland Portugal	3% of UK electricity from ocean energy by 2020 500 MW by 2020 550 MW by 2020
	Government funding	
Research and development programs/grants	United States	U.S. DoE hydrokinetic program (capital grants for R&D and market acceleration)
Prototype deployment and capital grants	United Kingdom New Zealand	Marine Renewable Proving Fund (MRPF) Marine Energy Deployment Fund (MEDF)
	Production incentives	
Feed-in-Tariffs	Portugal Ireland/Germany	Guaranteed price (in USD/kWh or equivalent) for ocean energy-generated electricity
Renewables Obligations	United Kingdom	Tradable certificates (in USD/MWh or equivalent) for ocean energy generated electricity
Prizes	Scotland	Saltire prize
	Infrastructure developments	
National marine energy centers	United States	Two centers were established (Oregon/Washington for wave/tidal and Hawaii for OTEC)
Marine energy testing centers	Most western European and North American countries	European Marine Energy Center (EMEC). There are about 14 centers under development worldwide
Offshore hubs	United Kingdom	Wave hub, connection infrastructure for devices
	Other regulatory incentives	
Standards/protocols	United Kingdom	A national standard for ocean energy (as well as participation in the development of international standards)
Permitting regimes	United Kingdom	Crown estate competitive tender for
Space/resource allocation regimes	United States	FERC/MMS permitting regime in U.S. outer Continental Shelf

7. Conclusions

More sustainable energy methods are being included within our culture to meet our energy needs and lessen our reliance on fossil fuels. The use of plentiful ocean energy necessitates the development of new technologies that will make ocean waves and tidal energy a profitable source of secure energy while reducing global CO_2 emissions caused by using fossil fuels. The current developments and prospects of maritime energy platforms were summarized in this research. Improved equipment design is envisaged as a result of a greater understanding of ocean energy and a comprehensive study of numerous potential devices. Ocean energy is a pollution-free, renewable natural energy source with little impact on the environment.

Nonetheless, the environmental impact of maritime energy exploitation must be fully understood to ensure that large-scale implementation is not hampered. Tidal power plants, wave energy converters, OTEC, and OTEG devices can all be used to collect ocean energy. Wave technology (45%), tidal stations (23%), studies on the economy or policy (15%), and concerns about the environment (17%) are among the major ocean energy research activities [250]. On the other hand, the investor confidence in the sector is being harmed by poor technological advancement paired with challenges recruiting finances and financing for first-of-a-kind array demonstration projects. Due to the considerable risk involved with projects and market formation delays, important developers and original equipment manufacturers have been forced to reduce or abandon their involvement in developing ocean energy technology.

Further research in control solutions is required because they offer a significant cost savings potential due to the higher absorbed energy while still maintaining grid code standards. There is no long-term experience with devices in terms of commercial operation and maintenance available. Furthermore, only a few studies have attempted to estimate the installation resource requirements (e.g., time and cost). Device spacing and other array design characteristics may have an impact on the operation and maintenance activities and costs. However, this is not generally recognized now and must be addressed. The economic and social implications of ocean energy are critical areas that should be prioritized in the future. The scope of the exploration and development should be expanded to include conflicting or competing uses of the marine environment such as fishing, shipping, offshore wind, and habitat preservation. There are issues with delivering electricity to onshore loads that need to be handled more seriously. Running cables through salty waters and an offshore system to connect ocean energy sources involves significant obstacles. Economic and technological considerations must also be made when choosing between AC and DC transmission for maritime power [250]. A complete cost–benefit analysis of ocean energy that considers variables such as grid connectivity and energy security could be crucial. Ultimately, while the cost per kWh of ocean energy generation projects remains high, expanding tidal and wave energy projects are envisioned to dramatically reduce power generation costs compared to competing for energy sources.

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