OCEAN IMPACT INITIATIVE

BLUE BUSINESS
OPPORTUNITIES SERIES

Ocean Energy Industry Review

ONE OCEAN Foundation

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About One Ocean Foundation

This research has been carried out by the One Ocean Foundation as part of its Ocean Impact Initiative project.

At the Foundation, we believe that protecting the ocean goes beyond mitigating existing damage — it involves addressing the root causes of the issue. Our approach extends conservation efforts: we actively collaborate with businesses and policymakers to drive systemic change, ensuring a sustainable future for marine ecosystems. The One Ocean Foundation is dedicated to promoting a nature-positive economy that balances resource use with the urgent need to protect and restore marine ecosystems and their biodiversity.

The distinctive feature of the One Ocean Foundation is that every project we undertake is rooted in science and designed to create measurable, long-term impact. Our initiatives are carried out under the guidance of our international scientific committee and through continuous collaboration with cutting-edge research centres and universities. Through collaboration with companies, we help them understand and reduce their environmental footprint while fostering policies that safeguard the ocean.

About the Ocean Impact Initiative

The Ocean Impact Initiative (formerly known as Ocean Disclosure Initiative) is part of the multi-year research "Business for Ocean Sustainability" promoted by the One Ocean Foundation (OOF) in collaboration with SDA Bocconi School of Management Sustainability Lab, McKinsey & Company and CSIC (Consejo Superior de Investigaciones Científicas) and aims to build knowledge about the relationship between business activities and the ocean.

The project commenced in 2019 with the goal of investigating the role of companies in addressing ocean challenges, focusing on the pressures on marine ecosystems, the level of awareness within the business community and the main responses (technological and organisational) implemented.

The Ocean Impact Initiative aims to provide a science-based framework and methodology with the objective of supporting businesses from all industries in taking action on ocean-related issues, promoting prevention and/or mitigation responses, and favouring disclosure and reporting.

In collaboration with

SDA Bocconi SCHOOL OF MANAGEMENT SUSTAINABILITY LAB

McKinsey & Company

CSIC Consejo Superior de Investigaciones Científicas

Blue Business Opportunities

The concept of Blue Business Opportunities (BBOs) was introduced in 2023 in the One Ocean Foundation's report "Business for Ocean Sustainability, Third Edition – Capturing the Blue Opportunity." Blue business opportunities refer to initiatives and business models that create economic value while supporting the health, resilience, and sustainable use of marine and coastal ecosystems. As defined in the report, BBOs have the potential to generate value for companies by cutting costs, improving efficiency, creating new sources of revenue, fostering organisational resilience and improving reputation and brand image. BBOs encompass a broad range of activities and are grouped into four main categories:

Nature-based Solutions:
including sustainable fisheries and aquaculture practices, marine ecosystem conservation and restoration, and the development and management of Marine Protected Areas (MPAs).

Ocean Pollution Control:
including technologies, systems, and services aimed at reducing, preventing, or removing marine pollution (e.g., plastics, chemical runoff, wastewater).

Coastal and Marine Engineering:
covering innovative infrastructure and coastal protection solutions, including climate-resilient ports, offshore renewable energy infrastructure, and nature-integrated coastal defences.

Ocean Data and Digital Technology:
involving the collection, analysis, and application of ocean-related data and digital tools to improve marine resource management, monitoring, and operational efficiency.

In this series, we highlight illustrative examples of blue business opportunities and explore key enablers for their scale-up, aiming to support business leaders, policymakers, and investors in accelerating the development of a sustainable and resilient ocean economy.

Introduction to Ocean Energy

There is great potential for energy that is stored in the ocean. More than 70% of the Earth's surface is covered by the ocean, and it acts as the largest solar collector and collects thermal energy from the sun, the gravitational pull of the moon drives tides, and wind generates ocean waves. As one of the most abundant and largely untapped renewable resources, the ocean offers immense potential to enhance energy security, stimulate economic growth, and reduce global CO_2 emissions.

Ocean energy is one of the world's most abundant untapped renewable resources

From the ocean, it is possible to obtain several forms of renewable energy — namely tidal energy, wave energy, ocean thermal energy conversion (OTEC), and salinity gradient energy — each derived from different physical phenomena and capable of being converted into low-carbon electricity. To date, tidal and wave energy technology represents the most advanced ocean energy technologies,[1] and are expected to become commercially viable in the short-medium term.[2]

The advantages of ocean energy are compelling: predictable generation patterns, high load factors, abundant resources, and potentially lower environmental impacts. These factors have drawn increasing attention from governments, investors, and industry.[3] In Europe alone, plans aim to deploy 100 GW of wave and tidal energy capacity by 2050[4] — enough to meet 10% of the EU's electricity demand and create hundreds of thousands of skilled jobs.

1. Lammerant, L., et al. (2020) "Potential impacts of solar, geothermal and ocean energy on habitats and species protected under the Birds and Habitats Directives" Available at: https://doi.org/10.1016/j.landusepol.2023.106592

2. Magagna, D., & Uihlein, A. (2015). Ocean energy development in Europe: Current status and future perspectives. International Journal of Marine Energy, 11, 84–104. https://doi.org/10.1016/j.ijome.2015.05.001

3. M. Melikoglu (2018). "Current status and future of ocean energy sources: A global review". Available at: https://www.sciencedirect.com/science/article/abs/pii/S002980181730714X

4. Ocean Energy Europe. (2025). "Powered by the ocean". Available at: https://www.oceanenergy-europe.eu/ocean-energy/

Over the past decade, members of Ocean Energy Europe (OEE) - a not-for-profit organisation representing the largest network of ocean-energy professionals worldwide - have invested over €1bn in R&D and innovation (RDI) activities. These investments have created the base of world-leading knowledge and expertise needed to build an industry.

European governments are starting to create the market visibility required for ocean energy to take decisive steps towards commercialisation, and private investors are taking an interest in the sector. Thanks to this new-found support, the ocean energy industry is scaling up significant, with over 100 megawatts (MW) of installed capacity planned for deployments in the coming years.[5]

Today, marine renewable energy is the fastest-growing sector of the Blue Economy – and one of the quickest-expanding industries in the EU – having seen its turnover jump from € 65 million in 2009 to € 4.1 billion in 2022.[6]

In the EU, ocean energy projects receive significant amounts of investment from public and private sources. A total of 70 ocean energy projects were funded under Horizon 2020 between 2014 and 2022, totalling € 183 million – including € 94 million for tidal energy and € 89 million for wave energy.[7]

Notwithstanding the substantial investment in ocean energy, the commercial viability of this sector remains hindered by numerous obstacles that impede the widespread adoption of ocean energy technologies, such as the considerable upfront costs, the technological uncertainties and the evolving regulatory framework, which does not provide clear guidelines for the industry. The 2020 EU strategy on offshore renewable energy aims to increase the contribution of ocean energy to the EU’s offshore installed capacity targets, from 1 GW in 2030 to 40 GW in 2050.[8]

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5. Ocean Energy Europe. (2025). “Powered by the ocean”. Available at: https://www.oceanenergy-europe.eu/ocean-energy/

6. European Commission (2025). “The EU Blue Economy Report”. Available at: https://medblueconomyplatform.org/wp-content/uploads/2025/05/the-eu-blue-economy-report-2025.pdf

7. Ibidem

8. Ibidem

To accelerate research and technological development in the field of ocean energy, an updated synthesis of current knowledge is urgently required at the global level. Such a review addresses the fundamentals, energy and power potentials, available devices and conversion systems, and the prospects of different ocean energy sources for both academia and industry.

The current analysis is based on a comprehensive review of the scientific literature related to different ocean energy technologies. Among the most influential sources consulted were publications by the International Renewable Energy Agency (IRENA), which offer robust and authoritative insights.

Ocean Energy Technologies

TIDAL ENERGY

The interaction of gravitational forces of the Moon and the Sun lead to a natural rise and fall in seawater level. These movements – the tides – can be harnessed to generate electricity.[9] Unlike wind or solar energy, tidal energy is not influenced by weather conditions, and its predictable nature makes it one of the most reliable sources of renewable energy.[10] The well-understood cycles of the Earth–Moon–Sun system allow tidal conditions to be forecasted accurately over long periods, ensuring a consistent and high-quality electricity supply.[11]

Tidal energy is one of the most predictable and reliable renewable energy sources

Tidal energy can be generated either by harvesting the potential energy of the difference in the water level or by using the kinetic energy in the flow of the incoming (flow) and outgoing (ebb) water when the flow's speed is at least 1.5 to 2 metres per second. Although the typical sea-level difference between high and low tide is below 1 metre, the tidal range can reach more than 20 metres.

Tidal energy has several advantages. Water is much denser than air, approximately 800 times, which means that tidal turbines can produce significantly more energy per unit area than wind turbines.[12] Its predictable nature ensures a consistent and reliable supply of electricity, unlike more variable renewable sources such as wind or solar.

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9. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

10. Ocean Energy Europe "Tidal Current". Available at: https://www.oceanenergy-europe.eu/ocean-energy/tidal-energy/

11. Li, G., & Zhu, W. (2023). "Tidal current energy harvesting technologies: A review of current status and life cycle assessment." Renewable and Sustainable Energy Reviews, 179, 113269. https://doi.org/10.1016/j.rser.2023.113269

12. Pacific Northwest National Laboratory. "Tidal Energy". Available at: https://www.pnnl.gov/explainer-articles/tidal-energy

Additionally, once installed, tidal energy systems produce minimal greenhouse gas emissions, and with proper maintenance, their infrastructure can remain operational for several decades, providing long-term, low-carbon energy.

Globally, the theoretical tidal energy resource is estimated at 800–1200 TWh per year, indicating significant potential to support the decarbonisation of energy systems.[13] However, this potential can only be exploited in a limited number of coastal regions where tidal conditions are strong enough and suitable for energy conversion technologies.[14] Areas with the highest resource availability include Argentina, Central America (Atlantic), France, North America (both coasts), the Republic of Korea, the Russian Federation and the UK.

TIDAL ENERGY TECHNOLOGY

Tidal energy can be harnessed through two main approaches: tidal barrage and tidal stream systems.[15]

Tidal barrage technology captures potential energy from the height difference between high and low tides by releasing stored water through turbines. This technology is relatively more mature than other ocean energy technologies; however, it now faces various deployment challenges related to limited site availability, high capital investment and environmental impacts. *Tidal barrage* technology accounts for about 98% of all installed ocean energy capacity,[16] with major plants in France, South Korea, and Canada.

In contrast, *tidal stream* technology converts the kinetic energy of moving water using submerged turbines similar to underwater wind turbines. It is rapidly advancing, offering greater scalability and lower environmental impact.[17] Turbine capacities have grown from around 100 kW to over 1.5 MW,[18] and deployment is increasing, though installation and maintenance in strong currents remain technically demanding.

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13. Ocean Energy Europe (N.D) “Tidal Current”. Available at: https://www.oceanenergy-europe.eu/ocean-energy/tidal-energy/

14. International Renewable Energy Agency (IRENA). (2020). “Innovation Outlook: Ocean Energy Technologies”. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

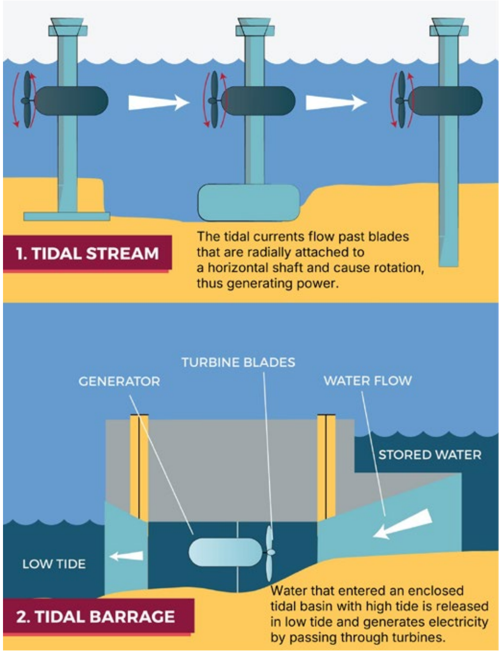
15. Li, G., & Zhu, W. (2023). “Tidal current energy harvesting technologies: A review of current status and life cycle assessment.” Renewable and Sustainable Energy Reviews, 179, 113269. https://doi.org/10.1016/j.rser.2023.113269

16. International Renewable Energy Agency (IRENA). (2020). “Innovation Outlook: Ocean Energy Technologies”. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

17. Ibidem

18. Ibidem

Figure 1: Tidal energy technologies



Source: Author's elaboration from: Soukissian T., et al. (2023). "European offshore renewable energy: Towards a sustainable future." *EMB Future Science Brief.*

POTENTIAL ENVIRONMENTAL IMPACT

Despite its many advantages, tidal energy development faces both environmental and technical challenges. While tidal barrages provide a reliable and predictable source of renewable energy, their construction can significantly impact local ecosystems. Both tidal barrage power plants and tidal stream generators can alter marine habitats and lead to persistent environmental changes. These impacts are caused both by the installation and the deployment of the devices and by the operations phase.

Key environmental pressures include modifications to water flow and hydrographical conditions, changes in turbidity, salinity, and sedimentation, as well as the introduction of underwater noise.

The physical presence of turbines, anchors, and cables on the seabed can disrupt habitats and the associated biodiversity.[19] Collisions with turbine blades or other moving components may increase mortality rates among marine organisms.[20] Moreover, noise and vibrations generated by turbines, vessel engines, and drilling activities during installation and operational phases can affect surrounding fauna, including larval stages, potentially altering developmental and behavioural patterns.

Tidal installations can alter water flow, turbidity, sedimentation, and marine habitats, affecting biodiversity and species migration

Changes in hydrographical conditions, including salinity and turbidity, due to the presence of tidal barrages that impede the natural water flow, may have cascading effects on the local biodiversity due to massive habitat changes. In particular, the presence of tidal barrages may affect the migration pathway of species like eels, salmonids, and shads and, therefore, their reproduction rate.[21]

WAVE ENERGY

Wave energy is a renewable energy source that captures the power contained in ocean surface waves, which are generated by wind blowing across the sea. Unlike tidal energy, which is driven by the gravitational pull of the moon and the sun, wave energy depends on meteorological conditions such as wind speed, duration, and fetch (the distance over which the wind blows).[22]

Wave energy captures power from ocean surface waves generated by wind

While this makes wave energy less predictable than tidal energy, it also allows for a wider geographical distribution of potential sites. Regions with strong and consistent winds — such as the North Atlantic, Pacific coasts, Southern Africa, Australia, and parts of Canada — represent highly promising sites for harnessing this source of energy.[23] Wave energy devices also have the potential to provide a more continuous supply of electricity compared to solar power, as waves often persist even after winds have subsided.

19. Lammerant, L., et al. (2020) "Potential impacts of solar, geothermal and ocean energy on habitats and species protected under the Birds and Habitats Directives". Available at: https://doi.org/10.1016/j.landusepol.2023.106592

20. Ibidem.

21. Frid, C., et al. (2012) "The environmental interactions of tidal and wave energy generation devices". Available at: https://doi.org/10.1016/j.eiar.2011.06.002

22. Omidvaran, Ali. (2024). "Tidal Energy." Available at: https://www.researchgate.net/publication/387136131_Tidal_Energy

23. Golušin, M., Dodić, S., & Popov, S. (2013). Strategic priorities of sustainable energy development. In Elsevier eBooks (pp. 243–333). https://doi.org/10.1016/b978-0-12-415978-5.00007-2

Locating wave energy converters offshore minimises visual impact and reduces competition for land use. Additionally, wave energy can be used to supply utility-scale power, as well as provide a clean and effective alternative to diesel for remote islands, offshore industries, fish farms, and oil and gas platforms.

Globally, wave energy is regarded as one of the most promising renewable energy sources, with an estimated annual potential of about 29,500 TWh[24], almost ten times Europe's total annual electricity consumption.[25] According to data from the International Renewable Energy Agency (IRENA), 33 wave energy converters with a combined capacity of 2.3 MW are deployed in 9 projects across 8 countries and 3 continents.[26] The only active project with a capacity above 1 MW is located in Hawaii and was deployed in early 2020. Other locations with active projects include France, Gibraltar, Greece, Israel, Italy, Portugal and Spain.

WAVE ENERGY TECHNOLOGY

Most technologies for the exploitation of wave energy are still focused on near-shore or on-shore installation, and the difference between them lies in their orientation toward the waves with which they interact, and in the working principle by which to convert wave energy into electrical energy.[27]

A wide range of technologies has been developed to harness this type of energy, reflecting the diversity of wave conditions and the challenges of the marine environment.[28] The most common include *point absorbers*, which use the vertical motion of waves to drive generators,[29] and *oscillating water columns (OWCs)*, which generate power from air movement inside a chamber.

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24. Ocean Energy Europe. "Wave energy". Available at: https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/

25. Ocean Energy Europe. (2025). "Wave Energy". Available at: https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/

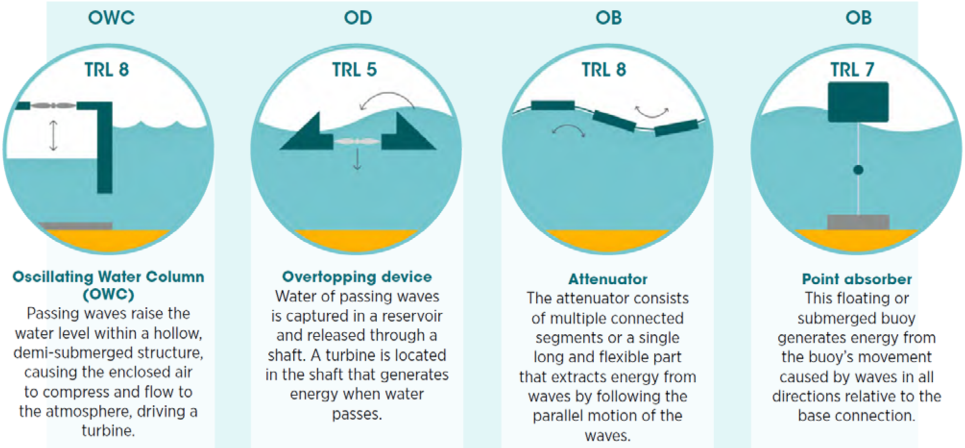
26. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

27. Golušin, M., Dodić, S., & Popov, S. (2013). Strategic priorities of sustainable energy development. In Elsevier eBooks (pp. 243–333). https://doi.org/10.1016/b978-0-12-415978-5.00007-2

28. Ocean Energy Europe. "Wave energy". Available at: https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/

Other systems, including *attenuators*, *overtopping devices*, and *submerged pressure differential converters*, are also being developed, though most remain at experimental or early commercial stages.

Figure 2: Wave energy technologies



Source: International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies".

POTENTIAL ENVIRONMENTAL IMPACT

Wave energy technologies may exert several pressures on the marine environment, including direct impacts on marine biodiversity, accidental release of pollutants, and the generation of underwater noise.[30]

The physical presence of the underwater devices may disturb marine species; indeed, turbines, pipes, anchors, cables and fishnet-like structures and vessel movements may cause potential collisions with and entanglement of some fish, marine mammals, turtles, and seabirds that are used to dive to get food.

29. Golušin, M., Dodić, S., & Popov, S. (2013). Strategic priorities of sustainable energy development. In Elsevier eBooks (pp. 243–333). https://doi.org/10.1016/b978-0-12-415978-5.00007-2

30. Ocean Energy Europe (N.D) "Wave energy". Available at: https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/ (Accessed: 04 August 2023)

The installation and operational phases of wave energy devices generate an amount of noise that has negative consequences on living organisms, particularly when exceeding certain limits. Indeed, the sound is essential to the behaviour of marine species, particularly marine mammals, and disturbances to the acoustic environment may interfere with the key life functions of such animals, especially concerning communication and echolocation. Moreover, the risk of polluting waters with hazardous substances due to undesirable leakages from the devices or vessels during installation, operation and maintenance phases is likely to occur (e.g. toxic materials like ammonia).[31] Underwater structures are also usually covered by antifouling paints to avoid the growth of encrusting organisms and reduce biological contamination.

Potential impacts of wave energy include collision and entanglement risks and the generation of underwater noise

OCEAN THERMAL ENERGY CONVERSION (OTEC)

The irradiation of the sun, or solar energy, is absorbed by the ocean and stored as thermal energy in its upper layers. OTEC power generation makes use of the temperature difference between the warm surface and the cold deep-sea layers (at 800 to 1 000 metres depth) and converts it through a thermal cycle into electricity, heat or cold in a heat cycle.[32] In order for such a conversion cycle to work, the temperature difference must be around 20 degrees Celsius (°C). This means that the surface temperature must be around 25 °C because the deep-sea water temperature is a relatively constant 4 °C at 1 000 metres depth.[33] Such conditions are only present in tropical regions between latitudes of around 30 degrees north and 30 degrees south.

OTEC generates energy by exploiting the temperature difference between warm surface seawater and cold deep-sea water

This is due to the hot surface water temperatures, the great depth of the waters and the steady temperatures across the seasons. Even though restricted to the tropics, this source of energy has significant potential. Beyond its significant energy potential, OTEC provides continuous, non-intermittent baseload power.

31. Rahman, A. (2022) "Environmental impact of renewable energy source-based electrical power plants: solar, wind, hydroelectric, biomass, geothermal, tidal, ocean and osmotic". Available at: https://doi.org/10.1016/j.rser.2022.112279

32. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

33. Ibidem

It can be integrated with seawater air conditioning for cooling, seawater reverse osmosis for freshwater production, and aquaculture using discharge water, creating additional revenue streams and making it particularly attractive for tropical islands and small island developing states (SIDS).[34]

OTEC technology is still very much in the R&D phase, and unlike wave and tidal technologies the players are not commercial but are mainly research institutes and universities. Although its deployment is limited to tropical regions, OTEC holds the largest global technical potential among ocean energy sources, estimated at around 44,000 TWh per year of continuous power generation.[35] OTEC test plants began in the late 1970s, starting in Hawaii, with later projects in Nauru, France, India, Japan, and South Korea.

Although still in the research and development phase, OTEC has the highest global technical potential among ocean energy sources

OTEC TECHNOLOGY

Three thermal energy conversion processes are being pursued to harness thermal ocean energy; they are *open-cycle, closed-cycle and hybrid devices*.[36] Several adaptations of these three cycles exist where, for example, working fluids differ slightly or additional turbines and other devices are added.

In *closed-cycle systems*, a low-boiling-point fluid such as ammonia is vaporised by warm seawater to drive a turbine and then condensed by cold water. *Open-cycle systems* use seawater directly to produce steam that turns a turbine and later condenses into freshwater. *Hybrid systems* combine both approaches, generating electricity while also producing desalinated water for additional uses.

34. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

35. Ibidem

36. Tetheys. (2025). "Capturing energy using temperature gradients across water depths." Available at: https://tethys.pnnl.gov/technology/otec

POTENTIAL ENVIRONMENTAL IMPACT

OTEC is generally considered a clean energy technology. In closed-cycle systems, ammonia is contained within the circuit, preventing emissions, while open-cycle plants release only negligible amounts of carbon dioxide compared to fossil fuel systems. The discharge water, typically released at around 60 m depth, is quickly diluted and vertically separated from the intake, minimising seabed and thermal impacts.[37]

Moreover, the operation of OTEC involves changes in water quality and temperature from bringing cold, nutrient-rich deep water to the surface. OTEC discharges may attract fish due to nutrient-rich water, benefiting fisheries, but could also harm eggs and larvae. Although intake screens limit marine life entrapment, some risk remains, and chlorine used for maintenance may temporarily alter water chemistry. With careful design and monitoring, OTEC plants can operate with minimal environmental impact.[38]

OTEC operations can alter water quality and temperature by bringing cold water to the surface

SALINITY GRADIENT

Salinity gradient energy (SGE), also known as osmotic energy, harnesses the difference in salt concentration between freshwater and seawater — most notably where rivers flow into the ocean.[39] Since seawater is about 200 times more saline than river water, this contrast creates a significant pressure potential that can be converted into electricity using specialised membranes. Each cubic meter of freshwater mixing with seawater can theoretically release around 2.2 MJ of energy — comparable to the power from a 260–280 m-high hydraulic dam. The salinity of the ocean is not homogeneous across the globe. Its concentration is lower near the poles, which is due mainly to the melting ice.

Salinity gradient energy harnesses the natural difference in salt concentration between freshwater and seawater

Other factors, including river runoff or melting glaciers, as well as heavy or a lack of precipitation, also impact the salinity in certain regions.

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37. Herrera, J., Sierra, S., & Ibeas, A. (2021). "Ocean Thermal Energy Conversion and Other Uses of Deep Sea Water: A review." Journal of Marine Science and Engineering, 9(4), 356. Available at: https://doi.org/10.3390/jmse9040356

38. Tetheys. (2025). "Capturing energy using temperature gradients across water depths." Available at: https://tethys.pnnl.gov/technology/otec

39. International Renewable Energy Agency (IRENA). (2014). "Salinity Gradient: Energy Technology Brief." Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Jun/Salinity_Energy_v4_WEB.pdf

Although the salinity levels vary, the presence of riverbeds, where freshwater discharges into the sea, is most important to harness salinity for energy generation purposes.

The amount of energy that can be generated is directly proportional to the difference in salt concentration, making freshwater–saltwater systems more efficient. Since estuaries occur worldwide, salinity gradient plants could, in theory, operate continuously and provide stable baseload power. This makes them a valuable complement to more variable renewable sources such as wind, wave, and solar energy.

Beyond natural estuaries, salinity gradient technologies can also be used in hybrid systems for industrial energy recovery—for instance, by utilising brine from desalination or wastewater treatment plants.

Although still in the early stages of development and less mature than tidal, wave, or OTEC systems, ongoing research and laboratory testing demonstrate its significant potential as a clean, predictable yet still largely untapped renewable energy source—particularly for regions with substantial river outflows and coastal access. However, the strict geographical requirements limit the salinity gradient's overall potential, resulting in a relatively modest estimate of 1,650 TWh per year.[40]

SALINITY GRADIENT TECHNOLOGY

Three main technologies have been developed to harness salinity gradient energy (SGE): *pressure-retarded osmosis (PRO), reverse electrodialysis (RED), and capacitive mixing (CapMix)*. PRO uses a semi-permeable membrane to create pressure from osmotic flow, driving a turbine. RED generates electricity directly by moving salt ions across selective membranes, while CapMix captures energy from changes in electrical capacitance between high- and low-salinity solutions.

39. International Renewable Energy Agency (IRENA). (2014). "Salinity Gradient: Energy Technology Brief." Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Jun/Salinity_Energy_v4_WEB.pdf

40. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

POTENTIAL ENVIRONMENTAL IMPACT

Unlike established renewable sources such as wind or solar, the environmental effects of salinity gradient energy (SGE) remain largely untested, as only a few pilot plants have operated long-term. Nevertheless, potential impacts can be inferred from the nature of its infrastructure and operation.[41]

Construction of SGE facilities — comprising membranes, pumps, and pipelines for freshwater and seawater intake and discharge — can disturb both terrestrial and marine habitats through land alteration, sediment movement, and noise pollution. Once operational, the intake of large water volumes may affect local hydrodynamics and marine organisms through impingement (organisms trapped against intake screens) and entrainment (organisms drawn into the system). Although modern intake screens can mitigate these effects, some level of impact is unavoidable. The introduction of hard structures underwater encourages biofouling — the colonisation of surfaces by marine life — which can impair system efficiency but also create artificial reef habitats that alter species composition and may promote invasive species. To prevent fouling and scaling, facilities require chemical treatments, including antifoulants and coagulants, which, if released, can change water chemistry, increase turbidity, and harm marine organisms.

Furthermore, SGE systems discharge brackish effluent that may contain chemical residues and alter local salinity and flow patterns. These hydrodynamic changes can influence nutrient cycling, larval transport, and species distribution, with effects varying by site.

In summary, while SGE is a clean and promising technology, its large-scale deployment will require careful environmental assessment, optimised intake and discharge design, and monitoring to minimise ecological disruption.

Chemical treatments and brackish discharge may change water quality and salinity, requiring careful management and monitoring

41. Seyfried, C., Palko, H., & Dubbs, L. (2018). "Potential local environmental impacts of salinity gradient energy: A review." Renewable and Sustainable Energy Reviews, 102, 111–120. Available at: https://doi.org/10.1016/j.rser.2018.12.003

COMPARISON OF OCEAN ENERGY TYPES

ASPECT	Tidal Energy	Wave Energy	OTEC *Ocean Thermal Energy Conversion*	Salinity Gradient
Energy Source	Gravitational pull of moon and sun causing sea-level changes and currents	Wind-generated surface waves	Temperature difference between warm surface and cold deep water	Salt concentration difference between freshwater and seawater
Main Technologies	Tidal barrage and tidal stream systems	Point absorbers, oscillating water columns (OWC), attenuators, overtopping devices	Open-cycle, closed-cycle, hybrid systems	Pressure-retarded osmosis (PRO), reverse electrodialysis (RED), capacitive mixing (CapMix)
Maturity Level	Most mature ocean energy type; several commercial-scale projects	Emerging; several prototypes and pilot plants	Early-stage R&D; limited pilot plants	Early R&D; a few demonstration plants
Resource Potential	~800–1200 TWh per year	~29,500 TWh per year	~44 000 TWh per year	~1,650 TWh per year
Predictability	Highly predictable and regular	Moderate; depends on wind conditions	Continuous (24/7 baseload)	Continuous and predictable in estuaries
Geographical Suitability	Coastal areas with strong tides (e.g., UK, France, Korea)	Coasts with high wave activity (Atlantic, Pacific, Australia)	Tropical regions (±30° latitude)	Estuaries and river mouths worldwide
Potential Environmental Impacts	Habitat alteration, noise, and potential fish migration disruption	Collision risks, underwater noise, pollution risk	Temperature and nutrient changes in discharge water	Changes in salinity and flow, chemical discharge, and biofouling

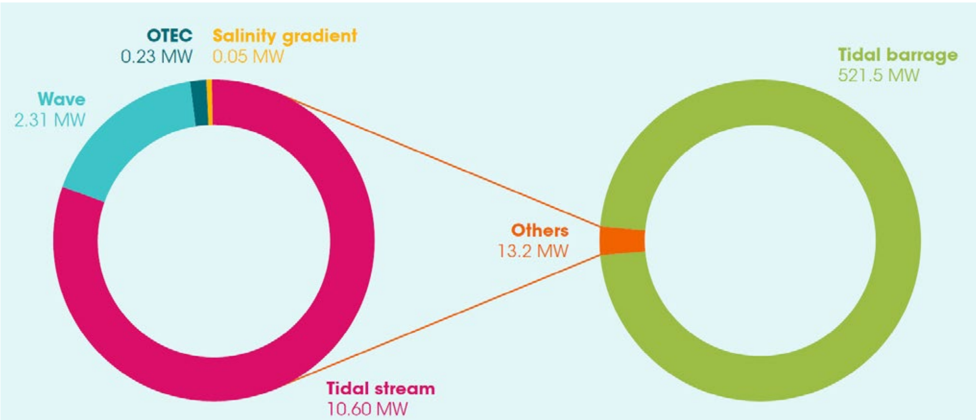
Global Outlook

GLOBAL DEPLOYMENT TRENDS BY OCEAN ENERGY TYPE

The global ocean-energy sector has major untapped potential, improving technology, and growing policy support — but deployment remains limited. Tidal energy currently dominates, with tidal-barrage plants in South Korea, France, and Canada providing over 98% of global capacity (about 521.5 MW).[42] Yet no major barrage projects have been built in nearly a decade due to site, environmental, and cost constraints, even as a 2.5 GW project pipeline shows ongoing interest.[43]

In contrast, tidal-stream systems are progressing toward pre-commercial deployment, especially in Europe. Wave energy is advancing too, but remains at an earlier stage, largely focused on prototypes and small pilot farms, and still behind tidal-stream technology in maturity and readiness.

Figure 3: Ocean Energy Deployment (MW)



Source: International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies".

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42. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

43. Ibidem

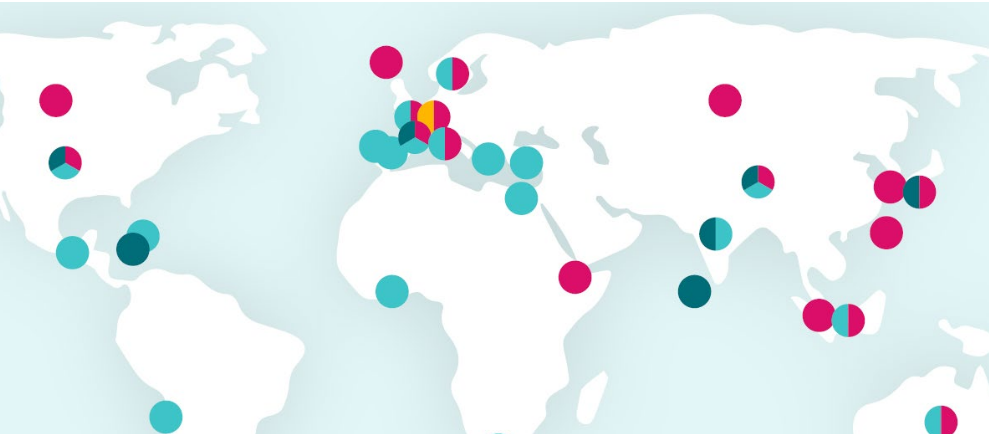
GEOGRAPHICAL DEPLOYMENT DISTRIBUTION OF OCEAN ENERGY

Ocean-energy deployment is uneven and concentrated in countries with strong marine resources and supportive policies. While 31 countries across six continents are deploying or planning projects, Europe leads with roughly three-quarters of current capacity and over half of planned installations, supported by funding, test sites, and market incentives like contracts for difference.[44] The UK and France are key tidal-stream hubs, while Portugal and Nordic nations lead in wave-energy testing.

Ocean-energy deployment is regionally concentrated, with Europe leading due to strong support

In Asia, South Korea and China focus on tidal power, while Japan and Pacific Island states (including Hawaii) pursue OTEC research. North America has strong tidal and wave potential — notably the U.S. West Coast and Atlantic Canada — but limited commercial rollout. Meanwhile, tropical nations in Southeast Asia and island regions are well-positioned for future OTEC, while estuary regions globally show theoretical SGE potential but remain experimental.

Figure 4: Global Distribution of ocean energy activity



Source: International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies".

44. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

Ocean Energy as a Blue Business Opportunity

BENEFITS

Ocean energy offers a wide range of benefits that extend beyond clean electricity generation, contributing to technological innovation, economic development, environmental sustainability, and energy security.[45] As one of the most predictable and continuous renewable energy sources, it holds significant promise for supporting the global transition to low-carbon energy systems, particularly for coastal and island nations. Energy harnessed from the ocean through offshore renewables can contribute to the decarbonisation of the power sector and other end-user applications relevant for a blue economy, for example, shipping, cooling, and water desalination.

Predictable and reliable power:
Tidal currents and ocean waves are highly predictable compared to wind or solar energy. This makes ocean energy a dependable source of electricity, capable of complementing other renewables and providing grid stability.

Low carbon and environmentally sustainable:
Ocean energy produces electricity with minimal greenhouse gas emissions, contributing directly to climate change mitigation. When developed responsibly, it has a smaller visual footprint than land-based renewables and can coexist with marine ecosystems.

45. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

Local energy security:

Coastal and island regions can leverage local ocean resources, reducing dependence on imported fossil fuels, increasing energy security, and improving resilience against energy price fluctuations.

Integration with other renewable energy sources:

Ocean energy can be combined with wind, solar, or other offshore renewables to create hybrid systems. This allows shared infrastructure, more efficient use of marine space, and a more consistent and reliable energy supply by balancing fluctuations from variable renewables.

Coupling with water desalination:

Ocean energy can be paired with desalination systems, using renewable electricity to produce fresh water from seawater. This integration provides a dual benefit of clean energy and sustainable water supply, particularly valuable for islands and water-scarce coastal regions.

Job creation and economic growth:

Developing ocean energy industries can stimulate local economies through manufacturing, installation, operation, and maintenance jobs, as well as opportunities in research, engineering, and environmental monitoring.

LIMITATIONS

Ocean energy technologies remain at an early stage of maturity, facing several barriers that restrict large-scale deployment.[46] Key challenges fall into five categories: technological, infrastructure, financial, regulatory and policy, market, and environmental.

Technological:

These barriers are related to long-term reliability, efficiency, and

and extreme weather can damage devices and increase maintenance requirements, slowing technological progress.

Infrastructure:

Grid access and supporting marine infrastructure are limited, particularly in remote coastal and island regions where ocean resources are strongest. High-cost installation vessels, port facilities, and subsea cables are required, adding logistical complexity.

Financial:

Manufacturing, installation, and maintenance costs remain high, electricity prices are not yet competitive with mature renewables like solar and wind. Limited operating history increases investor risk perception, making it harder to secure capital.

Regulatory and policy:

Unclear regulatory frameworks and lengthy permitting processes create uncertainty for developers. Inadequate revenue support instruments and poor reinforcement of standards further slow project timelines and investment decisions.

Market:

Deployment remains small in scale, limiting supply-chain development and investor confidence. The lack of commercial-scale projects delays cost reductions that typically come with learning and economies of scale.

Environmental:

Although less visually intrusive than land-based technologies, ocean-energy systems may affect marine life, sediment dynamics, and underwater sound levels. Further research and monitoring are required to ensure ecosystem protection.

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46. International Renewable Energy Agency (IRENA). (2020). "Innovation Outlook: Ocean Energy Technologies". Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Innovation_Outlook_Ocean_Energy_2020.pdf

STRENGTHENING THE RESPONSIBLE DEVELOPMENT OF OCEAN ENERGY

Advancing ocean energy must go hand-in-hand with ensuring its environmental integrity, community acceptance, and long-term sustainability. While economic viability and integration with other offshore activities can support deployment, the priority is to guide the sector's growth in a way that protects marine ecosystems and delivers public benefit.

Some ways to ensure the responsible development of ocean energy include:

Hybrid systems and synergies with other ocean uses (e.g., offshore renewables, aquaculture, desalination, hydrogen production) can make better use of marine space and infrastructure while providing a more consistent and reliable energy supply. In addition, coupling ocean energy with activities in the blue economy — including aquaculture, desalination, offshore cooling, and hydrogen production — can strengthen its commercial value and promote sustainable ocean-based industries.

It is important to mention that such approaches must be accompanied by rigorous marine spatial planning and precautionary principles to safeguard biodiversity and avoid conflicts with fisheries, shipping, and conservation areas.

Effective resource and site assessment is essential for advancing ocean energy. Projects should embed marine spatial planning and ocean mapping to improve access to baseline data.

Planning efforts must include cross-sector coordination and be paired with social, economic, and environmental impact assessments, including grid-capacity considerations. Close engagement with scientists, marine experts, and local knowledge holders is critical to ensure rigorous data collection, credible assessments, and science-based decision-making. Costs can be reduced through advanced modelling tools and by sharing data, methods, and best practices across industries, research institutions, and countries.

Islands and remote coastal regions present a particularly strong case for early adoption. With high dependence on imported fossil fuels and limited land availability, these areas can benefit from local, predictable, and renewable ocean energy resources that enhance energy security and resilience. Furthermore, ocean energy technologies can be integrated into coastal protection structures, combining power generation with climate adaptation measures such as breakwaters or storm barriers.

Yet deployment in these sensitive environments requires early and continuous engagement with local communities and scientists in the field, transparent environmental assessments and robust monitoring to understand and mitigate potential ecological impacts.

ONE OCEAN
Foundation

secretariat@1ocean.org
1ocean.org